PROJECT B: ALTERNATIVE AGRICULTURE AND VEGETATION MANAGEMENT

ALTERNATIVE AGRICULTURE AND VEGETATION MANAGEMENT IN THE WALKER BASIN

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

With increasing demands on available water resources in Nevada, research is needed to determine the practicality and profitability of growing low-water use crops. Currently, the majority of irrigated agricultural land in Nevada is used to grow alfalfa, a high-water use and relatively low-profit crop. In this study, we compared the performance of 14 varieties of 13 alternative crops, which included annual grain and biomass crops, under different watering regimes (4, 3, and 2 feet/acre) on several soil types in the Walker Basin, Lyon County, Nevada. The goal was to determine which species are the most productive in Nevada, as well as which species maintained the highest productivity under reduced water application. Teff and amaranth were the highest performing annual crops, with seed production comparable to production elsewhere. Additionally, both species produced seeds at the lowest watering levels. Warm season biomass crops were generally not as successful as cool season ones, though old world bluestem was an exception, establishing well and producing biomass comparable to cool season species. Additionally, bluestem was the top performing warm season grass in the lowest watering treatment. Cool season grasses established and grew well in both sites, and were very competitive with weeds. There was variability in performance of some species between sites, but tall wheatgrass was consistently a top performer, in both high and low water applications.

In some cases, farmers may choose to cease farming rather than continue to grow crops with large water requirements. When previously farmed land is reverted back to an unmanaged state, this can lead to soil loss and/or the creation of weedy acreage with low-quality forage. We compared the establishment of multiple restoration species (a mix of native grasses and shrubs), monitoring the relative success of planted species with either little (1 foot/acre) or no water addition. All native grasses established significantly better with water application, though there were differences in rank performance between sites. Indian ricegrass was the best performer at one site, with the highest biomass and weed suppression of the other grasses, while beardless wheatgrass was the top performer at the other restoration site. Sagebrush survived transplanting significantly better than other species, and greasewood, though it had low survival, had the fastest growth rate and responded the most to water addition. Watering will not continue in 2010, and additional monitoring will determine which species shows the best long-term potential for revegetation of former farmed sites in Nevada.

INTRODUCTION

Irrigation is the largest water use in the state of Nevada, with field crops accounting for 70% of total irrigated acreage (Nevada Agricultural Service). Ninety-three percent of the field-crop land in Nevada is utilized for hay production, primarily alfalfa (63% of hay acreage in 2007, Nevada Agricultural Service). Alfalfa is a water-intensive crop and may be poorly suited to an arid region where water is becoming increasingly scarce (Grimes et al. 1992). While alfalfa plants will survive with less water than is currently applied (four feet/acre), withholding water from alfalfa fields reduces yield and eventually permanently damages the plants (Ottman et al. 1996). Alfalfa is a relatively low-value crop (Breazeale and Curtis 2006), and little research has been conducted to gage the productivity of other low water-use alternatives. Thus, data are needed to provide Great Basin farmers with viable alternatives to alfalfa production. Other crops may be equally or more profitable to grow than alfalfa and with less water. While there is a strong interest within Nevada's agricultural community in growing specialty crops, no information is currently available on the suitability of alternative crops to Nevada's agricultural lands (USDA plants database http://plants.nrcs.usda.gov).

We tested the performance of three main types of plants under three different watering regimes: annual pseudograin crops, cool season biomass crops, and warm season biomass crops. Annual pseudograin crops can be used as either alternative food crops for humans or high-quality forages (Sedivec and Schatz 1991, Abule et al. 1995, Sleugh et al. 2001, Curtis et al. 2008). Because the growing season of annual crops is shorter than perennial ones, overall water use by these plants is normally lower than alfalfa. Biomass crops are currently under investigation for use as alternative cellulosic ethanol fuels (Milliken et al. 2007). Warm season grasses use C_4 photosynthesis, and have greater water use efficiency (WUE) than cool season grasses, which use C_3 photosynthesis. Alfalfa also uses C_3 photosynthesis and has WUE rates comparable to other C_3 species (Grimes et al. 1992). Warm season grass phenology dictates that growth occurs in the hottest part of the year, and long day lengths combined with increased temperature can lead to extremely high productivity in these species. In addition, warm season grasses are particularly recommended for biofuel production (Sanderson et al. 2006).

Nevada has a range of environmental variability that far exceeds the variability of the Northern Prairie, where most data on biofuel crops are collected. Warm season and cool season grasses have different responses to environmental variability that directly affect their suitability for biofuel production (Jefferson et al. 2004), and the warm season plant phenology requires that water be applied during the hottest part of the growing season, when water can sometimes be unavailable in Nevada. Additionally, competition with common weed species may be higher for warm season grasses, as soil resources may be preemptively uses by predominantly cool season weeds.

The first portion of this study evaluated the relative performance of annual vs. perennial species and C_3 vs. C_4 species when grown in conditions typical in the state, including soil characteristics, weed competitors, and limited water availability in some years. We present data on the productivity of perennial biomass crops at two sites under different watering regimes. Analysis on whether new crops have the potential to significantly increase the earning potential of farmers while decreasing water use is presented in Curtis et al. (this volume).

The amount of land used for agriculture in Nevada has been slowly declining. Irrigated land has dropped from 8,900,000 acres in 1983 to 6,300,000 acres in 2007-2008 (Nevada Agricultural Statistical Service 2008). While some of agricultural land has been converted to housing and suburban use, some farms have been abandoned following the sale and or transfer of water rights from the land. Abandoned farms generate an environmental legacy that includes air pollution from soil loss and acres of weedy wastelands with poor regeneration of native vegetation (Jackson and Comus 1999). In desert areas, land that has been previously used for agriculture does not automatically revert to native vegetation when farming ceases (Jackson and Comus 1999, Jackson and

Jackson 1999). If reseeding does not occur, weeds will proliferate and soil will be lost. Sowing perennial grasses and irrigating at a low level through the establishment phase may suppress weeds (Blumenthal et al. 2005, Bugg et al. 1991), increase water quality (Lodge 1994), and encourage establishment of native vegetation after a farm has been abandoned (Burke et al. 1995).

There is some evidence that seeded perennials may not persist on abandoned agricultural lands without management (Rein et al. 2007), but the effect of a minimal watering regime to assist establishment has not been tested in Nevada. Seeding perennial grasses may provide forage for large herbivores and habitat for birds and other small animals, both of which are superior to weed infested lands (Elstein 2004). The potential for and effectiveness of restoring agricultural lands using perennial grass seedings and shrub planting has not been researched in the Great Basin. Species commonly used in post-fire restoration in the Great Basin may also be effective in reclaiming abandoned agricultural land. In the second portion of this study, we tested the effectiveness of five different perennial grass species and four native shrubs, and included comparisons of commercially available varieties within two grass species. We expect that water would increase establishment and productivity of seeded grasses and shrubs, but also expected weeds to respond favorably to water application. Our hope is that over time, perennial species will come to dominate restored sites: as they become established, they may become more competitive for soil resources.

METHODS

Overview

These experiments were initially conducted at four locations in Mason Valley, Lyon County, NV (Figure 1) in 2007/2008. Establishment of all species was poor at two of these sites, and these were abandoned at the end of the 2007/2008 season, reducing the experiment to two remaining sites. Overall, 24 varieties of 22 species were planted, including warm and cool season biomass crops, alternative annual pseudograin crops, native grasses and shrubs. Annual crops were planted anew in the late spring in 2008 and 2009, while perennial grasses were established once, in either the fall of 2007 (cool season grasses) or the spring of 2008 (warm season grasses). Perennial shrub seedlings were transplanted into restoration sites at two locations in the fall of 2008.

The goal of the irrigation applications for the annual pseudograin crops, cool season biomass crops, and warm season biomass crops was to apply one of three watering levels: a full, 100% watering treatment designed to correspond to standard alfalfa farming practices (4 acre feet of water/year), a 75% treatment (3 acre feet/year), or a 50% treatment (2 acre feet per year). The goal of the irrigation applications for the restoration experiment was to apply either a 25% treatment (1 acre foot/year), or a no water treatment. Annual crops were harvested at the end of each growing season (2008, 2009). Establishment and density measurements of perennial grass species and weeds were recorded in 2008, as well as productivity for cool season grasses at one field and production data for a subset of annual crops. Biomass measurements of warm and cool season perennial grasses and weeds were obtained in 2009, as well as survival and growth measurements of transplanted shrubs in restoration fields, and production data was again obtained for a subset of successful annual crops.

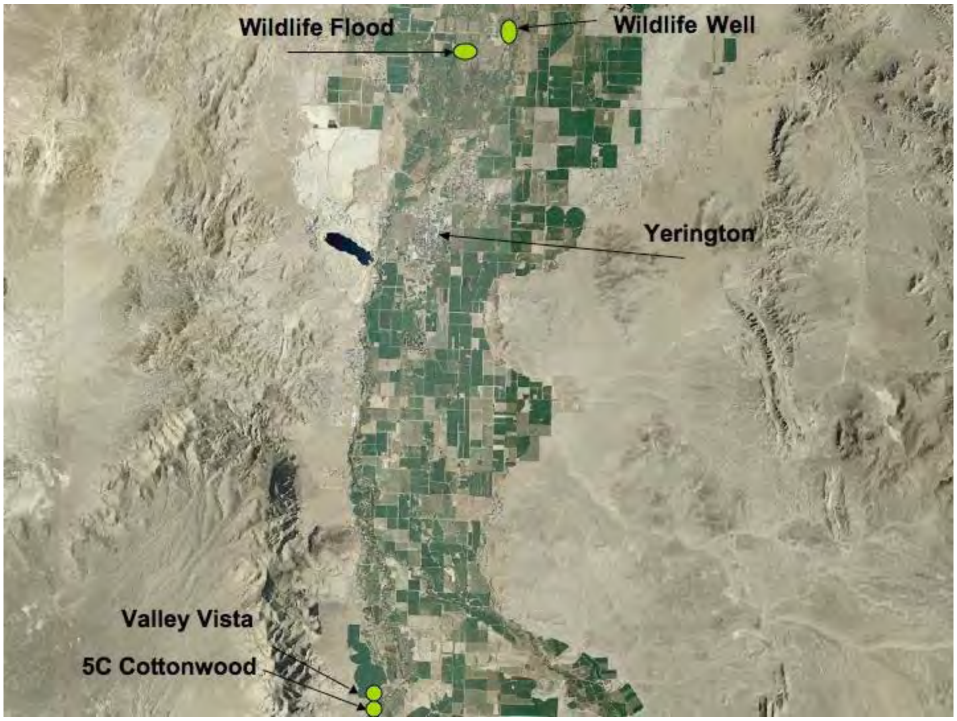


Figure 1. Location of all four field sites. Wildlife Flood and Wildlife Well were farmed in 2007/2008 only; Valley Vista and 5C Cottonwood were farmed for two growing seasons (2007/2008 and 2008/2009).

We anticipate maintaining the two successful fields for additional growing seasons. The current watering regime will be maintained on warm and cool season biomass crops, and productivity will be monitored for an additional 2-3 years. Restoration fields will be unwatered in 2010, and we will monitor the survival and productivity of restored species and weeds in these plots for an additional 2-3 years. If we receive additional funding, trials of the successful annual grain crops will be tested for the next 2-3 years, with alternative weed management methods incorporated into the planting design, in order to determine the best cultural practices for establishing these species.

Field Locations and Preparation

2007/2008

The Wildlife Flood (Figure 2a) and Wildlife Well (Figure 2b) sites were formerly utilized for forage cultivation at Mason Valley Wildlife Management Area, and are collectively referred to as the Wildlife sites (39°02’ N, 119°06’ W. The 5C Cottonwood site (5C) and Valley Vista sites occur on private ranch properties (Figure 2c), and are collectively referred to as the Ranch sites (38°51’ N, 119°11’ W). The 5C site is a historically cultivated field, which has been fallow for 20+ years, and the Valley Vista site was used for alfalfa cultivation up to the start of this experiment. Three fields (5C, Valley Vista, and Wildlife Well) were irrigated with sprinklers, and Wildlife Flood was irrigated with flood irrigation. These fields occur on different soil types with different salinities, as detailed by Miller et al. (this volume).

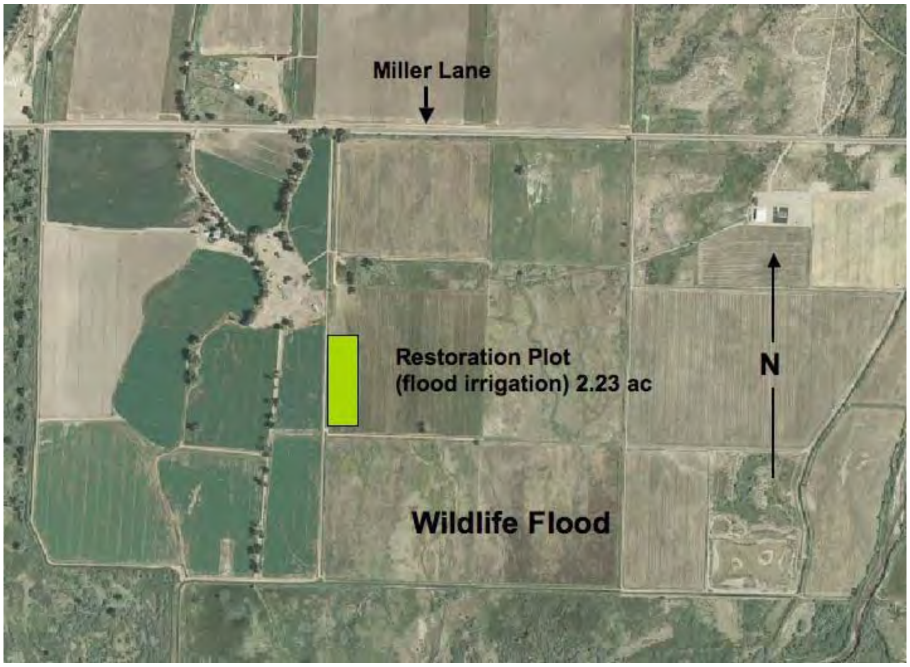


Figure 2a. Wildlife Flood site. Restoration site shown in rectangle; no crops were planted at this site.

Figure 2b. Wildlife Well site. Restoration field is eastern-most rectangle, alternative crops are in western rectangle.

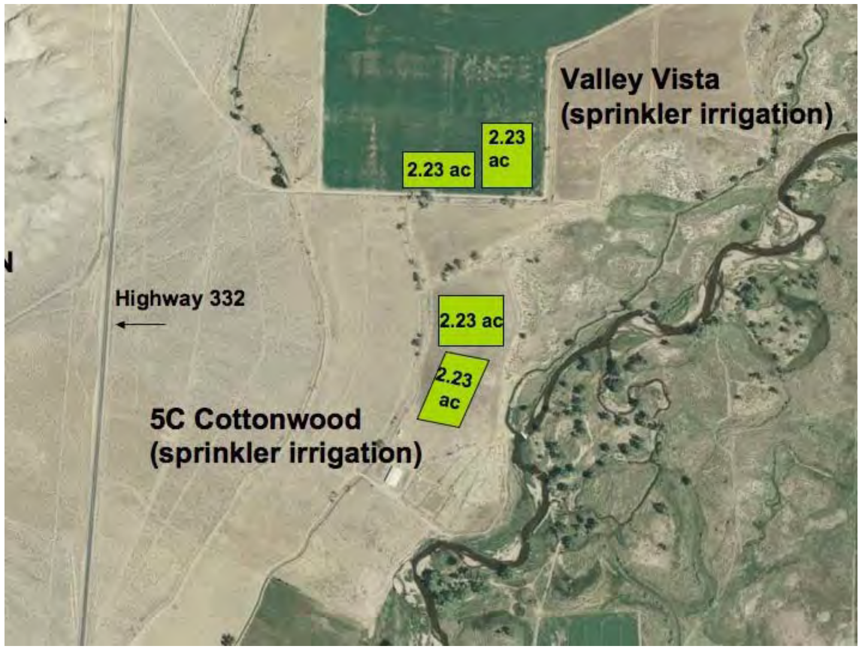


Figure 2c. 5C and Vista Valley sites. Restoration fields are west (Valley Vista) and south (5C) fields.

Both herbicide and mechanical treatments were used to prepare the fields for planting. An herbicide treatment (Glyphosate, 1.0 a.e lb/acre in 20 gallons water per acre,) was applied to the Valley Vista site on June 29, 2007 in an effort to kill the existing alfalfa. It was only marginally successful and the field was resprayed on August 20, 2007 with a tank mixture of Glyphosate (2 lbs a.e. per acre) and Dicamba (.5 lbs a.i. per acre) in 20 gallons of water per acre. In addition, the same herbicide mixture was applied to the Wildlife Well and flood sites on the same date. Herbicide was applied to the Well site in an effort to control creeping wild rye (*Leymus triticoides*) and willow (*Salix* sp.) resprouts. The application to the Wildlife Flood site was to control existing tall wheatgrass (*Thinopyrum ponticum).*

The three fields prepared for sprinkler irrigation (Wildlife Well, 5C and Valley Vista) were ripped, disced and floated in September of 2007. The Wildlife Well site was mowed prior to ripping, discing and floating to remove large amounts of standing willow (*Salix* sp.) biomass. The Wildlife Flood site was prepared for flood irrigation by mowing, ripping, and discing followed by laser-leveling and levee building to separate different watering treatments.

Establishment of Restoration Fields

2007/2008

Six sowing treatments (corresponding to seven varieties of five species, and one control, non-seeded treatment, Table 1a) and two watering regimes (no water and 25% water,) were combined in a factorial design, with three replicates of each species and water combination per field (Figure 3a). Watering regimes were applied in strips, with each strip alternately no- or 25% water, for a total of three treatment blocks. Two strips were non-randomly sown, while sowing treatments were random in the other four strips. Plots were 30 by 90 feet, and each strip contained a full complement of the six sowing treatments. Single varieties of beardless wheatgrass, inland saltgrass, and basin wild rye were sown, and two varieties of Indian ricegrass and of western wheatgrass were sown, at recommended seeding rates (Table 1a). When two varieties were sown, the plot was split and half the plot (30' by 45') was sown with one variety, and half with the other. Seeds were planted using a Truax seed drill, with seeds placed 0.5 inches deep, followed by press wheels. All plots except saltgrass plots were rolled with a cultipacker after seeding. The Well and Flood sites were sown Nov 19-20 2007. The 5C site was sown Dec 13, and Valley Vista was sown Dec 18. Saltgrass seeds were scarified by alternating temperatures (40° C and 20° C, each 12 hours) in the growth chamber from May 16 to July 14 prior to sowing into the 5C and Valley Vista fields on July 15 2008.

Table 1. Seeded plant abbreviations and seeding rates.

Common name	Scientific name	Variety	Lbs (pls)/acre	Code
	Restoration species			
a. Grasses				
Indian ricegrass	*Achnatherum hymenoides*	Nezpar, Rimrock	8	Ric
Basin wildrye	*Leymus cinereus*	Trailhead	10	Bas
Beardless wheatgrass	*Pseudoroegneria spicata*	Whitmar	8	Bea
Western wheatgrass	*Pascopyrum smithii*	Arriba, Rosana	12	WesA WesR
Saltgrass	*Distichlis spicata*	VNS	14	Inl
Control	Nothing sown	-	-	NS
b. Shrubs				
Shadscale saltbush	*Atriplex confertifolia*	-	-	
Fourwing saltbush	*Atriplex canescens*	-	-	
Greasewood	*Sarcobatus vermiculatus*	-	-	
Wyoming sagebrush	*Artemisia tridentata ssp. wyomingensis*	-	-	
c. Cool season grasses				
Tall wheatgrass	*Thinopyrum ponticum*	Alkar	15	Tal
Basin wildrye	*Leymus cinereus*	Trailhead	10	Bas
Mammoth wildrye	*Leymus racemosus*	Volga	12	Mam
Tall fescue	*Schedonorus phoenix*	Fawn	15	Fes
d. Warm season grasses				
Switchgrass	*Panicum virgatum*	Nebraska 28	7	Swi
Sand bluestem	*Andropogon hallii*	Woodward	12	San
Indiangrass	*Sorghastrum nutans*	Cheyenne	7	Ind
Prairie sandreed	*Calamovilfa longifolia*	Goshen	7	Pra
Bluestem	*Bothriochloa ischaemum*	WW Iron Master	8	Blu
e. Annuals & alfalfa				
Teff	*Eragrostis tef*	Brown	2	TefB
Teff	*Eragrostis tef*	Ivory	2	TefI
Buckwheat	*Fagopyrum esculentum*	Mancan	50	Buc
Amaranth	*Amaranth hybridus* x *hypochondriacus*	Plainsman	2	Ama
Pearl millet	*Pennisetum glaucum*	Tifgrain 102	3	Mil
Alfalfa	*Medicago sativa*	Mountaineer 2.0	20	Alf

a. Restoration plot layout					
I		**II**		**III**	
25	**0**	**25**	**0**	**25**	**0**
RicN RicR	RicN RicR	WesA WesR	NS	Inl	WesA WesR
Inl	Inl	Inl	WesA WesR	Bea	RicR RicN
Bea	Bea	NS	Inl	Bas	Inl
NS	NS	Bea	Bas	NS	Bea
WesA WesR	WesA WesR	Bas	RicN RicR	RicR RicN	Bas
Bas	Bas	RicR RicN	Bea	WesR WesA	NS

b. Biomass and grain crop layout								
I			**II**			**III**		
50	**75**	**100**	**100**	**75**	**50**	**50**	**75**	**100**
Ama	Ama	Ama	Bas	Blu	Blu	Ama	TefI	Alf
Bas	Alf	Swi	Mil	Fes	TefI	Fes	Ama	San
Buc	Buc	Buc	Pra	Pra	Mam	Alf	Fes	TefI
Alf	Ind	Ind	Blu	Ama	Alf	Tal	Buc	Fes
Ind	Tal	Mil	Ama	Mam	TefB	San	Alf	Mil
TefI	TefI	TefI	Swi	Mil	Fes	Ind	Blu	Mam
Blu	Blu	Blu	Alf	TefI	Pra	TefI	Mil	Blu
Pra	Pra	Pra	Ind	Bas	Tal	Buc	San	TefB
Tal	Fes	Fes	TefI	Alf	Buc	Mil	Ind	Ama
Mam	Mam	Bas	San	TefB	Mil	Blu	Bas	Buc
Fes	Bas	Mam	Buc	Ind	Bas	Swi	Mam	Swi
TefB	TefB	TefB	Mam	San	Ama	Pra	Tal	Ind
Swi	Swi	Alf	TefB	Tal	San	Mam	Swi	Tal
Mil	Mil	Tal	Fes	Swi	Swi	Bas	TefB	Bas
San	San	San	Tal	Buc	Ind	TefB	Pra	Pra

Figure 3. Examples of restoration (a) and biomass and grain crop (b) plot layout. Roman numerals correspond to blocks, watering treatments (0, 25, 50, 75, 100) correspond to strips, and individual boxes are 30’ by 90’ plots in (a), and 24’ by 30’ plots in (b).

2008/2009

Two-year old seedlings of four shrub species (Table 1b) were transplanted into the restoration plots at 5C and Valley Vista on December 2, 2008. A total of 77 shadscale, 118 four-wing saltbush, 93 black greasewood, and 132 Wyoming sagebrush individuals were planted across both sites. Seedlings were grown in an outdoor location in Reno, NV, in ½ gallon plastic pots, and were hand transplanted approximately 5 m apart. Seven shrubs were planted in each plot, with one of each species in each plot, and the remaining three spots assigned at random from the remaining plants available. Initial size measurements were recorded (height, width, and length) on 3/25/09, and final survival and size measurements were taken on 8/15/5009. A small number of shrubs were excluded from analysis, if their identification tags were removed or loss appeared to be from unexpected causes (e.g. deer pulled plants from the ground).

Establishment of Biomass and Alternative Annual Crop Fields

Cool season species (Table 1c), warm season grasses (Table 1d), and annual psuedograin crops (Table 1e) were sown in three of the four locations (5C, Valley Vista, and Wildlife Well). The fifteen different species were sown in strips receiving either 50%, 75% or 100% irrigation. Each strip contained a full complement of species, with plot measuring 24’ by 30’, and each species by watering treatment combination was replicated three times per field (Figure 3b). One set of irrigation treatments (a block) contained a non-random array of sown species, the other two blocks of irrigation treatments had species plots randomly assigned.

Cool season grasses were planted in November and December of 2007. The warm season grasses were planted in May 2008: Valley Vista was planted May 20, 5C on May 21, and Wildlife Well on May 22. All of these plots were sown using a Truax seed drill, with seeds planted 0.5 inches deep, followed by press wheels. A cultipacker was used after sowing on the cool season grasses. Annual pseudograins were planted 0.5 inches deep, except for teff, which was planted as near the surface as possible. In 2008 the annual grains were planted on May 20, 21, and 22, and on June 1 and 2, 2009.

Irrigation

In both years, the fields were irrigated using 3” hand lines with rainbird sprinkler heads set on a 30’ by 30’ pattern. The sprinkler heads used were ½” brass impact heads delivering approximately 2 gallons/minute/sprinkler. A totalizing flow meter was installed at all locations and used to determine irrigation application amounts. In both years a small amount of watering occurred starting at the beginning of April as a part of the irrigation installation and calibration process.

In 2008, the allowable water available for the 5C site was inadequate to complete the planned irrigation levels on all of the biomass and psuedograin experiments. The restoration plots at three sites received the planned treatment amount, as did the experimental plots at Valley Vista and Wildlife Flood sites. Irrigation at the Wildlife Well site was discontinued mid-season due to problems with the irrigation system, lack of plant establishment, and excessive weed competition.

The 5C, Valley Vista, and Wildlife Well fields were sprinkler irrigated beginning in May 2008. Wildlife Flood was first irrigated on May 5, 2008. On July 9, 2008 the sprinklers to the 50% watering treatment were turned off at 5C, when all treatments had received 2 ft/acre of water. The 75% and 100% irrigation treatments on the 5C site were not applied due to a lack of irrigation water. On July 18, 2008 the sprinklers to the 50% watering treatment were turned off at Valley Vista, followed by the 75% irrigation treatment on August 18, 2008. The final irrigation on Valley Vista occurred on September 8, 2008 when the 100% irrigation treatment levels had been reached.

Only the 5C and Valley Vista sites were irrigated in 2009, and available water was adequate to meet the experimental irrigation treatments on all experimental plots. The experiments were irrigated on a weekly basis beginning in late April (biomass crops and restoration plots), or early June (annual crops) using the equipment and techniques described above. The irrigation was discontinued in each treatment strip when the appropriate amounts of water had been applied. Irrigation was completed in the last week of August 2009 when the 100% level was obtained.

Weed Seed Bank Measurements

Soil cores were taken from all four restoration fields in December 2007 for weed seed bank analysis. Twenty-five haphazardly-placed cores (1” in diameter, 6” deep) were taken per strip. Cores were mixed within strips, and separated into two subsamples per strip. Each subsample was prepared for greenhouse germination (after Creech et al. 2008) by mixing 400ml of soil mixed with 200ml of sand, and placing it in a flat 25cm x 25cm pot which had a 1cm layer of perlite at the bottom, covered with landscaping cloth. Pots were placed on greenhouse tables covered with tarp under polyester quilt batting in order for moisture to wick up through the bottom of the pot. Pots were also watered from above as needed to keep both the soil and the quilt batting moist. Greenhouse temperatures were kept above 50°F and below 90°F, and pots experienced ambient day length. Pots were placed in the greenhouse Feb 5 2008, watering commenced, and germination was monitored. On 17 March 08, the soil within each pot was mixed, and watering and germination monitoring continued until April 17. At this point the pots were allowed to completely dry for one month. Soil was mixed within each pot on May 17, and pots were watered and germination was recorded through June 17 2008. Seedlings were identified to species, when possible, but data presented here is total density of all weed species.

Weed Control

The restoration and biomass/annual pseudograin crop fields were sprayed, mowed, and hand-weeded as needed in an attempt to control common tumble mustard (*Sisymbrium altissimum*), tansy mustard (*Descurainia pinnata*), filaree (*Erodium* sp.), lambsquarters (*Chenopodium album*), kochia (*Kochia scoparia*), annual bursage (*Amabrosia anthicarpa*), goatshead (*Tribulus terrestris*) cheatgrass (*Bromus tectorum*),barnyardgrass (*Echinochloa crus-galli*), and annual love grass (*Eragrostis spp.*).

Prior to planting in May of 2008, all plots in restoration, biomass and alternative crop fields were treated with 0.5 lbs a.e./acre 2,4-D ester in 20 gallons/acre of water. The 5C and Valley Vista sites were mown to a height of 2 inches in June 2008 as a post-emergence weed control treatment for annual grasses. Additionally, post-emergence weed control herbicide sprays were applied in to 5C and Valley Vista in June 2008, using a 4-wheeler with 15 foot boom applying 15 gallons/acre of water ± .025% NIS (nonionic surfactant). In these treatments the teff, pearl millet and warm season grasses were treated with 0.33 oz/acre escort. The cool season grass plots were treated with 0.5oz/acre escort ± 0.5 pound/acre a.e 2,4-D low volatile ester ± 2.5% by volume AMS (ammonium sulfamate). Buckwheat, amaranth, and alfalfa plots at these two fields were not sprayed, but were hand-weeded during June and July 2008. Alfalfa plots were mowed at Valley Vista on June 27 and at 5C on July 2, 2008. Warm season grass plots at 5C were mowed to a height of 2" on July 7, 2008. In late June, prior to planting, the saltgrass plots at 5C and Valley Vista were sprayed with roundup (0.76lb/acre glyphosate, 0.0475 lb/gal concentration, ± 0.025% NIS) to control summer annual weeds growing in the plots. Mowing of the warm season grass plots to a height of 6" continued throughout the growing season, at approximately every two weeks in an attempt to reduce competition from annual grasses.

The 2009 weed control efforts consisted of herbicide application mowing and hand weeding on the biomass/alternative crop experiments. No weed control efforts were undertaken on the restoration plots in 2009. The warm and cool season grass biomass plots on the 5-C and Valley Vista sites were sprayed on April 27 and 28, 2009 with 2,4-D amine at 1.5 pounds a.e. plus .25% NIS in 15 gallons of water per acre. The spray was applied using the equipment described previously. The plots were mowed in mid-May to a height of approximately 6" in an attempt to reduce competition from annual grasses. The Valley Vista plots were spot sprayed by hand using Weedmaster (Dimethylamine salt of dicamba 12.4%, Dimethylamine salt of 2,4-dichlorophenoxyacetic acid 35.7%) @ 1oz weedmaster/gallon of H2O for broadleaf weed control.

The annual psudeograin plots on 5-C and Valley Vista were sprayed on April 27 and 28, 2009 with 2,4-D amine at 1.5 pounds a.e. plus .25% NIS in 15 gallons of water per acre. The spray was applied using the equipment described previously. The plots were then rototilled to a depth of 3 inches in mid-May to control annual weeds described previously. In late May and June, prior to and following planting, the plots were spot (hand) sprayed with Round-up Super Concentrate (glyphosate isoproylamine salt 50.2%) at 2.5 fluid oz/gallon H2O to control all emerged annual plant species. All annual pseudograin plots were hand weeded at both sites. Hand weeding continued throughout the growing season on a weekly basis or as required.

On July 2, 2009 the east half of each buckwheat and amaranth plot on the Valley Vista site was hand sprayed with Poast (sethoxydim 18%) @ 1.9 fluid oz/gallon H2O. This treatment was necessary as the annual grass populations were unable to be controlled using hand weeding and the competition was threatening the viability of the crop species on these plots. Only half of each plot was sprayed, as we were uncertain about the effects of the herbicide on the desired species. The treatment was successful and the production data was obtained from the treated side of the plots.

Fertilization

The plots were not fertilized in 2007-2008 as potential weed competition was deemed to be a major factor and soil test did not indicate the need for fertilizer applications. During 2009 all of the cool and warm season grass plots on the 5-C and Valley vista site were fertilized with 476 pounds per acre of ammonium sulfate (21-0-0). The pseudograin plots on each location were fertilized with the same material at 238 pounds per acre. The fertilizer was applied using hand broadcasters on May 18, 19 2009. No other fertilizers were applied during the course of the experiment.

Monitoring Germination and Establishment

Establishment of seeded species was recorded in 2008 by sampling plots with a rectangular 22 x 31cm frame. Cool season biomass plots were sampled in a stratified random manner with five samples taken per plot. Sampling dates were April 18 for Valley Vista, April 21-22, 2008 for 5C, May 5 for Wildlife Well, and May 6 for Wildlife Flood. Weed density and cover data were also collected at this time. Weed species were either morphotyped or positively identified, and the number of individual weed plants (all species/morphotypes) and the percent cover within the frame was assessed for each quadrat. Here we present data for all weed species combined for simplicity. Establishment of warm season biomass and annual crops was sampled on July 13-15, 2008, using the same methodology. Weed density and cover were not collected for warm season and annual species because weed control efforts at this point were plot and species specific, including mowing and herbicide use that differed (by necessity) by species.

Restoration plots (except saltgrass, which wasn't planted until July 2008) were sampled with the same methodology and over the same time frame. The only exception was in plots with two varieties, where three samples were taken in each half of the plot. Weed densities and cover were measured at all four restoration fields in late April through early May and again in late June through early July 2008. For weed sampling, five stratified-random samples were taken per plot using a rectangular 22 x 31cm frame. When two native seed varieties were sown in a plot, three samples were taken from each half of the plot. Restoration plots were sampled again, using the same protocol to determine mortality over a 5-7 week period: the 5C and Valley Vista sites were sampled on June 12, and Wildlife Well and Wildlife Flood sampled on June 13 2008. Initial shrub size was measured on March 25, 2009, by measuring the height of the tallest point, the length of the widest area, and the width of the shurb perpendicular to its length.

Establishment of seeded species was recorded in 2008 after sowing, by sampling plots with a rectangular 22 x 31cm frame. Cool season biomass plots were sampled in a stratified random manner with 5 samples taken per plot. Sampling dates were April 18 for Valley Vista, April 21-22 for 5C, and May 5 for Wildlife Well. Weed density and cover data were collected at this time. Restoration plots (except saltgrass) were sampled similarly and on the same dates, however plots with two varieties had 3 samples taken in each half of the plot. The Wildlife Flood site was sampled on May 6 2008. Restoration plots were sampled again, using the same protocol to determine mortality over a 5-7 week period: the 5C and Valley Vista sites were sampled on June 12, and Wildlife Well and Wildlife Flood sampled on June 13 2008. Warm season biomass and alternative crops were sampled post-emergence in a completely random manner, using the same frame size and sampling frequency as the other plots. Establishment of seeded plants was monitored on July 13-15 2008. Weed density and cover were not collected in these plots, because weed control efforts at this point were plot and species specific, including mowing and herbicide use that differed (by necessity) by species

Harvest and Productivity

Restoration Plots

Density and biomass of native grasses and weeds were recorded on August 11-12, 2009. The plots were monitored with five 25 cm2 quadrats randomly placed throughout the plot, with the exception that plots with two varieties were sampled with three quadrats per variety. After crop wet biomass was recorded, a subsample of the target restoration species from each plot was collected and weighed wet, oven dried at 40°C and reweighed to obtain a formula for wet/dry biomass conversion. Data is presented as dry biomass, in grams/m^2. Because of the large variability in weed identity from plot to plot, an average water content would not have been very helpful for determining dry weights across plots. Therefore, weed biomass was not dried, and is presented as wet weights, in grams/m^2. Shrub size survival and size was measured on August 15, 2009, again, measuring height, length, and width of plants.

Biomass Harvest

In 2008, biomass data was only collected from the cool season grass plots located on the Valley Vista site. The cool season biomass production was collected from a 20 square meter plot subplot using a Carter forage harvester. A grab sample was obtained, weighed, oven dried and reweighed to convert wet weights to dry. The results are presented as 100% dry matter and are displayed in tons/acre. In 2009, all grass biomass plots from both sites were evaluated for production of seeded species and weed species by clipping and weighing. Sampling took place September 3, September 8-11, and September 14-16 2009. Three randomly located 50 cm^2 quadrats were placed within each plot, except for one species at one site (Tall Fescue at 5C), which had poor establishment. For this species, 25cm^2 quadrats were placed subjectively within the plot in areas where establishment had occurred. Plants were cut to approximately 1 cm above the ground, and separate wet weights were taken for crop and weed biomass. A subsample of wet material of each crop was collected, dried, and weighed for wet/dry conversions.

Alfalfa Harvest

No alfalfa production data was obtained in 2008 as the seeded stands were not fully established. In 2009 the alfalfa plots were harvested 3 times (June 8, July 21, September 3) at the early bloom stage of growth. Each plot was harvested using a Carter forage harvester. Total biomass was weighed from a sub-plot approximately 6.8 square meters in size. A grab sample was obtained, weighed, dried, and reweighed for conversion to dry biomass. The results are presented as 100% dry matter and are displayed in tons/acre

Alternative Grain Harvest

The annual pseudograin crops were harvested during October of 2008 and 2009. In 2008 the teff varieties were evaluated using a Kincaid plot combine to cut a 53.5 square meter area within each plot. The resulting seed was hand cleaned using screen sieves and forced air to separate chaff and contaminates from the seed. In 2009, the teff crops were harvested within a 9 square meter area in each plot using a sickle bar mower. The seed heads were then clipped by hand, and the seeds were collected by rubbing the dry seed heads on a screen. The resulting seeds were then cleaned as previously described. In 2008 and 2009, the amaranth plots were hand harvested by clipping all the seed heads from 3 randomly located, 1 square meter sub-plots in each main amaranth plot. In 2008, measurements were only taken at the 5C, as the plots at the Valley Vista site were lost due to weed competition. The seeds were separated by rubbing the heads on a screen and then cleaned as described previously for teff. The buckwheat and pearl millet plants did not produce enough seeds for harvest in 2008 or 2009.

Data Analysis

All analyses were conducted with JMP (JMP 5.0, SAS Institute, Cary NC), and significance was measured at the $P = 0.05$ level. In all figures, different letters indicate significant differences as measured by Tukey's HSD tests, and bars are standard error. Unless otherwise indicated, transformations were not required to meet assumptions of ANOVA. Unless specified otherwise, ANOVA model effects were: field, block (nested within field), watering treatment, species, and all two and three way interactions between field, species, and water treatment. Due to extreme differences in variance between the Ranch sites (5C and Valley Vista both had high establishment) and the Wildlife sites (Wildlife Well and Wildlife Flood both had low and variable establishment), the Ranch and Wildlife locations were analyzed separately for the 2008 measurements.

Early establishment (April 2008) and end of year one (June 2008) survival of seeded restoration species and of weeds was analyzed using ANOVA. Response variables were the number of established seeded individuals per m^2 and the percent weed cover. Varieties of Indian ricegrass and western wheatgrass were analyzed separately with a similar model separately (with variety in place of species) to determine if the varieties should be kept apart in the full analysis. The two varieties of Indian ricegrass did not perform significantly differently in 2008 or 2009 and were combined for analysis. The Arriba and Rosana varieties of western wheatgrass performed differently ($P < 0.0001$), and so were kept separate in the full analysis. Seed bank data from restoration plots was analyzed with subsamples of strips within blocks averaged prior to analysis, and these averages were analyzed with ANOVA model with field and block nested within field as the model effects. Dependent variables were the total number of weeds, the number of forbs, and the number of grasses per m^2.

Second year measurements were analyzed with the same ANOVA model. Performance of restoration grasses (biomass and density) was analyzed in two ways: once with all species in the model, and separately for the two varieties of Indian ricegrass and western wheatgrass, to test for performance differences between the commercially available varieties. Survival of shrubs was analyzed with logistic regression, and final shrub size (length x height x width, log transformed) was analyzed with the standard ANOVA model, except that initial size of the shrub was included as a covariate, and site was not included, as not all species survived in all watering treatments in both sites. Additionally, growth rate was calculated as (final size-initial size)/initial size.

Early establishment (April 2008) of seeded biomass species and alternative grains was analyzed using ANOVA without watering treatment in the model (because they were not yet different), while second season productivity measurements were analyzed including watering treatment in the model. Number of seeded individuals per meter established, percent seeded species cover, and percent weed cover (cool season grass plots only) were the response variables analyzed from 2008, while productivity of planted species and weeds were analyzed in 2009. Alternative crop density was log transformed for analysis, while all other dependent variables fit model assumptions in their raw form. Annual pseudograin production was analyzed separately for each field site in 2008, because the watering treatments were not applied at the 5C site, while data from 2009 included both sites and watering treatments in one analysis. Second year productivity of alfalfa under differing watering treatments was analyzed in two ways. First, total productivity was summed over the entire three harvests to determine overall differences in yield (site, block, and watering treatment as model factors), and secondly, repeated measures ANOVA was used to determine how biomass changed over time in different watering treatments.

RESULTS

Restoration Plots

Year One: Establishment and Initial Weed Cover

There were significant differences in April establishment in Ranch sites (Table 2a, Figure 4), and species that established well in one site generally established well in both fields (no significant field * species interaction, Table 2a). The small amount of early watering that took place had no effect on establishment at the Ranch sites (Table 2a). In contrast, establishment varied between the two Wildlife sites, as there was a significant three-way interaction (species*field*water), with main effects also significant (Table 2b). Species performance was differently affected by the watering treatments in the two Wildlife sites (Figure 5), with poor establishment at Wildlife Well (generally less than 5 plants/m^2), regardless of the watering treatment. Additional water did increase establishment at Wildlife Flood ($P = 0.01$, Figure 5). Establishment was significantly different between the three blocks at the Ranch sites, and was nearly significant ($P = 0.0502$) at the Wildlife sites, indicating spatial variation in site suitability for these native species.

Weed cover in April was influenced by the early watering treatment at both the Ranch sites (Table 2a) and the Wildlife Well site (Table 2b). At the ranch sites, watered plots had fewer weeds than non-watered plots (no water, weed cover: 19.4 ± 0.87 percent; with water: 16.5 ± 0.88 percent), and the same was true at the Wildlife Well site (Figure 6). At the Wildlife Flood sites in April, there was no difference in weed cover in the designated water plots (2.1 ± 0.45) or the designated non-watered plots (1.9 ± 0.21).

Greater differences in seeded species establishment emerged between the two Ranch sites when plant densities were measured in June of 2008. In general, Valley Vista had greater establishment (125 ± 150 plants/m^2) than 5C (92 ± 113 plants/m^2, Table 2c). In addition, there were species-specific differences in performance between these two fields (field*species interaction, Table 2c, Figure 7). In particular, bearded wheatgrass established much better at Valley Vista than at 5C. The Arriba variety of western wheatgrass established very poorly at both sites. Watering treatment also affected establishment at the Ranch sites: plants in watered plots had significantly poorer establishment (4.7 ±35.5 plants/m^2) than plants in unwatered plots (5.0 ± 21.5 plants/m^2, Table 2c).

Table 2. Results of ANOVA testing the effects of water and field locations on establishment of restoration species at Ranch (a,c) and Wildlife sites (b,d) in April (a,b) and June (c, d).

	a. **Ranch sites: April establishment**				b. **Wildlife sites: April establishment**			
	Crop Density		***Weed Cover***		***Crop Density***		***Weed Cover***	
Variable	F_{df}	*P*	F_{df}	*P*	F_{df}	*P*	F_{df}	*P*
Field	0.0_1	0.995	1.8_1	0.186	25_1	**<0.0001**	1.6_1	0.213
Block(field)	4.1_2	**0.0184**	1.7_2	0.154	3.0_2	0.0502	35_2	**<0.0001**
Water	0.64_1	0.424	5.5_1	**0.0199**	6.4_1	**0.0124**	11_1	**0.0012**
Species	25_4	**<0.0001**	2.1_4	0.0638	1.5_4	0.191	1.1_5	0.360
Water*field	1.2_1	0.268	1.2_1	0.265	13_1	**0.0004**	10_1	**0.0017**
Field*Species	2.0_4	0.0995	1.2_4	0.325	3.1_4	**0.0180**	2.0_5	0.0772
Species*water	0.62_4	0.649	0.49_4	0.783	2.8_4	**0.0287**	1.4_5	0.232
Species*water*field	1.5_4	0.207	0.89_4	0.487	4.7_4	**0.0011**	0.38_5	0.864
	c. **Ranch sites: June establishment**				d. **Wildlife sites: June establishment**			
	Crop Density		***Weed Cover***		***Crop Density***		***Weed Cover***	
Variable	F_{df}	*P*	F_{df}	*P*	F_{df}	*P*	F_{df}	*P*
Field	7.2_1	**0.0079**	150_1	**<0.0001**	13_1	**0.0004**	25_1	**<0.0001**
Block(field)	9.5_2	**0.0001**	1.5_2	0.235	0.036_2	0.965	7.7_2	**0.0006**
Water	24_1	**< 0.0001**	45_1	**<0.0001**	1.9_1	0.174	15_1	**0.0002**
Species	14_4	**<0.0001**	0.6_5	0.690	2.1_4	0.0779	1.3_5	0.277
Water*field	0.68_1	0.411	12_1	**0.0007**	0.71_1	0.399	1.6_1	0.207
Field*Species	5.7_4	**0.0002**	0.81_5	0.542	1.8_4	0.125	1.3_5	0.283
Species*water	1.6_4	0.188	0.75_5	0.590	1.5_4	0.120	1.2_5	0.334
Species*water*field	0.64_4	0.633	1.4_5	0.231	1.2_4	0.325	2.4_5	**0.0350**

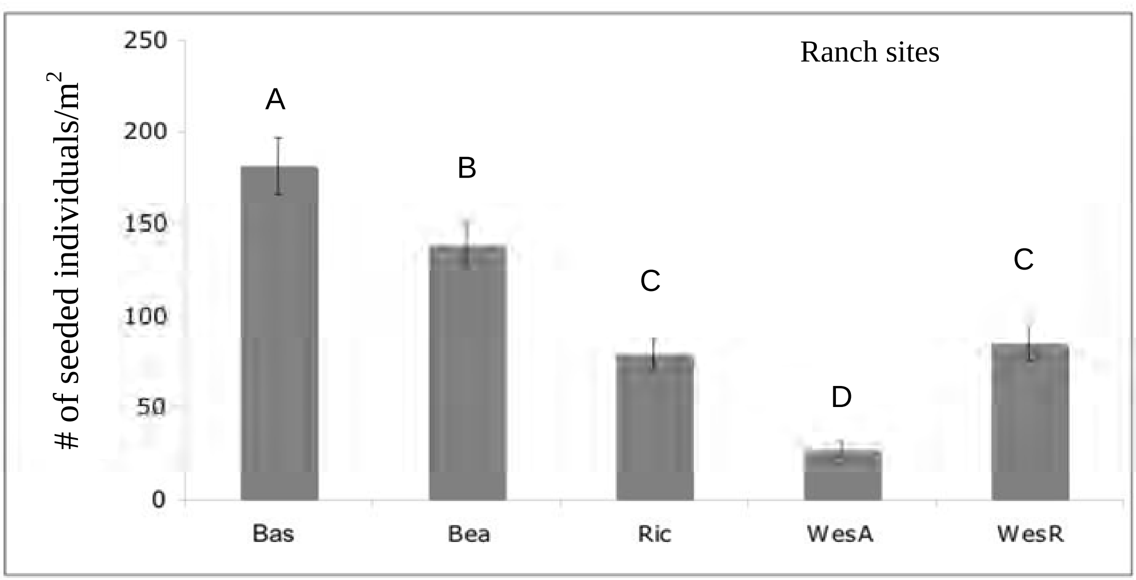


Figure 4. Establishment of native grass species in restoration plots at the two Ranch sites (combined) in April 2008.

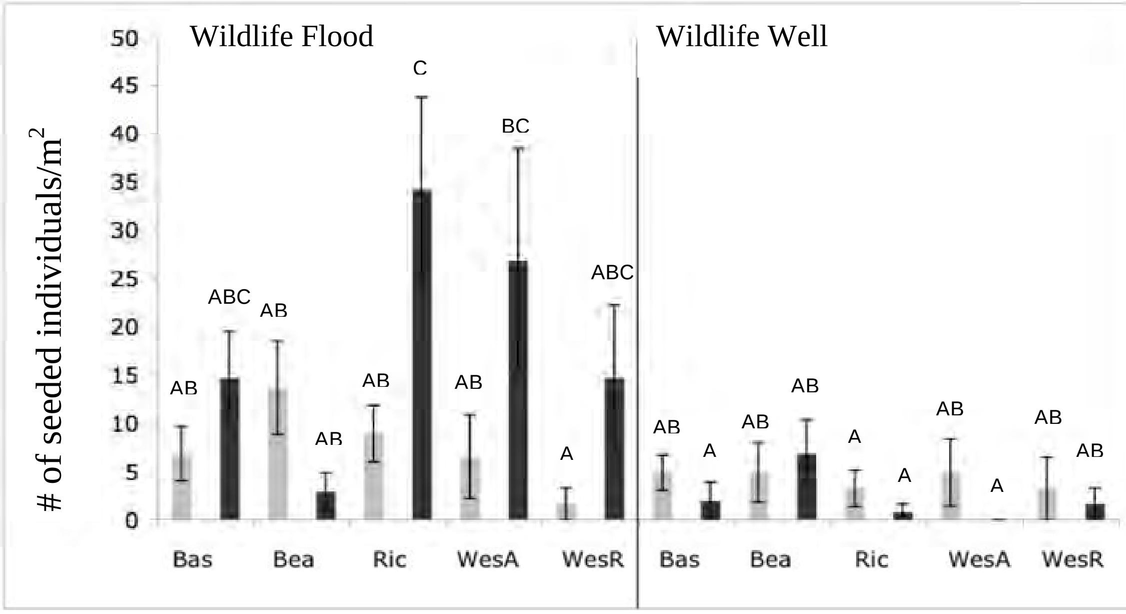


Figure 5. Establishment of native grasses in restoration plots at the two Wildlife sites in April 2008. Dark bars are watered (1 acre/foot) plots, light bars are unwatered plots.

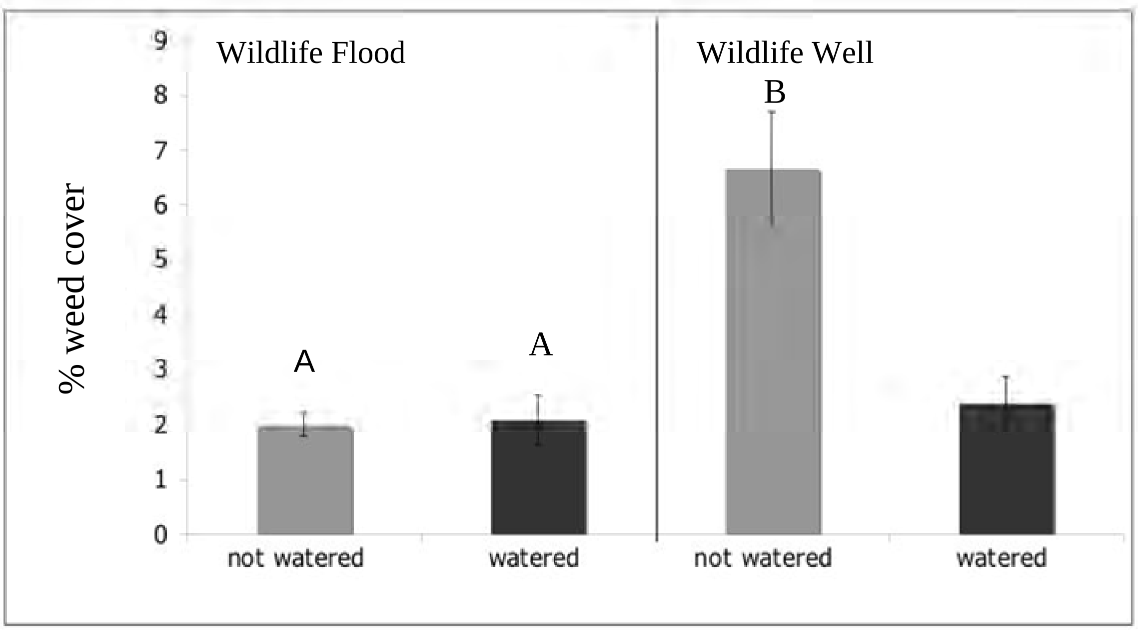


Figure 6. Percent cover of weeds at the two Wildlife sites in April 2008.

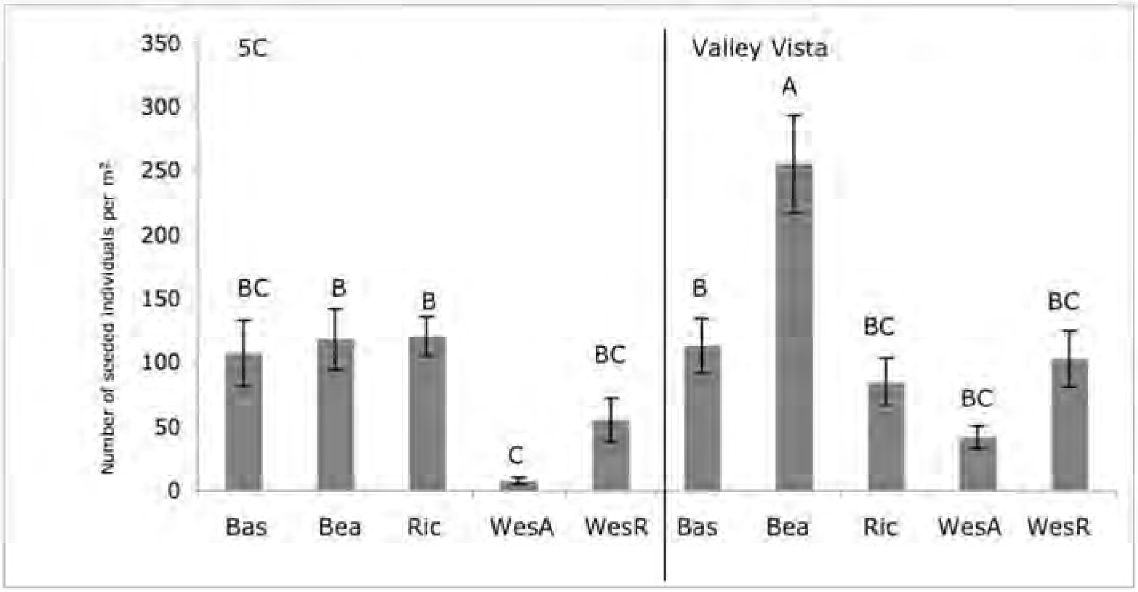


Figure 7. Establishment of native grass species in restoration plots at the two Ranch sites in June 2008.

Mortality at the Wildlife Well site resulted in markedly poorer measured establishment in June (0.4 ± 2.5 plants/m^2) compared to Flood (3.6 ± 8.0 plants/m^2, Table 2d), a reversal of the relationship measured in April. Watering treatment improved seeded species establishment at the Wildlife sites, with watered plots showing 2.4 plants/m^2 (± 26.5) and unwatered plots showing 1.4 plants/m^2 (±16.3, Table 2d).

In general, watering treatments increased June 2008 weed cover at all sites (Table 2c, Table 2d, Figures 8 and 9). At the ranch locations, sites responded differently to the watering treatment (significant field*water interaction, Table 2c). Watering at Valley Vista resulted in a greater increase in weed cover compared to 5C (Figure 8). There were three-way interactions between water addition, site, and species at the Wildlife sites (Table 2d, Figure 9. Water generally increased weed production, except for within basin wild rye plots and western wheatgrass var. Arriba plots at the Wildlife Well site and control plots at the Wildlife Flood site (Figure 9), where watering either reduced or had no effect on weed cover.

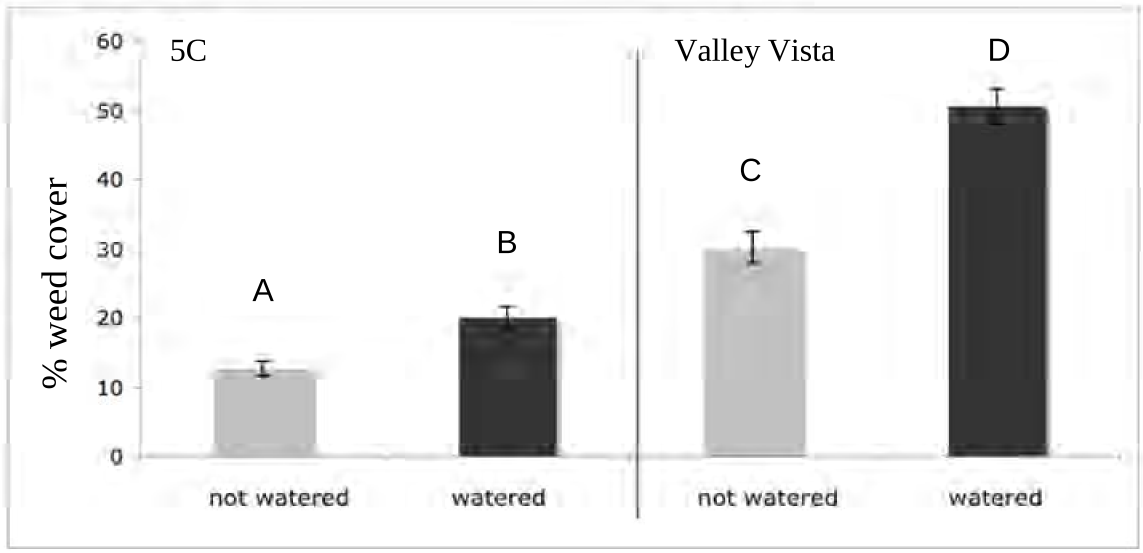


Figure 8. Percent cover of weeds in watered and unwatered plots at the two Ranch sites in June 2008.

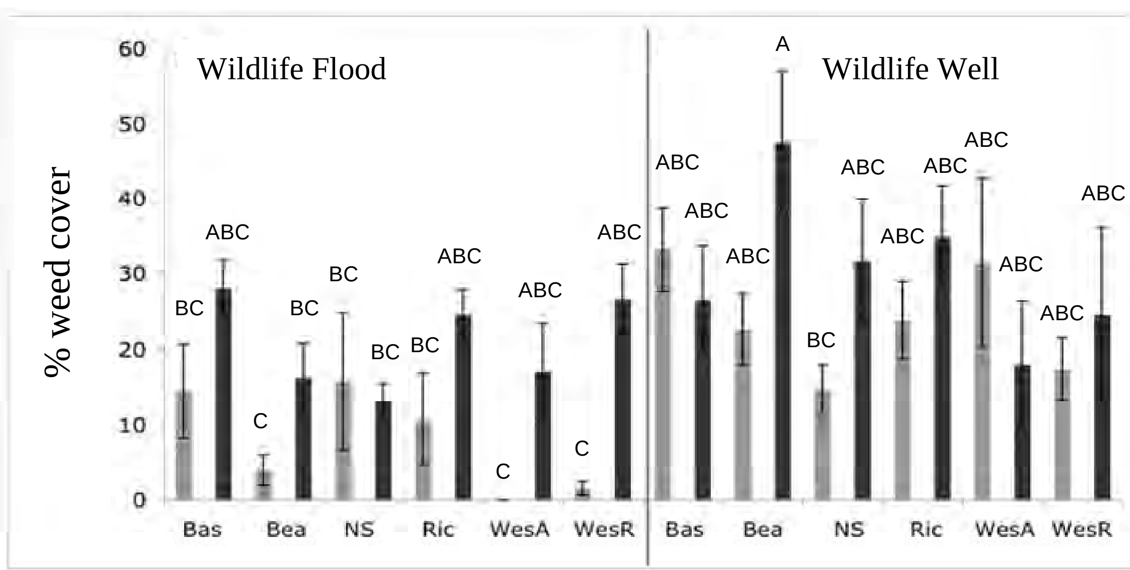


Figure 9. Percent cover of weeds at the two Wildlife sites in June 2008.

There was a difference between Wildlife and Ranch sites in measured seed bank density, with Wildlife sites containing a significantly greater number of seeds (Table 3, Figure 10). This is in contrast to the generally lower amount of weed cover observed growing in these fields (21.4%) compared to the Ranch fields (28.4% cover).

Table 3. Results of weed seed bank analysis from restoration plots.

Variable	F_{df}	*P*
Field	13.0_3	**0.0002**
Block(field)	1.8_4	0.1742
Overall	6.6_7	**0.0009**

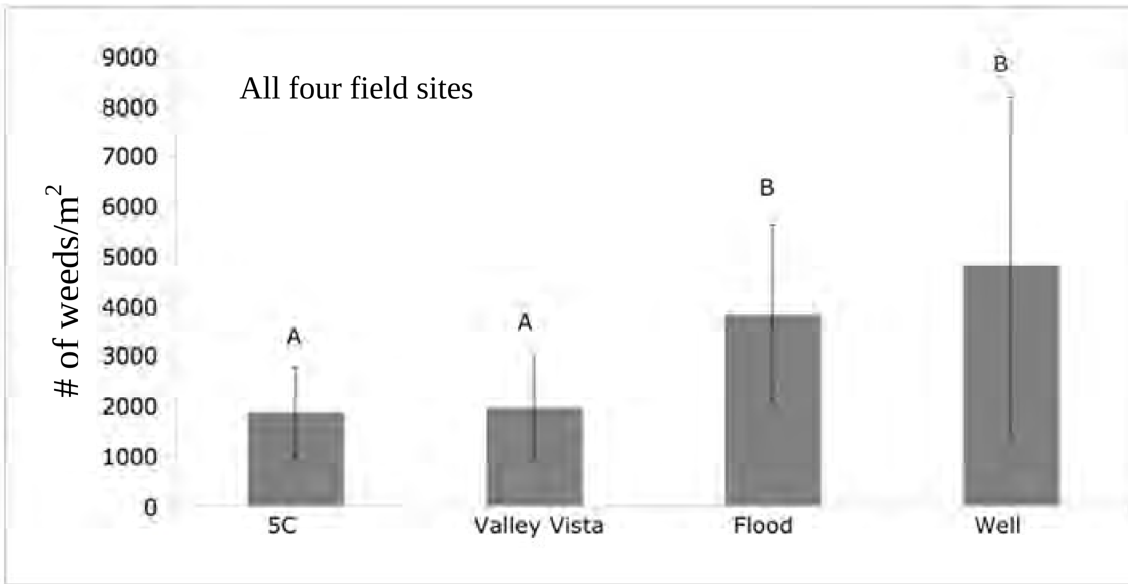


Figure 10. Comparison of weed seed bank densities from all four sites.

<u>Year Two: Density and Biomass</u>

After two years of growth, restoration species differed significantly in their density and responded differently to watering treatments (significant species*water interaction, Table 4a), though densities were similar between the two sites (Figure 11). Saltgrass did not establish at either site, regardless of watering treatment. Western wheatgrass established very well under the 25% watering treatment, but not at all without water. Beardless wheatgrass basin wildrye, and Indian ricegrass had similar densities at 25% water of around 30 plants per m^2, and low densities in the 0 water treatment (between 1 and 4 plants). Biomass differed by species, field, and watering treatment (significant species*water*field interaction, Table 4b). There was very low biomass of native grasses in the no water treatment at 5C (Figure 12a), and almost no plants established in the no water treatment at Valley Vista (Figure 12b). Species performance differed between sites: at 5C, Indian ricegrass had the highest biomass in the 25% watering treatment, while at Valley Vista, the most biomass was made by beardless wheatgrass, followed by western wheatgrass (Figure 12).

Table 4. Results of ANOVA testing the effects of water and field locations on plant density and biomass of restoration species at 5C and Valley Vista (a,b), 2009.

	Ranch sites: Restoration grasses				**Ranch sites: Weeds**			
	a. Crop Density		***b. Crop Dry Biomass***		***a. Weed Density***		***b. Weed Wet Biomass***	
Variable	F_{df}	*P*	F_{df}	*P*	F_{df}	*P*	F_{df}	*P*
Field	0.0_1	0.8597	5.8_1	**0.0170**	5.6_1	**<0.0001**	5.7_1	**0.0179**
Block(field)	2.6_2	**0.0366**	1.0_2	0.3919	2.2_2	0.0502	1.4_2	0.2349
Water	204.6_1	**<0.0001**	316.1_1	**<0.0001**	117.1_1	**0.0124**	63.5_1	**<0.0001**
Species	29.9_4	**<0.0001**	21.8_4	**<0.0001**	10.1_5	0.191	9.4_5	**<0.0001**
Water*field	1.9_1	0.1651	9.5_1	**0.0023**	6.0_1	**0.0004**	6.8_1	**0.0097**
Field*Species	1.6_4	0.1641	11.0_4	**<0.0001**	2.9_5	**0.0180**	1.3_5	0.2534
Species*water	$0.31.6_4$	**<0.0001**	20.0_4	**<0.0001**	9.1_5	**0.0287**	8.3_5	**<0.0001**
Species*water*field	1.1_4	0.3357	9.5_4	**<0.0001**	3.1_5	**0.0011**	1.5_5	0.1999

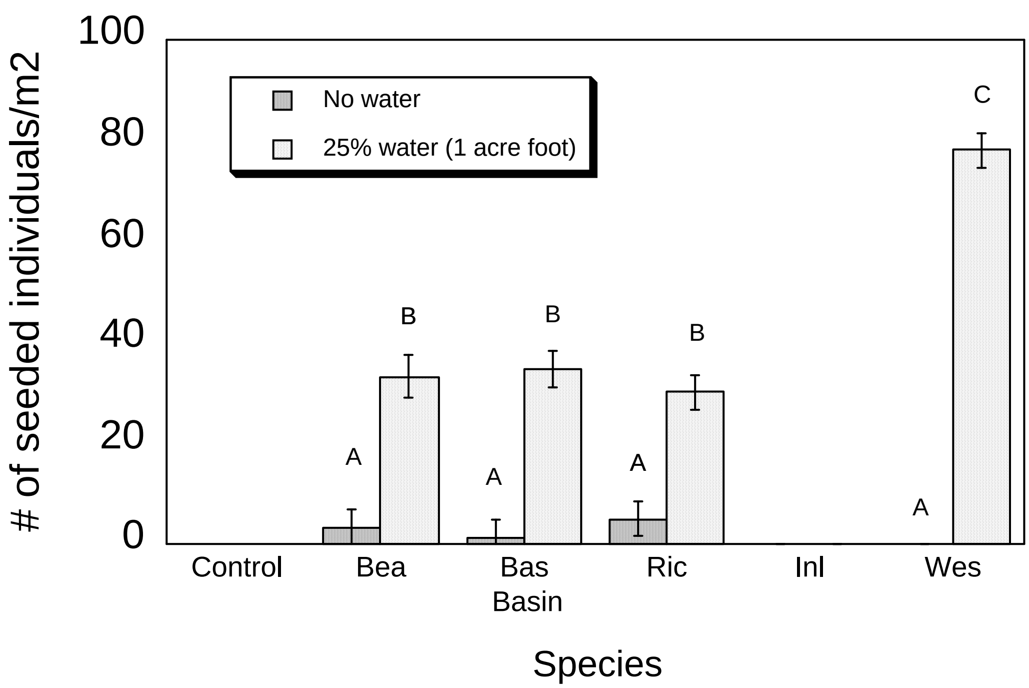
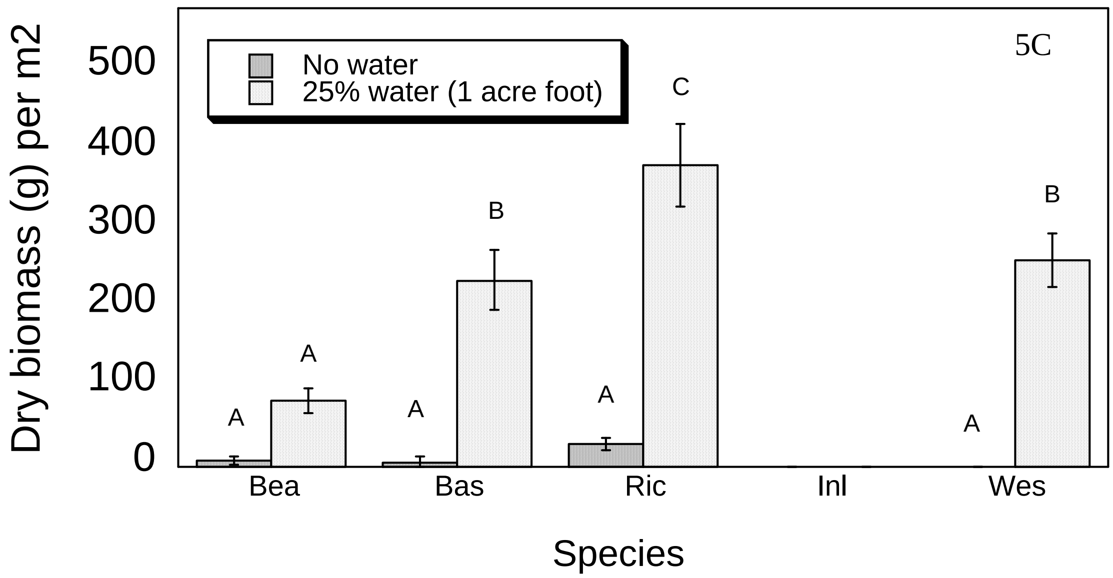


Figure 11. Density of native grass species in restoration plots at the two Ranch sites (combined) in August 2009.

a.



b.

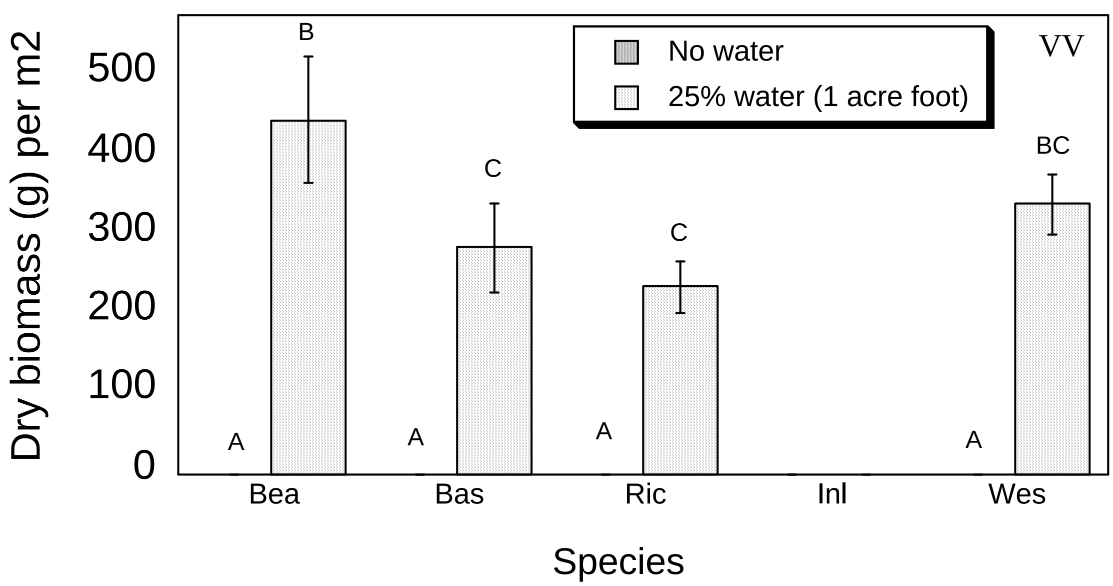


Figure 12. Biomass of restoration grass species at the two Ranch sites in 2009.

Weed densities differed significantly between species, field, and watering treatment (significant species*water*field interaction, Table 4c), while weed biomass was affected by watering treatment, species, and site (significant species*water and field*water interactions, Table 4d, Figure 13). Weed biomass was higher overall at the Valley View site, and at both sites, the most weeds grew in the 25% water application of the non-seeded control plots (NS) and the Saltgrass plots (Inl), which had no establishment. The four remaining native grasses all suppressed weed biomass in the 25% water treatment, though there were differences in performance between the two sites. For example, Indian ricegrass suppressed weed biomass the most at 5C (Figure 13a) but was not as competitive as other species at Valley Vista (Figure 13b).

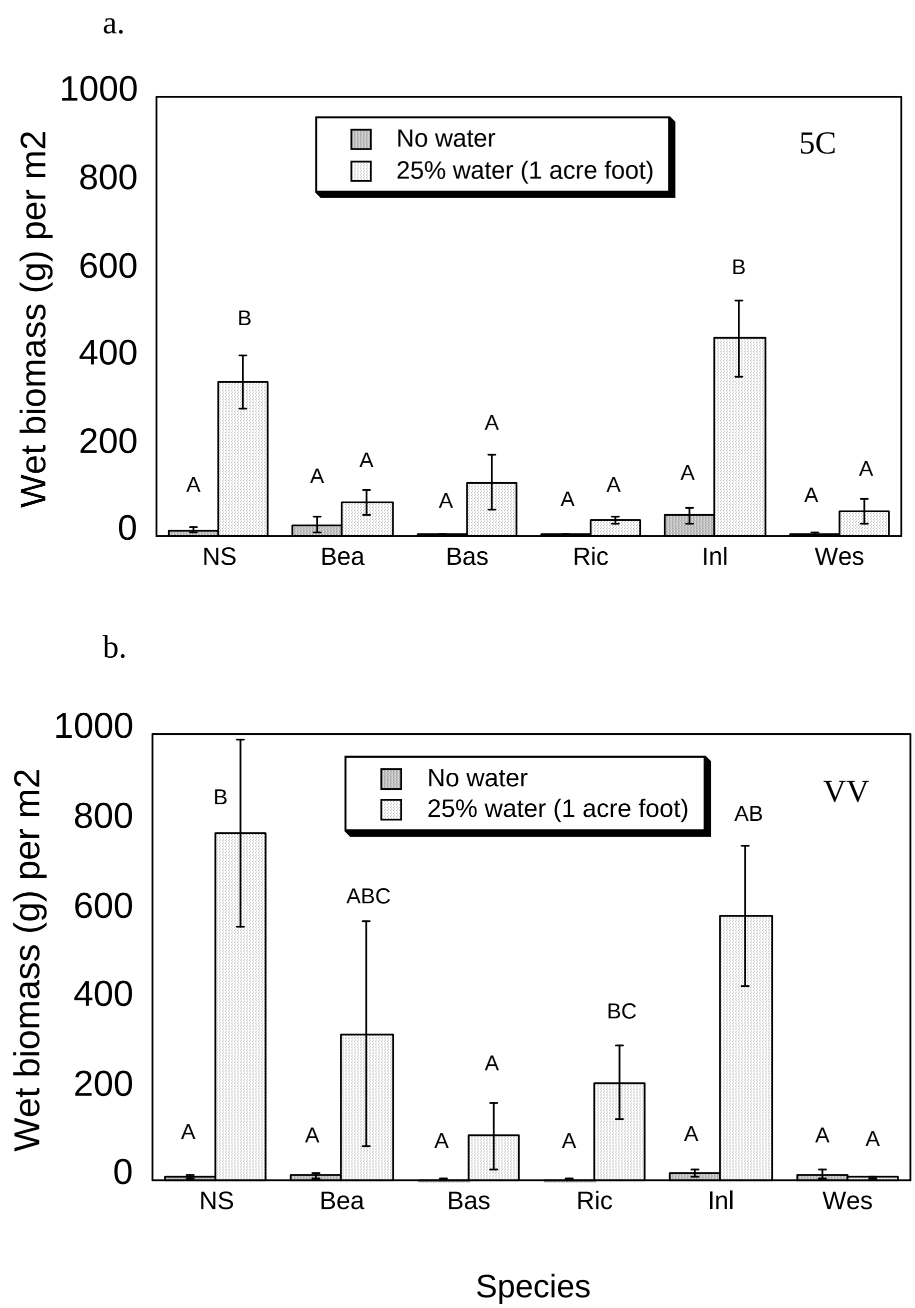


Figure 13. Weed biomass in restoration plots at the two Ranch sites, 2009.

The two varieties of Indian ricegrass established at similar densities in the two sites ($F = 0.02_1$, $P = 0.9060$), but had different biomass under the 25% watering treatments (variety*water; $F = 5.2_1$, $P = 0.0266$). Nezpar outperformed Rimrock at both fields (5C: Nezpar 485.3 ± 86.6, Rimrock 280.5 ± 38.1; VV Nezpar 275.7 ± 54.9, Rimrock 197.8 ± 34.6; grams/m2, mean ± standard error). The two varieties of Western wheatgrass had similar densities in the two sites ($F = 1.3_1$, $P = 0.2700$), and biomass did not differ ($F = 2.2_1$, $P = 0.1410$).

Shrub Establishment

The watering treatment did not affect the survival of shrub transplants ($\chi^2 = 0.001$, $P = 0.9710$), and survival was similar between the two sites ($\chi^2 = 0.002$, $P = 0.9636$) but species differed considerably ($\chi^2 = 18.5$, $P = 0.0003$). The best survivor was sagebrush, with an overall survival rate of 55.6%, followed by four-wing saltbush at 27.4% (Table 5). No shadscale plants survived at all, and greasewood survival was very low (6.7%). The watering treatment significantly increased the size and growth rate of surviving shrubs (size: $F = 8.5_1$, $P = 0.0004$; growth rate: size: $F = 17.1_1$, $P < 0.0001$), and species differed in these measures (size: $F = 16.0_1$, $P < 0.0001$; growth rate: $F = 11.6_1$, $P < 0.0001$) and were differentially affected by the watering treatment (size: species *water, $F = 3.3_1$, $P = 0.0403$; growth rate: size: $F = 9.9_1$, $P = 0.0001$). Fourwing was the largest plant (average volume = 6477.8 cm^3 ± 980.4) but only increased in size by 32.0% with additional water. Sagebrush was the smallest plant (1607.6 cm^3 ± 599.1), and increased in size by 298.9% with additional water. Greasewood (average size of 3530.6 cm^3 ± 2118) had the highest growth rate and responded the most to additional water, increasing in size by 1084% in the 25% watering treatment.

Table 5. Survival of shrubs in restoration fields, 2009. Values are combined for the two Ranch sites.

Species	Water	Number planted	Number survived	% survival
4-wing saltbush	0	59	16	27.1%
Greasewood	0	47	4	8.5%
Sagebrush	0	65	32	49.2%
Shadscale	0	33	0	0%
OVERALL		**204**	**52**	**25.5%**
4-wing saltbush	25%	47	13	27.7%
Greasewood	25%	39	2	5.1%
Sagebrush	25%	61	38	62.3%
Shadscale	25%	42	0	0%
OVERALL		**189**	**53**	**28.0%**

Biomass and Alternative Grain Plots

Biomass crops: Establishment and Weed Cover

Overall, cool season grasses established better than warm season grasses. Cool season grasses established better at the Ranch sites compared to the Wildlife Well site (Figure 14). Species performance differed between sites (significant field*species interaction, Table 6a, Figure 14). All species had similar establishment at the 5C and Wildlife Well sites, but at Valley Vista, basin wildrye had the greatest establishment, which mammoth wildrye had the lowest establishment (Figure 14). Weed densities varied by field and by species (Table 6b, Figure 15). Within the cool season grass plots, the highest initial weed densities occurred at the Valley Vista site, followed by the 5C and

Wildlife Well sites. Overall, basin wildrye plots had the fewest weeds (43 ± 41 plants/m^2), and mammoth wildrye plots had the greatest number of weeds (55 ± 64 plants/m^2), due to differences in performance at the Valley Vista site. Weed densities were not different among cool season grass species plots at either the 5C or the Well fields (Figure 15).

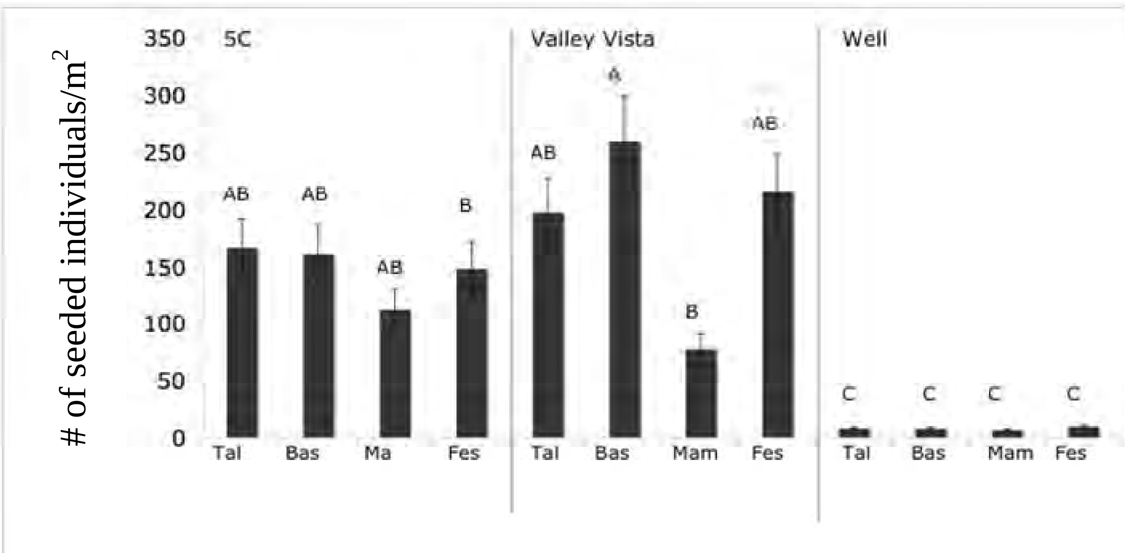


Figure 14. Cool season grasses establishment at three fields in April 2008 (cool season grasses were not planted at the Wildlife Flood site).

Table 6. Statistical summary of early establishment (April 2008) analysis.

	Cool season crops					
	a. Crop Density		***b. Weed Cover***		***c. Weed Density***	
Variable	F_{df}	*P*	F_{df}	*P*	F_{df}	*P*
Field	380_2	**<0.0001**	77_2	**<0.0001**	76_2	**<0.0001**
Block(field)	2.3_6	**0.0333**	5.4_6	**<0.0001**	6.3_6	**<0.0001**
Species	4.4_3	**0.0046**	2.2_3	**0.086**	2.8_3	0.086
Field*Species	2.3_6	**0.0362**	3.3_6	**0.0035**	3.4_6	**0.0035**

	Warm season crops				Alternative crops			
	d. Crop Density		***e. Crop Cover***		***f. Log(Crop Density)***		***g. Weed Cover***	
Variable	F_{df}	*P*	F_{df}	*P*	F_{df}	*P*	F_{df}	*P*
Field	33_2	**<0.0001**	40_2	**<0.0001**	75_2	**<0.0001**	200_2	**<0.0001**
Block(field)	3.2_6	**0.0044**	1.5_6	0.170	2.1_6	0.0534	6.1_6	**<0.0001**
Species	7.7_5	**<0.0001**	16_5	**<0.0001**	56_5	**<0.0001**	8.6_5	**<0.0001**
Field*Species	4.2_{10}	**<0.0001**	6.1_8	**<0.0001**	1.9_{10}	**0.0382**	7.3_{10}	**<0.0001**

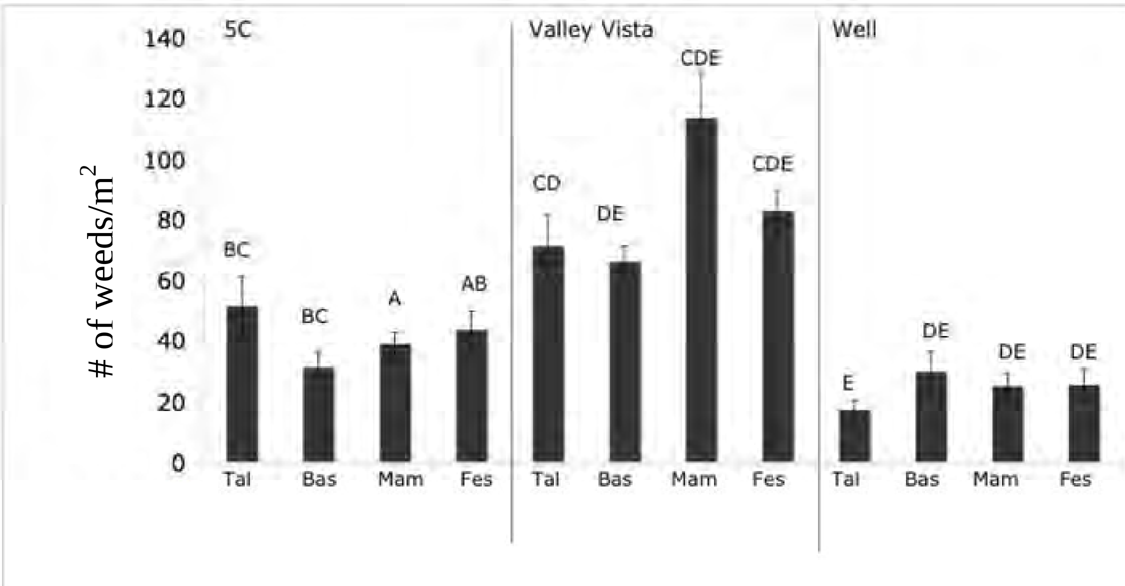


Figure 15. Weed densities in cool season grass plots in all three field sites 2008.

In 2008, cool season grasses at the Valley Vista site differed significantly in overall performance (*F* = 34.21; *P* < 0.0001), with mammoth wildrye and tall wheatgrass outperforming basin wildrye and tall fescue (Figure 16). In general, increased water led to increased production (*F* = 47.41, *P* < 0.0001), but species responded differently to the watering treatments (species*water treatment interaction, *F* = 6.21, *P* <0.0001, Figure 12c). Most species produced statistically equivalent biomass in the 75 and 100% watering treatments, except basin wildrye, which produced considerably more biomass in the 100% level treatment than it did at lower levels (Figure 16). Tall wheatgrass grew as much biomass in the 50% watering treatment as did tall fesuce and basin wildrye at 100%. At the two highest watering levels, tall wheatgrass and mammonth wildrye outperformed the other two species (Figure 16).

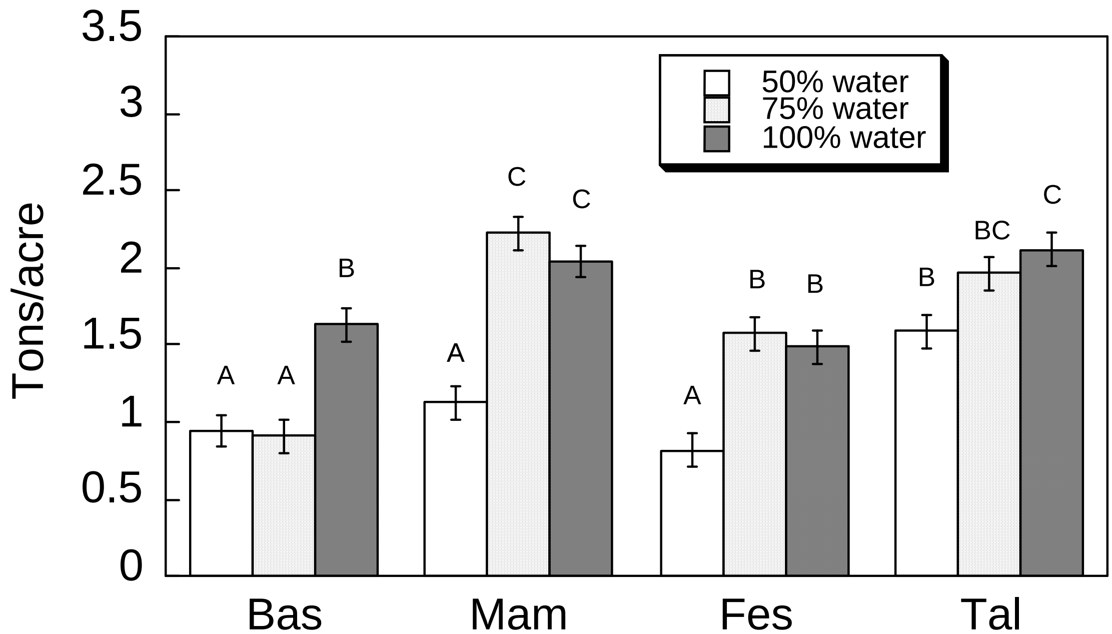


Figure 16. First year growth of cool season grasses at Valley Vista, harvested in 2008.

Warm season grass densities in April 2008 were different between sites and species (significant site*species interaction, Table 6d). The 5C site had the highest plant establishment of warm season grasses overall, followed by Valley Vista and Wildlife Well (Figure 17). Indiangrass established poorly at the Valley Vista site, but performed better at the other two locations (Figure 17). Old world bluestem and sand bluestem established at the highest densities overall. There were no significant differences in plant species performance at the Wildlife Well site, but old world bluestem outperformed switchgrass, prairie sandreed, and Indiangrass at the 5C and Valley Vista sites. Indian grass and prairie sandreed had the lowest establishment densities at the two ranch locations (Figure 17).

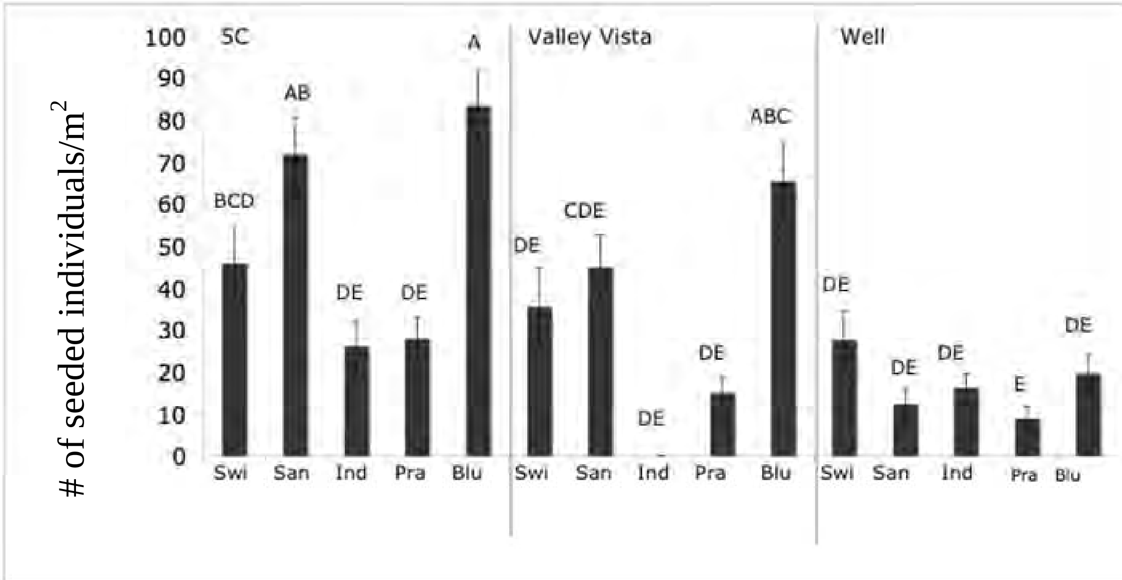


Figure 17. Seeded species establishment of warm season grasses in all three fields, 2008.

Year Two Productivity

Warm and cool season grasses differed significantly in their biomass (Table 7a, Figure 18), with cool season grasses outperforming warm season species at both locations. This difference was more pronounced at Valley Vista (significant field*season interaction, Table 7a). All species increased production with increased water, and overall, species differed in biomass (Table 7a, Figure 19). Ranking of productivity differed between the two sites, but overall, tall wheatgrass and old world bluestem were consistently top performers at both sites (Figure 19). All species responded similarly to increased water addition (no species*water interaction, Table 7a). Productivity of some species at the lowest watering treatment rivaled that of others at the full 100% treatment, e.g. tall wheatgrass biomass in the 50% treatment was higher than all but one of the warm season grasses at 100% water, at both sites (Figure 20).

Table 7. 2009 productivity of warm and cool season biomass crops at 5C and Valley Vista (a,b).

	Ranch sites: Biomass crops *a. Grass Dry Biomass*		*b. Weed Wet Biomass*	
Variable	F_{df}	*P*	F_{df}	*P*
Field	4.4_{1}	**0.0363**	5.9_{1}	**0.0153**
Block(field)	2.8_{4}	**0.0231**	5.1_{4}	**0.0005**
Water	372.5_{2}	**<0.0001**	18.1_{2}	**<0.0001**
Season	393.8_{1}	**<0.0001**	310.6_{1}	**<0.0001**
Species(season)	689.8_{7}	**<0.0001**	34.1_{7}	**<0.0001**
Water*field	2.7_{2}	0.0689	8.1_{2}	**0.0003**
Field*Season	18.3_{1}	**<0.0001**	2.7_{1}	0.1028
Season*water	1.1_{2}	0.3228	7.7_{4}	**0.0005**
Species*water*field	1.7_{2}	0.1785	0.8_{4}	0.4520

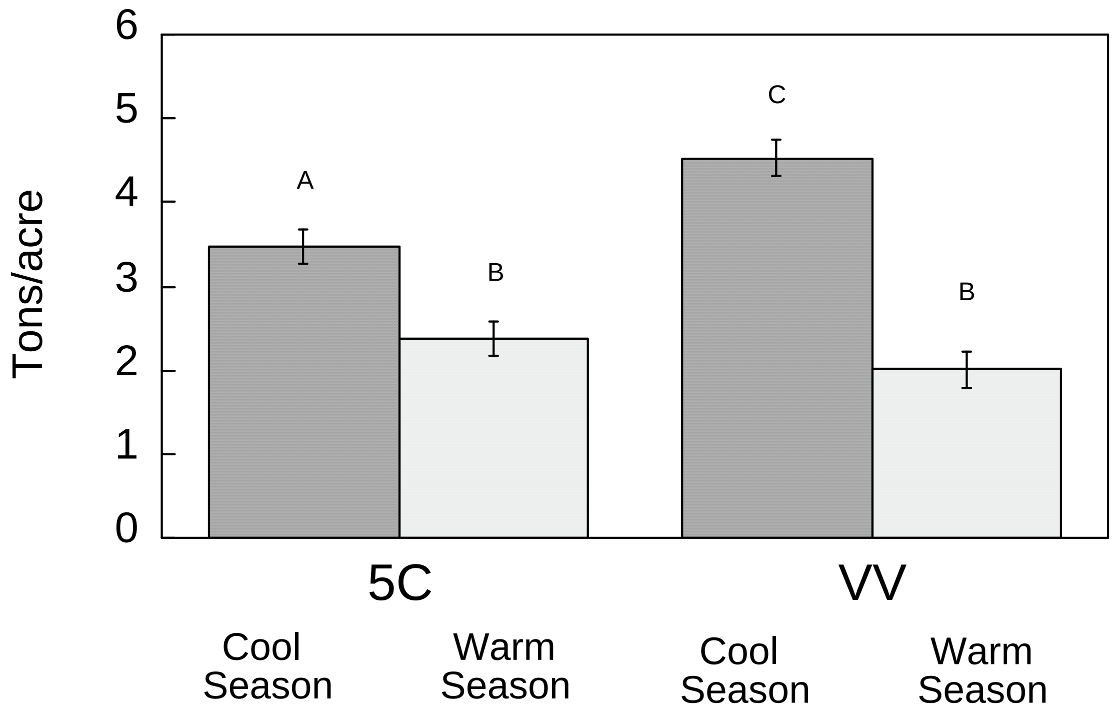


Figure 18. Productivity of warm and cool season grasses in 2009, averaged across watering treatments and sites.

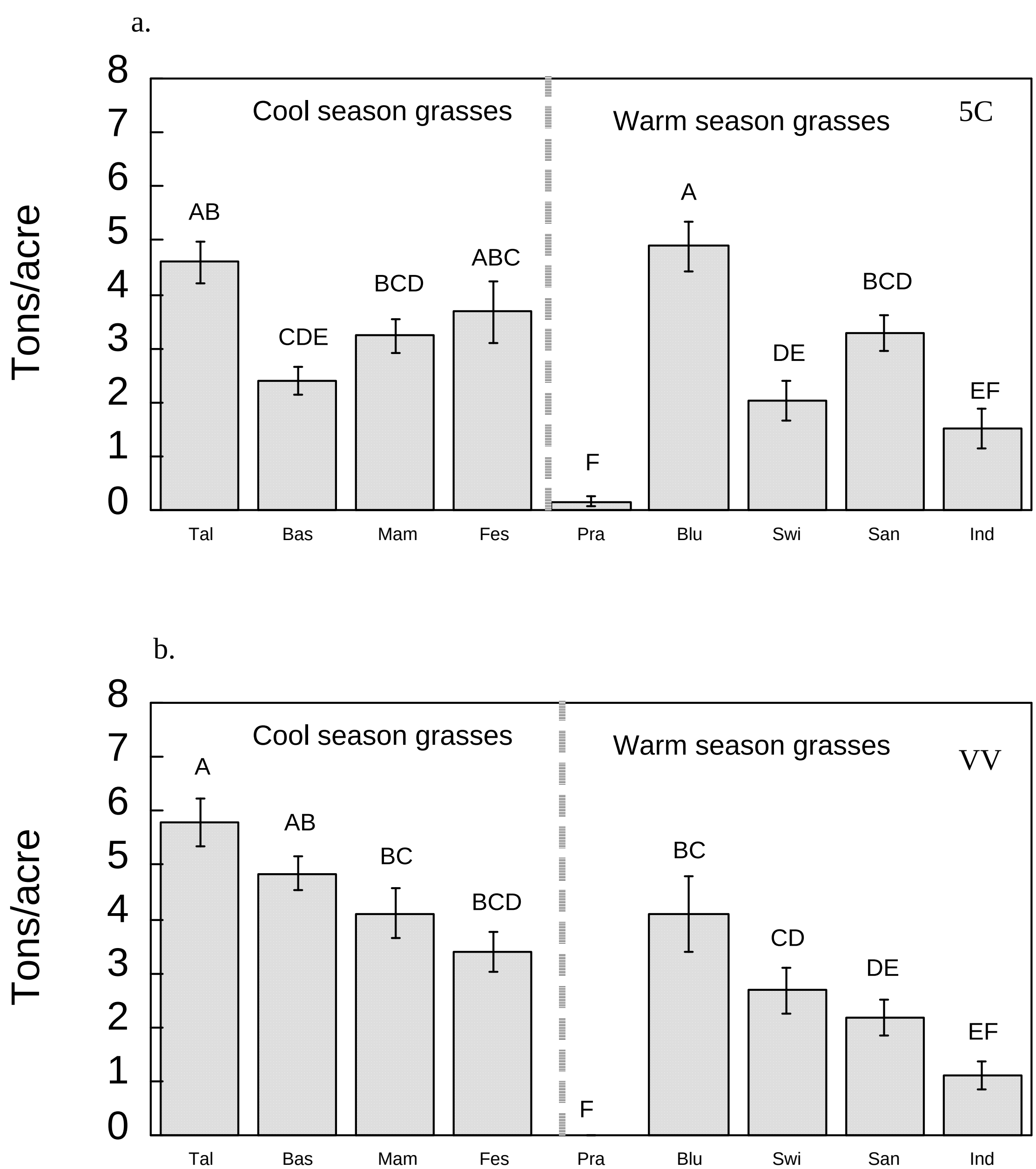


Figure 19. Biomass crop production at the 5C (a) and Valley Vista (b) sites in 2009.

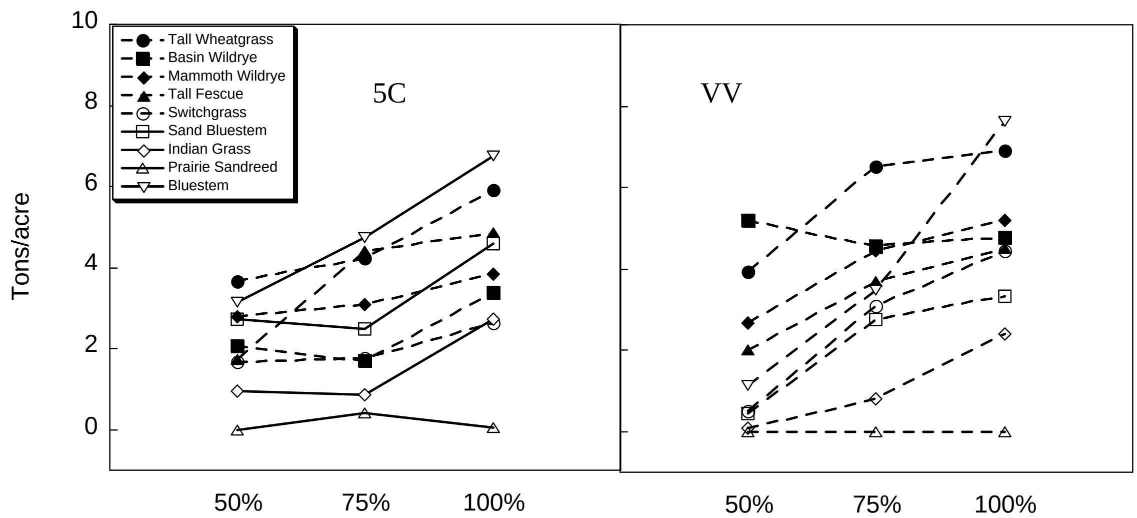


Figure 20. Individual species response to watering treatments at the 5C and VV sites, 2009.

Weed biomass was significantly affected by most model factors (Table 7b), including field, seasonality of the grass (warm vs. cold), species, and watering treatment, though seasonality had the largest affect on weed biomass. Overall, weed biomass (g/m^2) was much higher in warm season grass plots than in cool season plots (cool season, 239.0 ± 26.4, warm: 862.8 ± 23.6), higher at the 5C site (5C: 594.0 ± 25.0; Valley Vista: 507.8 ± 25.0) and increased with water application (50%: 460.8 ± 35.3; 75%: 559.2 ± 40.0; 100%: 58.0 ± 58.0). Additionally, species differed in their competitive ability with weeds, and there were site*water and season*water interactions (Table 7b), with water application increasing weed biomass more at the 5C site than at Valley Vista, and increased water improving weed performance more in warm season grasses than in cool season grasses (Figure 21).

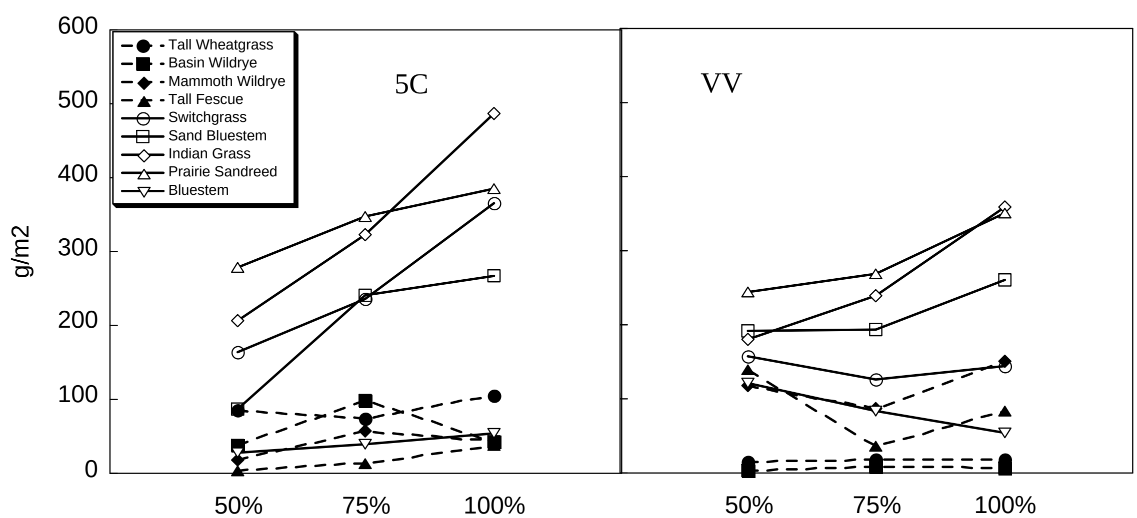


Figure 21. Weed biomass from biomass crop fields, 2009.

Annual Crops

Establishment

Species differed in establishment in different fields (significant species*field interaction, Table 6f). Alfalfa established very well at the Valley Vista and 5C sites (Figure 22). The high measurement of 377 ± 34 plants/m^2 at Valley Vista was probably influenced by the fact that alfalfa already existed at this site and attempts to eradicate established plants were not 100% successful prior to sowing. However, the establishment of alfalfa was not significantly different from either teff variety or from buckwheat at any site. Amaranth establishment, though low (15 ± 16 plants/m^2) at 5C, was not significantly different than alfalfa due to the high variability in crop densities for both species. Pearl millet and amaranth established at the lowest densities at the Valley Vista and Well sites (Figure 22).

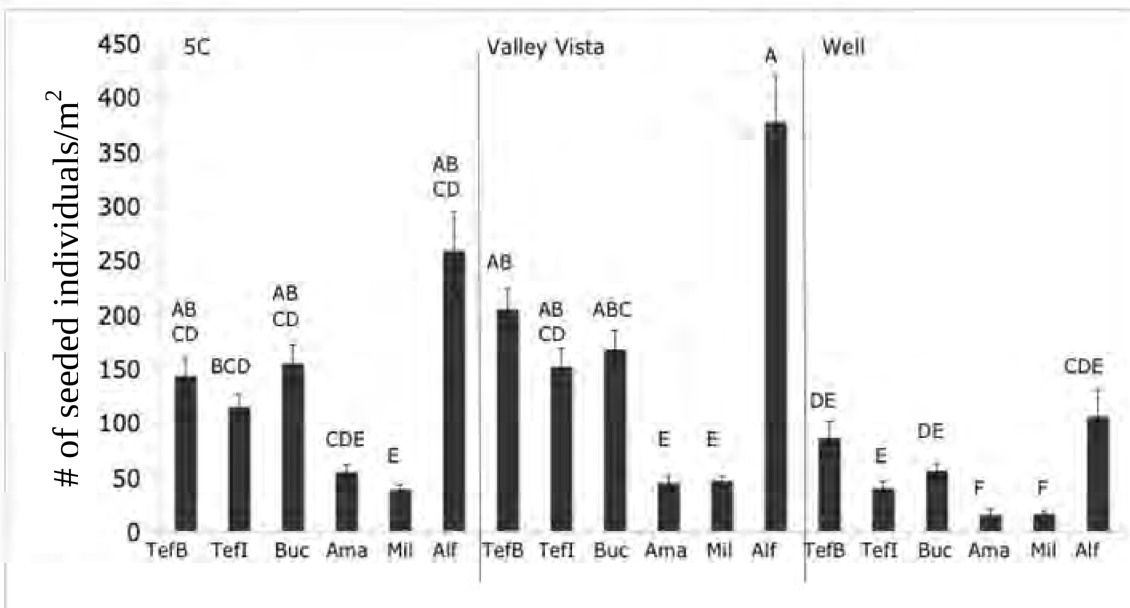


Figure 22. Establishment of alternative annual grain crops in July 2008 in all three fields.

Results for crop cover also differed by site and species (significant field*species interaction, Table 6g), but showed a different pattern than results for crop density (Figure 23). Alfalfa cover was relatively low at 5C, in contrast to its high establishment, while amaranth and teff had the highest cover at this site (Figure 23). Teff had high cover at the Valley Vista site as well, but amaranth cover was the lowest of all species at Valley Vista (Figure 23). There were no significant differences in species cover at the Wildlife Well site.

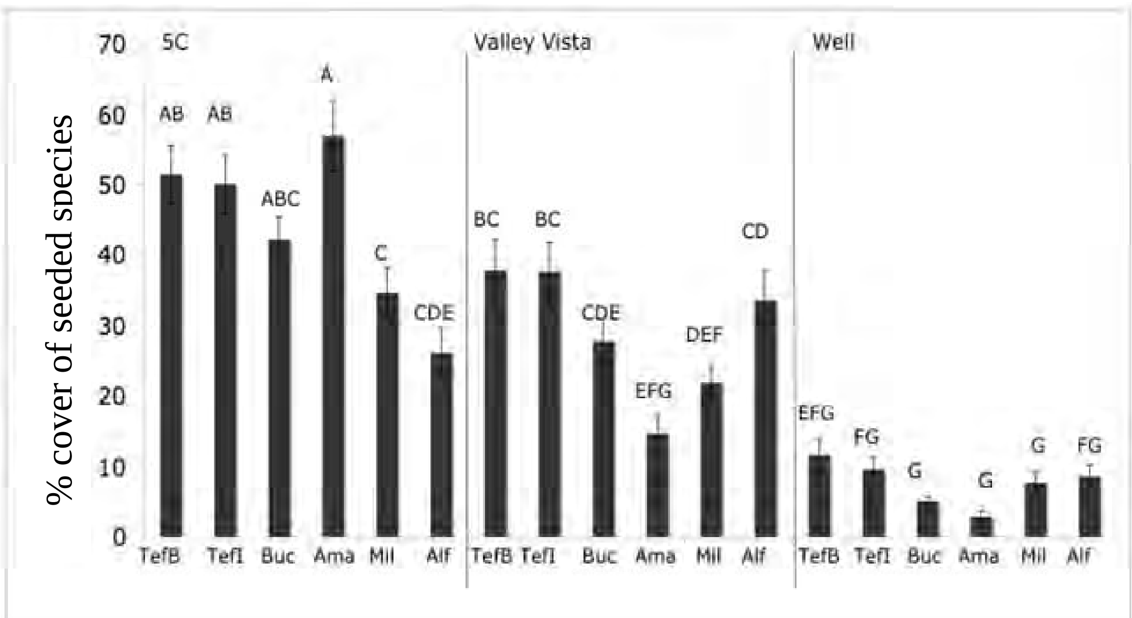


Figure 23. Percent cover of seeded species cover in alternative crop plots in July 2008, in all three field sites.

End of Season Density and Productivity

Amaranth and teff were the only species to produce enough biomass for analysis in 2008 and 2009, and amaranth was only harvested at the 5C site in 2008 because of low productivity at Valley Vista. At the 5C, there was no difference in production between white and brown teff (F = 0.51, P = 0.4839, Figure 24). Amaranth production was 637 lbs/acre (Figure 24). At the Valley Vista site, teff varieties performed equally (F = 0.34, P = 0.5716), and both varieties responded to difference in watering treatment (F = 4.02, P = 0.0489, Figure 24). While the interaction between teff varieties and the watering treatment was not statistically significant, we present the results separately to inform future studies. Brown teff had a more incremental response to increased water, while white teff performed equally at the 50% and 75% treatments, with a jump in production with 100% water (Figure 24).

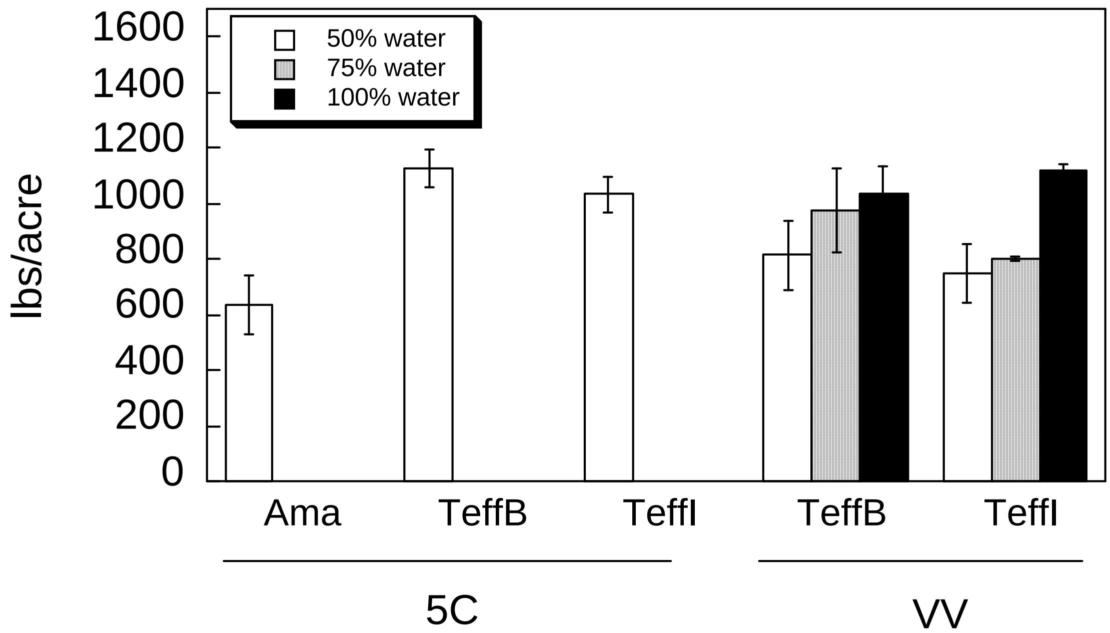


Figure 24. Pseudograin production in 2008. The 5C site only received 50% water total, so values are averaged across all plots.

In 2009, white teff did not produce seeds, and only brown teff was harvested.In 2009, both amaranth and teff increased production in response to increased water (amaranth: $F = 8.34$, $P = 0.0110$; teff: $F = 8.55$, $P = 0.0103$, Figure 25). Though results were not statistically different between the two sites, results are presented here. Average yields at the Valley Vista Site for 50, 75, and 100% watering treatments were 918, 930, and 1021 pounds per acre respectively. On the 5-C site, the differences between watering treatments were more pronounced but average yields were lower: plots irrigated at 50, 75 and 100% produced 476, 725, and 925 pounds per acre. Amaranth increased production with additional water, but production was statistically equivalent at the 75% and 100% treatments, while brown teff showed the same incremental increase in production observed in 2008. Amaranth production was not statistically different between the two sites, but values are presented here for information: production in the 50, 75, and 100% watering treatments at the 5-C sites were 554, 773, and 857 pounds/acre, respectively, while yields were 437, 655, and 638 pounds/acre respectively.

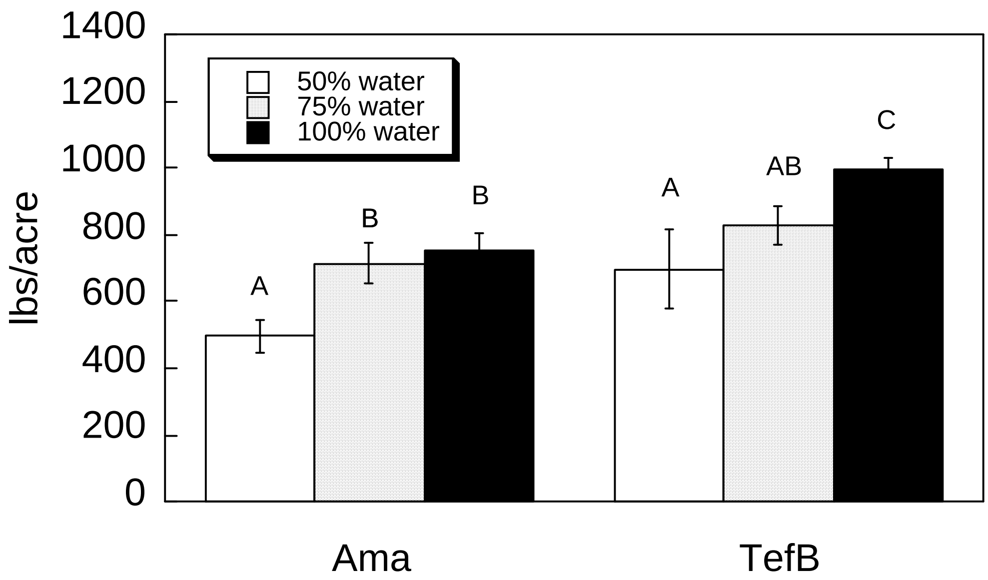


Figure 25. Pseudograin production in 2009, averaged across the two Ranch sites.

Alfalfa

Cumulative total harvest of alfalfa did not differ between sites, nor was it significantly affected by the watering treatments (Table 8). The watering treatments did, however, significantly affect harvest over time, with the 50% watering treatment in particular showing a marked decreased in productivity at the final cut (Figure 26). Productivity in the 75% and 100% water applications were almost identical, at both sites, and did not decrease over time (Figure 26).

Table 8. Overall productivity of alfalfa at 5C and Valley Vista (a) and repeated measures analysis of productivity over time (b).

	a. Overall productivity	
Variable	F_{df}	*P*
Field	1.6_{1}	0.2474
Block(field)	0.5_{4}	0.7680
Water	2.1_{2}	0.1970
Field*Water	0.2_{2}	0.8534
	b. Productivity over time	
Variable	F_{df}	*P*
Field	2.3_{1}	0.1550
Water	3.1_{2}	0.0878
Field*Water	0.3_{2}	0.7511
Time	19.5_{2}	**0.0004**
Time*Field	1.0_{2}	0.3916
Time*Water	6.7_{4}	**0.0014**
Time*Site*Water	0.8_{4}	0.5222

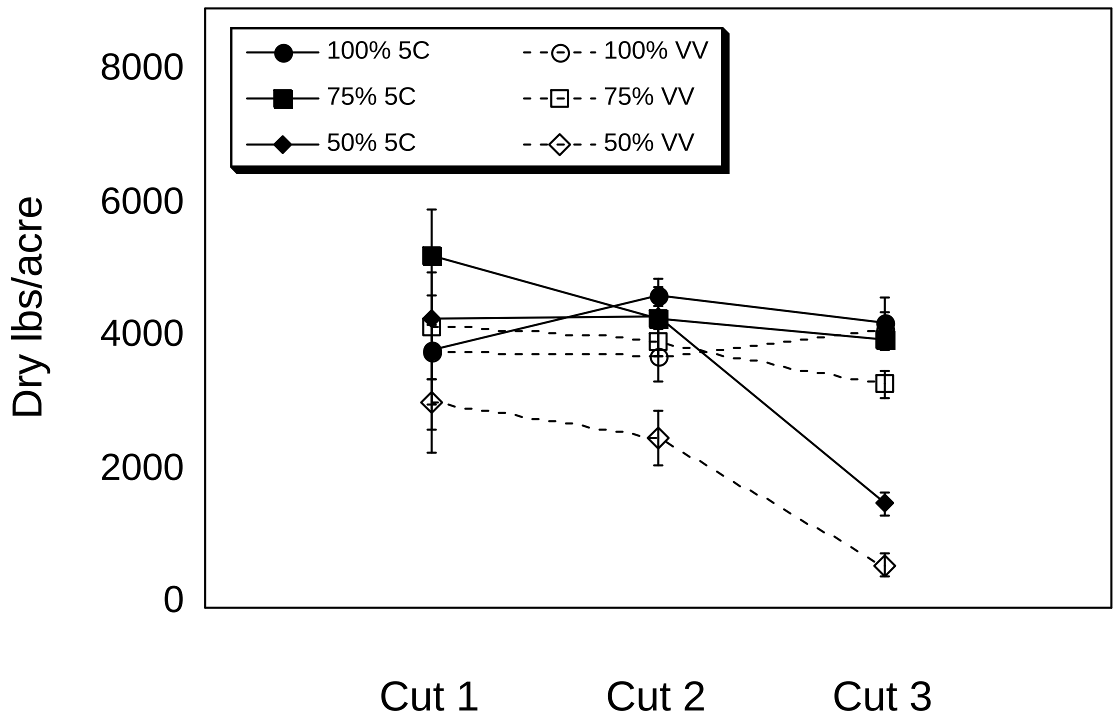


Figure 26. Alfalfa production in 2009, on both ranch sites. Cut 1 was taken on June 8, cut 2 on July 21, and cut 3 on September 3.

DISCUSSION

Permitted irrigation levels in Mason Valley and other parts of Nevada are dependent on water right priorities and the amount of irrigation water available from storage in upstream reservoirs. This amount is dependent on snowfall and other precipitation amounts received in the fall and winter of the previous year. Due to this uncertainty, water availability is unpredictable from year to year, and, as we experienced in 2008, in some years late season water is not available. This is likely to affect productivity of warm season grasses and annual grain crops more than cool season grasses or alfalfa, which makes these types of crops somewhat more risky.

Restoration Plots

Results in the restoration fields were very promising, and it is possible that effective restoration could be accomplished with even lower water applications, as 1 acre foot of water resulted in very high establishment of native grasses. Densities were very low in unwatered restorations (on average, 1.8 plants/m^2), which are lower than typical results in wildland restorations (Leger, unpublished data). In contrast, densities were very high in watered plots (on average, 36.5 plants/m^2), which is considerably higher than what is common in natural settings. Clearly, thinning will occur during the next (unwatered) seasons. The hope is that strong intraspecific competition will not weaken all plants, but that large individuals will quickly take up resources and survive, while smaller plants will die.

At the sandiest site (5C), Indian ricegrass was the top performer, establishing at high densities, producing the highest biomass, and suppressing weeds effectively. This species can establish very well in restoration settings (e.g. Thompson et al. 2006), and its affinity for sandy soils is well known. At the more fertile site, beardless wheatgrass and western wheatgrass produced the most biomass, and western wheatgrass was the best at suppressing weeds. Saltgrass (*Distichilis spicata*) did not establish at all in these fields, and seed germination is notoriously difficult for this species (Cluff et al. 1983), which typically reproduces clonally in the wild. Restoration with this species can be very desirable, as it is drought tolerant and capable of growing on saline soils (e.g. Bustan and Pasternak 2003), but it is more successful when rhizomes are used, rather than seeds (Shadow 2007). Shrub survival was typically low, but surviving individuals are important as a seed source for additional recruitment in favorable years. Surprisingly, sagebrush seedlings survived the best at this site, even though shadscale, fourwing, and greasewood are more common shrubs in the surrounding undeveloped vegetation. In the next growing season, these plots will not be watered, and we expect mortality to occur, as densities are considerably higher in watered plots than they are in desert systems. Western wheatgrass in particular, which established in the highest densities and is typically recommended for planting in slightly higher precipitation zones (10-12 inches, Ogle et al. 2000), may suffer during the next growing season. We will continue to monitor these plots, and determine which species are best able to survive with no additional water application.

Biomass Crops

Warm season grasses did not establish as well nor produce as much biomass as their cool season counterparts in this arid system, a result consistent with others (Robins et al. 2009, Robins in press). We believe that competition from weeds played a large role in this (discussed in detail below). A notable exception was the warm season grass old world bluestem, which established well in the first year, maintained relatively high productivity under low water application, and was competitive with weeds. Switchgrass, in particular, is of interest for use as a potential biofuel due to its rapid growth in other systems (e.g. Robins in press, Lee and Boe 2005, Liebig et al. 2005, Gilbert et al. 1979), but establishment of this species was low in our fields. It is possible that production could be high in Nevada, if weed control is sufficient, and we recommend additional trials with this species. Cool season grasses had much better establishment, overall productivity in year two, and suppressed weeds to a larger degree than did warm season species. Tall wheatgrass was the top performer at both sites, but all cool season grasses had similar biomass output in 2009. Productivity of perennial biomass crops is typically measured when these plants are 3-4 years old, and as our plots are only two years old, our yields are lower than other published reports, for warm season (e.g. Gilbert et al. 1979, Maun 1981, Duralia and Reader 1993, Hendrickson et al. 2000,Robins in press) and cool season grasses (Klebesadel 1985, Klebesadel 1993, Bartholomew and Williams 2008, Robins in press).

Pseudograins

All the pseudograins and alfalfa produced more than enough plants per square foot to establish successful stands during 2008 and 2009. In 2008, pearl millet and amaranth had the lowest number of plants per square foot of the seeded species while alfalfa had the highest initial establishment of all the species. However, by July 2008, all of the annual pseudograins had higher percent cover than alfalfa due to their rapid growth habit. In spite of the successful establishment displayed by all species in both years, only teff and amaranth produced adequate amounts of grain to be harvested in both years. Buckwheat and pearl millet flowered but failed to produce enough viable seed to be harvested.

Literature indicates that low levels of humidity, dry winds and high temperatures during flowering can severely reduce buckwheat yields due to flower and seed abortion (Berglund 2003, Oplinger et al. 1989). Although the plots were normally irrigated every seven days, the leaves on the buckwheat plants were usually wilted during the hottest portion of the day within three days of being irrigated. The buckwheat peak flowering times corresponded to the hottest temperatures of the growing season and hot afternoon winds were common throughout the summer months. Earlier planting dates were not possible due to the buckwheat plants sensitivity to frosts which occur commonly in late spring in western Nevada. Based on our results buckwheat cannot be recommended as a possible alternative crop at this time.

According to published work, pearl millet does not suffer from the same problems with high temperatures and drying winds as buckwheat (Lee et al 2004). However, in both years of this experiment the plants failed to set seed at either location. Plants appeared to growing normally, with emerged flowers and pollen evident. But, very few viable seeds were produced at either location. Irrigation was unlikely a factor, as seed set failed in all water treatments, at both sites, and in both years. Very little information is available concerning production of this plant under irrigation or growth in the climatic regions of western Nevada. It may be that the conditions considered "hot and dry" in the Southeastern United States, where all of the experimental results were developed, are less damaging to the flowers than "hot and dry" conditions in western Nevada. Further experimental work, including earlier planting dates, may be warranted for this plant, as it has potential as a high value food or forage crop.

Amaranth grain yields were comparable to other published studies, even though competition from weeds affected crops. At the 5C in 2008, where only 50% irrigation was applied due to water shortages, mean yields were still 637 pounds per acre. For comparison, reported average yields from Nebraska over a three year period were 700-880 pounds per acre (Baltensperger et al 1991), while the University of Minnesota expected yields ranging from 600 to 1500 pounds per acre (Putnum et al 1989). During 2009, when weed management was more successful and all plots were irrigated fully as planned, yields were higher. Production generally increased as the amount of irrigation water applied increased, with yields ranging from a low of 437 pounds per acre (Valley View, 50% water) to a high of 857 pounds per acre (5C, 100% water). Lower production values obtained on the Valley Vista site were the result of more intensive competition from weeds as the Valley Vista site consistently produced higher weed biomass throughout the experimental period.

Teff production during 2008 on the Valley Vista site mirrored that found with amaranth in that yields of both brown and white varieties increased as the amount of irrigation water applied increased. As with the previously mentioned crops, weed pressures were substantially higher on the Valley Vista location and resulted in lower production values for teff at that site. Weed management was again a major challenge during the 2009 season at both locations, and undoubtedly reduced yields. In contrast to 2008, white teff grain yields were non-existent during the 2009 growing season at both locations. The probable reason lies in the variety provided by the supplier in 2009. There are no named varieties of white teff available in the United States, which makes verifying seed source difficult. Though the same variety of white grain teff was requested in 2009 in 2008, the supplier may have inadvertently shipped a forage variety, as he also shipped a white forage variety to the author for testing in separate trial. The result was the white seeded variety produced large healthy plants but produced little to no grain in 2009. The brown teff variety produced normal plants and grain in 2009 at both locations. The brown teff yields produced during both years are similar to those produced commercially in other similar locations in Nevada. The average yields of brown teff during 2009 on approximately 1100 acres in 14 different locations was slightly above 1000 pounds per acre with full irrigation amounts, while average yields from approximately 800 acres on nine different locations in 2008 was approximately 1200 pounds per acre (Davison, unpublished data). No information on white teff grain yields has been developed as of the publication of this document.

The results indicate that teff and amaranth both show promise as potential alternative crops, and both species produced yields at low water (50%) applications, which makes them amenable to low-water farming. Further research is needed to test these species on larger areas and in additional locations. Commercial teff production is currently occurring in northwestern Nevada and is proving to be economically viable and is currently using approximately two thirds as much water to produce as alfalfa.

Weed Competition in Pseudograins and Biomass Crops

Competition from winter and summer annual weeds was the major impediment to the establishment and optimum production of all species evaluated in the alternative crop trials. This was especially true at the Wildlife well site, which was abandoned in late 2008 due to excessive weed pressure and lack of establishment of the seeded crops, and at the Valley Vista site which was an actively producing alfalfa stand prior to the establishment of the experimental plots in 2007. The 5-C site had been fallow for over 20 years and the weed pressures were generally lighter than those experienced on the Valley Vista site during the course of the experiments. A major challenge to management of these weeds is the lack of labeled herbicides for use on the seeded crop species, a problem that is especially apparent in the pseudograin crops. There are currently no herbicides labeled for teff, amaranth, or buckwheat, while 2,4-D or Peak (Prosulfuron: 1-(4-methoxy-6-methyltriazin-2-yl)-3-[2-(3,3,3-trifluoropropyl)-phenylsulfonyl]-urea are possibly labeled for use on pearl millet. However, even those uses are questionable if the millet is produced for grain and not forage (Berglund, 2003,Meyers, 2002, Meyers, 2002 Sakaliene 2008).

The winter annual weeds were managed primarily by pre-plant sprays of Glyphosate , 2,4-D and tillage. Following crop emergence the primary method of weed control was hand weeding and mowing. Broadleaf herbicides (2,4-D, Dicamba) were used postemergence on the grass species (teff, pearl millet) on an experimental basis and was generally successful in managing the broad leaf weeds. However, it could not be used on amaranth or buckwheat post emergence due to potential crop damage. Hand weeding of the winter annual broad leaved species proved to be achievable on the experimental plots, but would not be economically possible on a field scale due to the relative low value of the crops and large amount of manpower required. Cheatgrass was a not a major problem on the pseudograin plots in either year, likely due to late spring planting dates and the ability to remove it before the crop was planted. Generally, winter annual weeds were less of a threat to the establishment and production of the pseudograins than were the summer annual weed species.

The major competitors to the successful establishment and production of the pseudograins were the summer annual weeds; annual love grass (*Eragrostis spp.*), lambsquarters (*Chenopodium album*), and redroot pigweed (*Amaranthus retoflexus*). These species were managed using a combination of pre-plant herbicide sprays (glyphosate, 2,4-D) and tillage, resulting in a clean seedbed at planting. However, the soil seed bank was adequate at both experimental locations to produce enough weed seedlings to effectively compete with the planted species in both years of the experiment. Postemergence weed control was a combination of herbicide applications (2,4-D, Dicamba) on the grass crops and mechanical (hand weeding, mowing) on the broad-leaved crops. The mechanical methods were moderately successful on reducing populations of lambsquarters and redroot pigweed, but generally unsuccessful on reducing populations of annual love grass. The authors believe annual love grass populations were high enough to reduce yields of all the planted species at all locations. We base that statement on the observation of crop plants that grew adjacent to plot edges bordering sprinkler lines which were generally free of all plant growth. These plants were measurably larger in size, and produced larger seed heads than the same plants growing within the plots dominated by annual love grass. Annual love grass populations in 2009 were sprayed postemergence with Poast (sethoxydim 18%) on a portion of the amaranth and buckwheat plots located on the Valley Vista site. The Poast application was successful in that the annual love grass populations on the sprayed portions of the plots were reduced substantially without apparent damage to the crop species. However, Poast is not labeled for use by the public could not be used in a commercial endeavor.

The bio-mass crops were subject to severe competition from the same weed species as the pseudograin crops. A major difference was that all the bio-mass crops were perennial and once established the seeded species provided competition to the establishment of the annual weed species. The primary challenge to these crops was during the establishment phase and that was especially true for the warm season grass we tested. A second difference between pseudograin and the grass bio-mass crops is the number of labeled herbicides labeled for use with these species. Several broad leaf herbicides can be used on these grasses during the establishment and production phases. The list of herbicides labeled for grass weed control is much more limited and grasses are a major competitor during the establishment phase.

The herbicide treatments were generally successful in removing the majority of annual broadleaved weeds during both years of the experiment. The mowing treatments were generally ineffective at significantly reducing the populations of annual love grass or cheatgrass. Once established the cool season grasses generally competed very well with all the weeds found on the site. All species formed a dense, ground cover that precluded substantial establishment of the weedy species. This fact was more pronounced in 2009 when the cool season grasses generally produced less than one-half the weed biomass as that measured in the warm season grasses and the resulting bio-mass production was higher than that found on the warm season grass plots. In contrast, establishment and production of all the warm season grasses was negatively impacted by the competition from annual grasses. Indian grass and prairie sand reed were the least successful in establishing commercial stands at all locations. Old word bluestem, sand bluestem and switchgrass successfully established at all locations. However, total weed biomass production values generally equaled or exceeded the total biomass production values of the least successful warm season grass species in 2009.

The primary reason for the excessive annual grass weed populations found in the warm season grass plantings, but not the cool season grasses, is related to time of emergence and growth of crops and weeds. Both of the two primary competitors, cool season cheatgrass and warm season annual love grass, emerged and began a rapid growth period before the warm season species tested in this project. Cheatgrass germinates in the fall and is nearly mature before the warm season species grasses break dormancy and begin growth in the late spring. Annual love grass typically germinates at approximately the same time as the warm season grasses but its initial growth is much more rapid. Stands of both of these weeds rapidly colonized areas where the warm season species had failed to establish (especially true for Indian grass and sand bluestem), and severely reduced bio-mass production of the affected species. As warm season grasses often take up to three years to become fully established, the effect of competition from annual grasses may lessen in the future.

Cool season grasses have several competitive advantages over warm season grasses grown under the climatic conditions found in Northwest Nevada. When planted into a clean seed bed during the fall, cool season grass species are able to germinate and grow rapidly after the ideal time for germination of winter annual weeds and prior to the emergence of summer annual weeds. Therefore, the cool season grass seedlings are able to readily compete with both classifications of weeds. Moreover, the availability of broadleaf herbicides further reduces the competitive pressures experienced by the crop plants during the establishment year. Finally, cool season grass stands fully establish much more rapidly than warm season grasses. This results in the cool season species completely occupying a site in a shorter time frame reducing the opportunity for weedy species to become established and compete with the seeded species.

The results of this study demonstrate the critical nature of herbicides for weed control, especially on crops that are of relatively low value. While mechanical weed management techniques such as hand weeding and mowing can be cost effective in high value vegetable and fruit crops, the low values of field crops and the intensive nature of such methods precludes their use on a large scale. Much of the literature indicates the pseudograins evaluated will effectively compete with common weeds if planted in weed free seed beds and effective mechanical weed control is applied in the initial growth stages (Berglund 2003, Meyers 2002a, Meyers 2002b, Sakaliene et al. 2008). Our experience did not reflect that position. In fact, the crops evaluated had to be constantly hand weeded through the entire growing season. Likewise, mowing when applied on a regular basis failed to adequately control annual grass weeds in the perennial grass biomass crops.

While teff and amaranth show promise as pseudograin crops for Nevada, large scale adoption by producers will require additional research aimed at developing effective weed control strategies. This research should include crop safety experiments using various herbicides and investigating cultural practices necessary to reduce competition during the early stages of crop growth. In addition, government programs such as the Inter-regional Research Project 4 (IR-4) aimed at testing and obtaining pesticide labels for minor crops such those tested should be utilized to obtain registration of promising materials. Finally, both pseudograin species and some biomass crops are capable of producing reasonable yields at low water applications, and these species may be a valuable component of reduced-water agriculture in arid systems.

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PROJECT B: ALTERNATIVE AGRICULTURE AND VEGETATION MANAGEMENT

WATER USE EFFICIENCY AND PRODUCTIVITY OF ALTERNATIVE CROPS FOR AGRICULTURE IN NEVADA U.S.A. UNDER CONDITIONS OF LOW WATER AVAILABILITY

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

ET evapotranspiration

NEE net ecosystem CO_2 exchange

VPD vapor pressure deficit

WUE water use efficiency

ABSTRACT

The productivity of crops in arid regions depends directly on the availability of irrigation water. However in years with low snowfall water is greatly limited. The objectives of our study were to: (1) quantify the evapotranspirative water losses of a selection of alternative agricultural crops under low water availability, and (2) explore ecological mechanisms by which plant WUE may be determined. Aboveground biomass yield was greatest for *Eragrostis tef* (299±24 g m^{-2} dry mass), followed by *Fagopyrum esculentum* (216±25 g m^{-2}), *Medicago sativa* (173±35 g m^{-2}, the species presently planted by farmers), *Festuca arundinacea* (102±19 g m^{-2}) and *Leymus cinereus* (74±13 g m^{-2}). Crop daytime evapotranspiration (ET) measured at the end of the irrigation period (451±94 mm) of an 84-day growing season was greatest for *Medicago* (11.7±1.4 mm day^{-1}), followed by the other species (8.2 to 6.3 mm day^{-1}). However, daytime ET of *Medicago* exceeded ET rates of the other species by factors of 1.4 to 8.0. Crop WUE, expressed as aboveground biomass yield per pre-harvest daytime ET, of *Fagopyrum* exceeded WUEs of *Leymus*, *Medicago* and *Festuca* by factors of 1.7 to 2.8. However, WUE expressed in biomass yield per irrigation water applied shows *Eragrostis* as the overall winner.

Key Words: Water use efficiency; crop water savings; dry land agriculture; arid land irrigation; evapotranspiration; net ecosystem CO_2 exchange

INTRODUCTION

Agriculture in arid climates supplies vast quantities of the world's food and forage needs (e.g., Smith 1995) and is equally important in supporting local economies and populations. However, agricultural production in these regions depends most on directing precipitation, runoff, and stream- and groundwater to croplands where plants are cultivated. Thus in arid ecosystems, plant production is directly dependent on the amount of irrigation water provided.

Over the last several decades federal and state land water management agencies in the western U.S., are confronted with increasing demands for water resources. For instance, how much groundwater can be extracted from existing aquifers before supplies to natural springs, riparian and low-basin phreatophytic ecosystems is harmed? How much water can be extracted from natural streams and rivers to irrigate commercial crops within large drainage basins and still have sufficient water supplies downstream to maintain the natural structure and function of riparian and lake ecosystems? How much agricultural irrigation water is needed in a region to maintain the economic viability of the local economy? To what extent can a shift in commercial agricultural plant species with lower water requirements for growth and yield alleviate the tension between competing water resource uses? The study presented in this paper seeks to provide empirical data that can be used to help address if changes in agricultural practices under conditions of low availability of irrigation water can help alleviate some of these demands.

The specific objectives of the study presented in this paper were: (1) to quantify the evapotranspirative water losses of a selection of alternative agricultural crops in the Walker River Basin of western Nevada, U.S.A. during a year in which irrigation water allotments originating from the Walker River were below average; (2) to calculate plant and ecosystem water use efficiencies of alternative crops; and (3) to explore ecological mechanisms by which plant water use efficiency may be determined. Our study focused on the production of aboveground biomass.

MATERIAL AND METHODS

Study Site

The study site was located at the 5C Cottonwood Ranch near Mason, Nevada (38°50'51.08" N 119°11'00.19" W) that was cultivated up to ca. 1988 and for the past 20 years the land has been used as a livestock feedlot. Five crop species (Table 1) were selected (out of a total of 15) for this study based on their potential to have a higher water use efficiency (WUE) than alfalfa (*Medicago sativa* L.), the crop most commonly grown in this region. We measured performance throughout the growing season of four of these species (forbs: *Medicago*, *Fagopyrum esculentum* Moench—buckwheat; graminoids: *Leymus cinereus* (Scribn. & Merr.) A. Löve—basin wildrye, and *Festuca arundinacea* Schreb.—tall fescue, renamed as *Schedonorus phoenix* (Scop.) Holub) and only measured final aboveground biomass yield of one other species (*Eragrostis tef* (Zuccagni) Trotter—tef grass, an east African cereal crop planted mainly in Ethiopia but also being considered for use as a high quality forage species—Abule et al. 1995). Each crop species was planted (Table 1) in individual 9.1 x 7.3 m plots with six replicates for each crop species. Some plots planted with *Festuca* failed to germinate, leaving only four valid plots available for study.

Fields were prepared for sowing and sprinkler irrigation in September 2007 by ripping, disking and floating the surface soil. Seeds of the cool season grass, *Leymus*, were sown on 17 December 2007 at depth of 12 mm at a density of 484 m^{-2} of Pure Live Seeds. The overlying soil was compacted using a cultipacker to ensure good soil-seed contact. The other four species were sown on 21 May 2008 using a Truax seed drill (New Hope, MN, U.S.A.), with seeds planted at 12 mm deep at the following densities: *Medicago*, 980 m^{-2}; *Fagopyrum*, 678 m^{-2}; *Festuca*, 1130 m^{-2}; and *Tef*, 614 m^{-2}, followed by press-wheel compaction. These species-specific densities were chosen based on previous field evaluations that determined optimal forage or grain yields for individual species which generally parallel each other (J. Davison, pers. comm.). We hand-weeded a 1.5 x 1.5 m area in each of the 22 experimental plots on 17 July 2008 within the area where ET and net ecosystem CO_2 exchange (NEE) were measured (see below) to prevent confounding effects of non-target species (weeds) on assessment of target species performance.

Fields were irrigated starting on 30 April 2007 using 7.6 cm diameter hand lines with the sprinkler heads set on a 9.1 x 9.1 m pattern. Brass impact sprinkler heads (12.5 mm) each delivered approximately 7.6 liters of water per minute. Fields were irrigated every 7-10 days up to 5 August 2008, for a total of 11 irrigations (Figure 1). This period of irrigation would be typical for a year with low water allotments. The approximate amount of water applied was calculated based on pump pressure, pipe diameter, sprinkler-head flow ratings, and duration of application. The calculated amount

Table 1. Alternative agricultural plant species and varieties evaluated at Valley Vista Ranch in the Walker River Basin, Nevada, for total water use (mm) and water use efficiency (biomass or seed yield per mm water ET, and net ecosystem CO_2 exchange per net ecosystem ET) along with their common names, families, seeding rates, sowing dates and ecology.

Species	Variety	Common name	Family	Ecology	Seeding rate		Sowing date
					(lbs. acre^{-1})	(kg ha^{-1})	
Eragrostis tef	Dessie	Tef	Poaceae	Annual C3 grass	2	2.2	21 May, 2008
Fagopyrum esculentum	Macan	Buckwheat	Polygonaceae	Annual forb	50	56.1	21 May, 2008
Medicago sativa		Alfalfa	Fabiaceae	Annual/perennial forb N_2 fixer	20	22.4	21 May, 2008
Leymus cinereus	Trailhead	Basin wildrye	Poaceae	Perennial cool season C3 grass	15	16.8	17 December, 2008
Festuca arundinacea	Fawn	Tall fescue	Poaceae	Perennial cool season C3 grass	20	22.4	17 December, 2008

of water applied at each 7-10 day irrigation across the two 0.30 ha experimental blocks used in this experiment was increased from 12 mm on 30 April to 115 mm on 5 August 2008 (Figure 1). The total calculated amount of irrigation water applied over the growing season (21 May to 7 August 2008) averaged 762 mm across the two blocks. The mean (± SE) actual amount of water applied over the latter part of the growing season (total of 451±94 mm from 12 June to 7 August 2008; n=7 tipping bucket rain gauges) was calculated from amounts measured using HOBO logging tipping bucket rain gauges (Onset Computer, Bourne, Massachusetts, U.S.A.) with one gauge installed on 12 June 2008 in seven of the 22 experimental plots. One tip of the tipping bucket was equivalent to 0.2 mm of water.

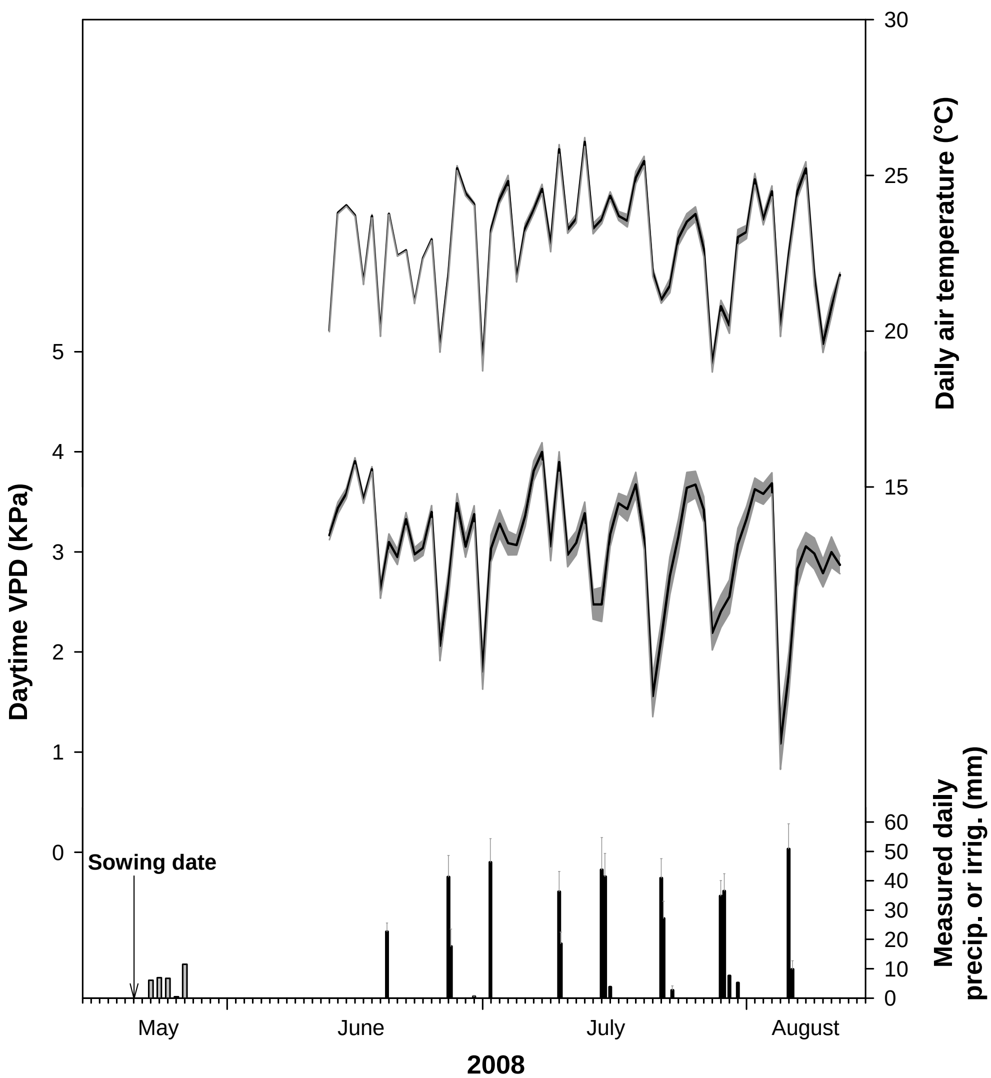

Figure 1. Time course of growing season (2008) mean (±SE, n=7 locations in experimental field) daily air temperature, daytime VPD, and daily sprinkler irrigation—filled bars (or, in May, natural rainfall—open bars) measured at the 5C Cottonwood Ranch site in Mason Valley, Nevada, USA.

Air temperature and relative humidity were recorded every 15 minutes using a shielded HOBOPro T/RH mini-logger at the same plots where the rain gauges were placed (Figure 1).

Static Chamber Measurement of Evapotranspiration (ET) and Net Ecosystem CO_2 Exchange (NEE)

ET and NEE were measured on all 22 1.0 m^2 plots using a 1-cubic meter static chamber (Arnone and Obrist 2003; Jasoni et al. 2005; Obrist et al. 2003) on three dates (21 July, 1 August, and 7 August 2008). On each sampling date when foliage was green, ET and NEE from each 1.0 m^2 plot were measured three to four times during an 8 h daytime period. Briefly, the static chamber method involves sealing the chamber over each 1.0 m^2 plot for 1 minute, measuring the rate of change in the water vapor and CO_2 densities inside the dome with a high frequency (10 Hz) open-path infra-red gas analyzer (LI-7500, LICOR Inc., Lincoln Nebraska, U.S.A.) with data logged every second using a laptop PC running the LI-7500 software, and adjusting this rate by accounting for the volume of the chamber, the area covered by the chamber, and changes in air temperature and air pressure during each 1-minute measurement. Only the initial linear portion of the change in water vapor and CO_2 densities inside the dome during each 1-minute sampling period was used to calculate ET and NEE, respectively; typically this was the first 20 to 40 seconds.

Plant Cover, Leaf Area, and Aboveground Biomass Measurements

Each 1.0 x 1.0 m subplot was photographed from a height of 2 m at each sampling date with a 8-megapixel Canon A630 color digital camera to estimate plant green cover. A greenness index was calculated by printing each digital photograph on 22 x 28 cm paper, overlaying a 2.4 x 2.4 cm transparent grid, counting the number of grid cells that were at least 50% green, and expressing this as a percentage of the total number of grid cells. On 12 August 2008, we clipped plant shoots in each of the 22 1.0 x 1.0 m subplots to a height of 5.1 cm above the surface of the soil. Leaves were separated from stems and dried separately at 70°C. We measured the area of a subsample of leaves from each subplot (LICOR LI-3000 leaf area meter) and dried these separately to calculate Specific Leaf Area (SLA, cm^2 g^{-1}). To capture biomass growth below 5.1 cm, we clipped all shoot biomass to the ground in a 30 x 30 cm area inside each 1.0 x 1.0 m plot. Mass of harvested dry biomass was measured on a balance (Mettler Toledo PB-3002-S, Columbus, Ohio, U.S.A.).

For dates when no harvesting occurred, we estimated aboveground biomass, leaf area index (LAI) and leaf biomass using final harvest data and linear regressions of harvested biomass, or leaf biomass, on percent canopy green cover measured immediately before harvest. LAI was then calculated by multiplying leaf biomass by the SLA of a small subset of leaves harvested from the canopy of each of the 22 subplots on each sampling date.

Calculations and Statistical Analyses

We calculated water use efficiency by dividing final biomass yield by the mean pre-harvest daytime ET rate. Water consumption per unit leaf area at harvest was calculated by dividing mean daytime ET measured on each plot on 7 August 2008 by the leaf area of that plot on 12 August 2008. Leaf biomass allocation was calculated as the percentage of aboveground biomass accounted for by leaf biomass for each experimental plot. SLA was calculated as the ratio of leaf area to leaf biomass for a random subsample of leaves taken on each sampling date. Vapor pressure deficit (VPD) was calculated using the air temperature and RH data collected by the HoboPro T/RH loggers.

Time course data were analyzed using repeated measures analysis-of-variance (ANOVA) with "plant species" as the primary independent variable and "experimental plot" (i.e., 1.0 x 1.0 m) taken as the statistical unit (e.g., von Ende 1993, with n=4 to 6 plots). Plant performance data collected at the end of the study period were analyzed using a one-way ANOVA with "plant species" as the independent variable. In cases where the variance around mean values was non-homogeneous, data points were transformed using $\log_{10}$ (cf. Zar 1984) and then subject to ANOVA. Linear regression analysis of (a) mean aboveground biomass at harvest across all continuously monitored test species on mean WUE (g biomass at harvest liter^{-1} of daytime ET-H_2O) measured on 7 August, and (b) plot-level aboveground biomass at harvest on plot-level WUE were calculated using Stata® (Stata Corp., College Station, Texas, U.S.A.). Stata® was used for all ANOVAs, as well.

RESULTS

Air temperatures (mean daily values of 18 to 27°C) and natural rainfall (0 mm) measured at the site from mid-June to the end of the observation period (12 August 2008; Figure 1) were typical for this area of the Walker River Basin valley (WRCC 2009). Mean daytime VPD values measured at 0.5 m above ground surface ranged from 1 to 4 kPa during this period and indicated the potential for strong VPD-modulated reductions in leaf stomatal conductance within plant canopies (e.g., Bunce 1982; Körner 1994; Oren et al. 1999) for all five test species.

The plant canopy green cover data indicated that significant differences had already developed among test species (P<0.0001) by the first sampling date (23 July 2008; Figure 2a). Plant cover of the two species of forbs, *Fagopyrum* (80-83%) and *Medicago* (62-80%), exceeded that of the two grass species, *Leymus* (40-50%) and *Festuca* (28-37%), by almost 45% in mid-July and by nearly 35% in mid-August. Percent green cover increased during the last three weeks of the growing season for all species (P<0.01) other than *Fagopyrum*, which had already reached its peak by mid-July (ca. 82±4%). On average, percent cover of the two grass species did not differ from each other (P=0.2350). Cover of the two forb species also did not differ from each other viewed over the 3-week observation period (P=0.2925).

Similar temporal patterns and differences in mean aboveground biomass among species were observed over the 3-week period, although differences among the four test species, and among the species over the four observation dates, were not statistically significant (Figure 2b). However, biomass of *Fagopyrum* (185±20 g m^{-2}) measured in mid-July exceeded the mean biomass of the three other species (65±12 g m^{-2}) by 185% (Figure 2b, P<0.01). By harvest time, differences between *Fagopyrum* (216±25 g m^{-2}) and *Medicago* (173±35 g m^{-2}) had narrowed to a point where biomass yields of the two species were similar (P=0.3484; Figure 2b, Figure 3a). Thus, for the four test species

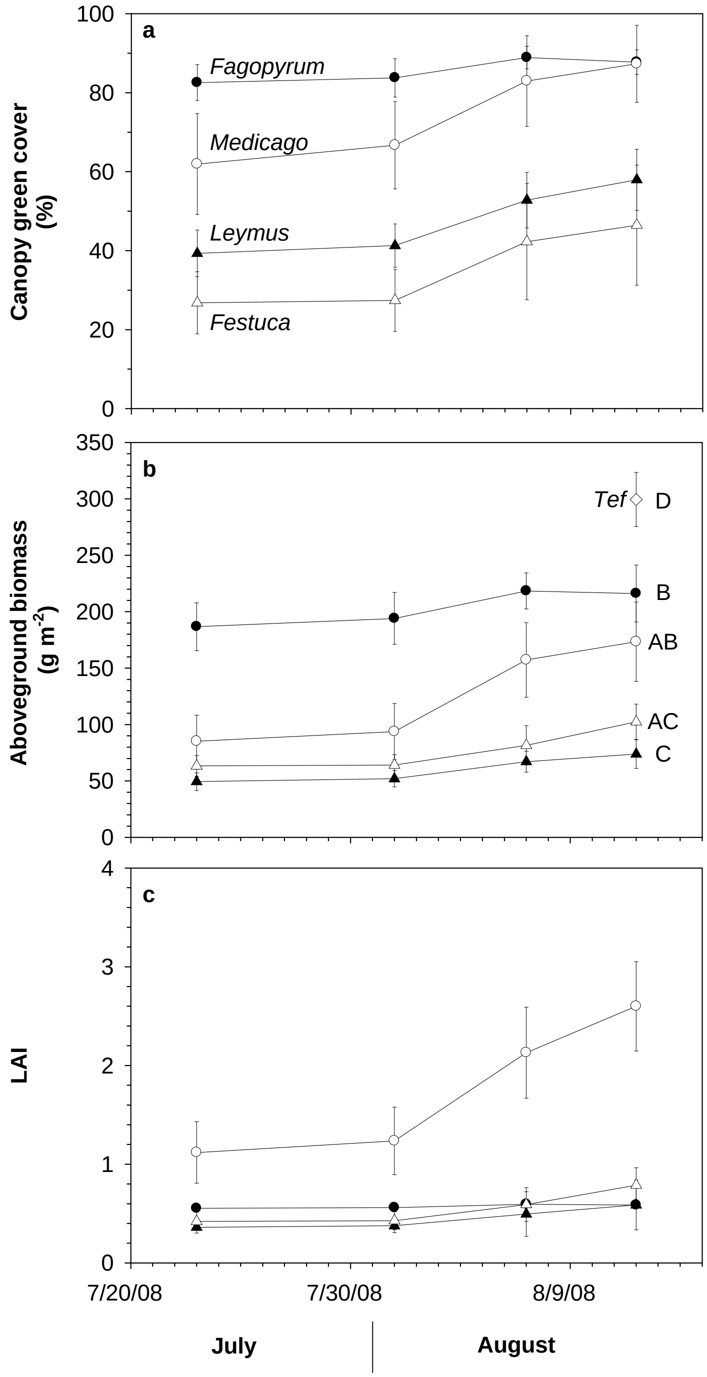

Figure 2. Time courses of growing season (**a**) crop canopy green cover, (**b**) aboveground crop biomass, and (**c**) leaf area index—LAI of the four continuously monitored test species (mean ± SE, n=4 to 6 experimental plots) measured in July and August 2008 at the 5C Cottonwood Ranch site in Mason Valley, Nevada, USA.

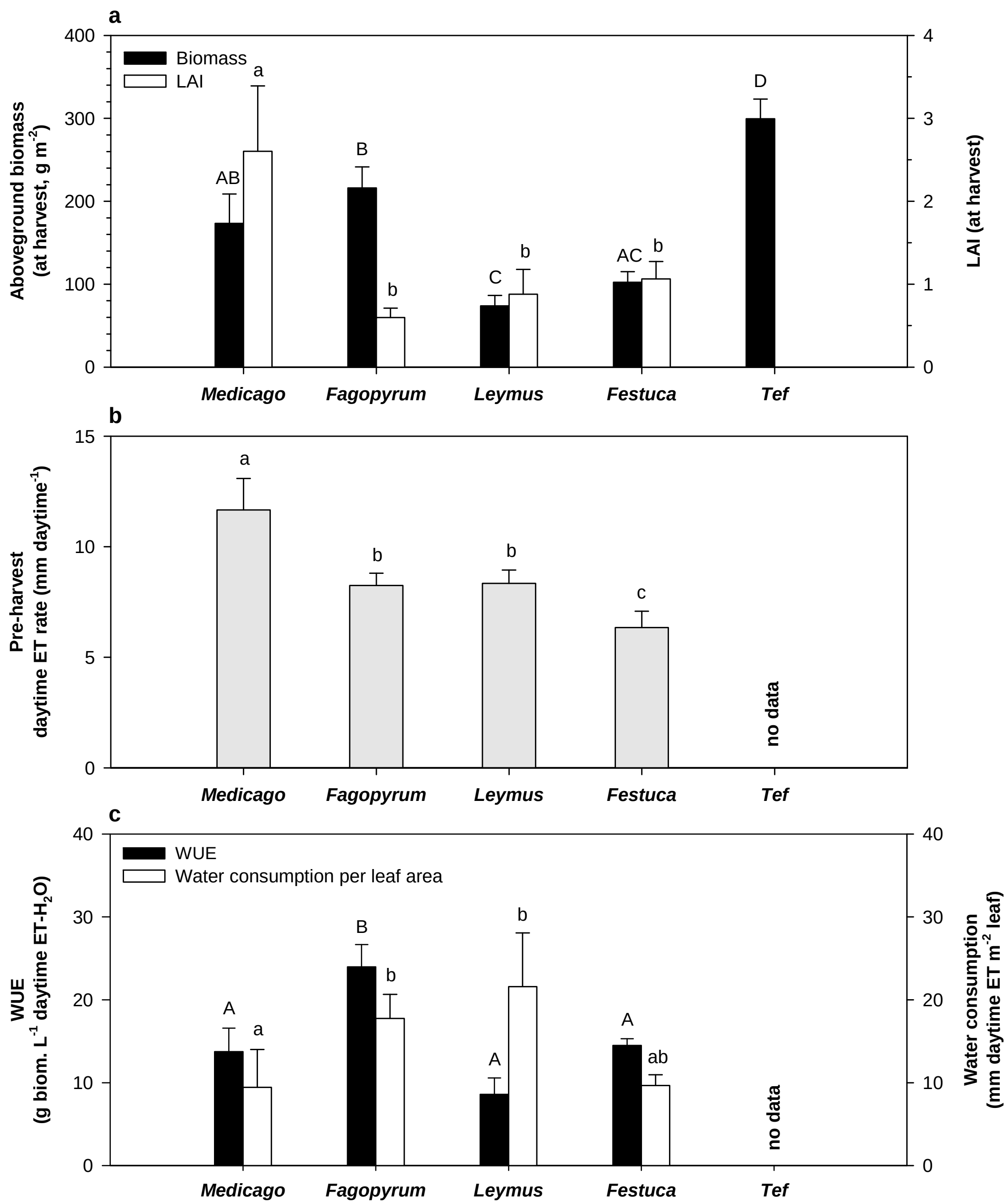

Figure 3. End of growing season (**a**) crop aboveground biomass yields and LAIs; (**b**) pre-harvest daytime ET rates; and (**c**) water use efficiency expressed as final biomass yield per unit of daytime ET measured in August 2008 one week before harvest (mean ± SE, n=4 to 6 experimental plots), and water consumption per unit leaf area, at the 5C Cottonwood Ranch site in Mason Valley, Nevada, USA.

evaluated over the entire 3-week period, mean biomass yields of *Fagopyrum* and *Medicago* at harvest were about 2.3 times greater than the mean biomass yields of *Leymus* and *Festuca* (although the biomass yields of *Leymus* and *Festuca* were statistically indiscernible; P=0.1590, $n_{Festuca}$=4, n_{Leymus}=6 plots) (Figure 3a). However, *Eragrostis* showed the highest biomass yield of all five of the species at 299±24 g m^{-2}—about 40% larger than the mean yield of *Fagopyrum*.

Allocation of aboveground biomass yield to leaves in each of the two species of forbs differed significantly, with a much higher allocation to leaves in *Medicago* (ca. 55±8%) than in *Fagopyrum* (30±5%; Figure 3a, $P_{species}$<0.0001). However, allocation to leaves remained constant within each of these species over the 3-week observation period (P_{date}=0.1799; $P_{spp\ x\ date}$=0.1827). Aboveground biomass of the two grass species consisted entirely of leaves. SLAs of the two forb species were over twice as high as those measured in the two grass species (P<0.0001) with SLAs of *Medicago* remaining constant at around 225 cm^2 g^{-1} and SLAs of *Fagopyrum* remaining at ca. 215 cm^2 g^{-1} through 1 August 2008 but then dropping to ca. 175 cm^2 g^{-1} by harvest (Figure 3b).

LAI of the two grass species, and that of *Fagopyrum*, appeared to have saturated under prevailing levels of irrigation and soil fertility before 23 July because no significant changes in LAI of any of these species were observed over the 3-week observation period (mean LAI of these three species: 0.45±0.31; Figure 3c). In contrast, LAI of *Medicago* was three to six times greater than the LAIs of the other species and increased from 1.12±0.31 in mid-July to 2.60±0.45 at harvest in mid-August 2008. At the time of harvest, LAIs of *Medicago* exceeded the LAIs of the other three continuously monitored test species by a factor of almost six (Figure 3c). LAI of *Eragrostis* was not measured at harvest.

ET measured two to four times during the daylight hours on each experimental plot on each of three separate dates showed no striking diurnal patterns (Figure 4a), although ET rates of some species peaked just before midday (e.g., *Medicago* and *Leymus* on 7 August 2008). Differences in ET between plots planted with different species only became apparent on 1 August 2008, with ET of plots containing *Medicago* significantly exceeding ET rates of plots containing *Leymus*, *Fagopyrum* and *Festuca*. On 1 August, mean daytime ET of *Medicago* exceeded ET of *Leymus* and *Fagopyrum* by a factor of 1.7, and ET of *Festuca* by a factor of 3.1 (Figure 4a). On 7 August, mean daytime ET of *Medicago* exceeded ET rates of *Leymus*, *Fagopyrum* and *Festuca* by factors of 1.4 to 8.0. The diurnal patterns in ecosystem ET for each of the three sampling dates translate into the patterns shown in Figure 6a.

The daytime ET rates of by experimental plots planted with *Medicago* measured five days before harvest (on 7 August) were the highest of the four species that were continuously monitored over the 3-week observation period (11.7±1.4 mm d^{-1}, $P_{species}$=0.0059; Figure 3b). This amounted to a 42% higher rate than measured in *Fagopyum* plots ($P_{species\text{-}2\ spp.\ comparison}$=0.0010), a 40% higher rate than that measured in *Leymus* plots ($P_{species\text{-}2\ spp.\ comparison}$=0.0012), and a 84% higher ET than that measured in *Festuca* plots ($P_{species\text{-}2\ spp.\ comparison}$=0.0010).

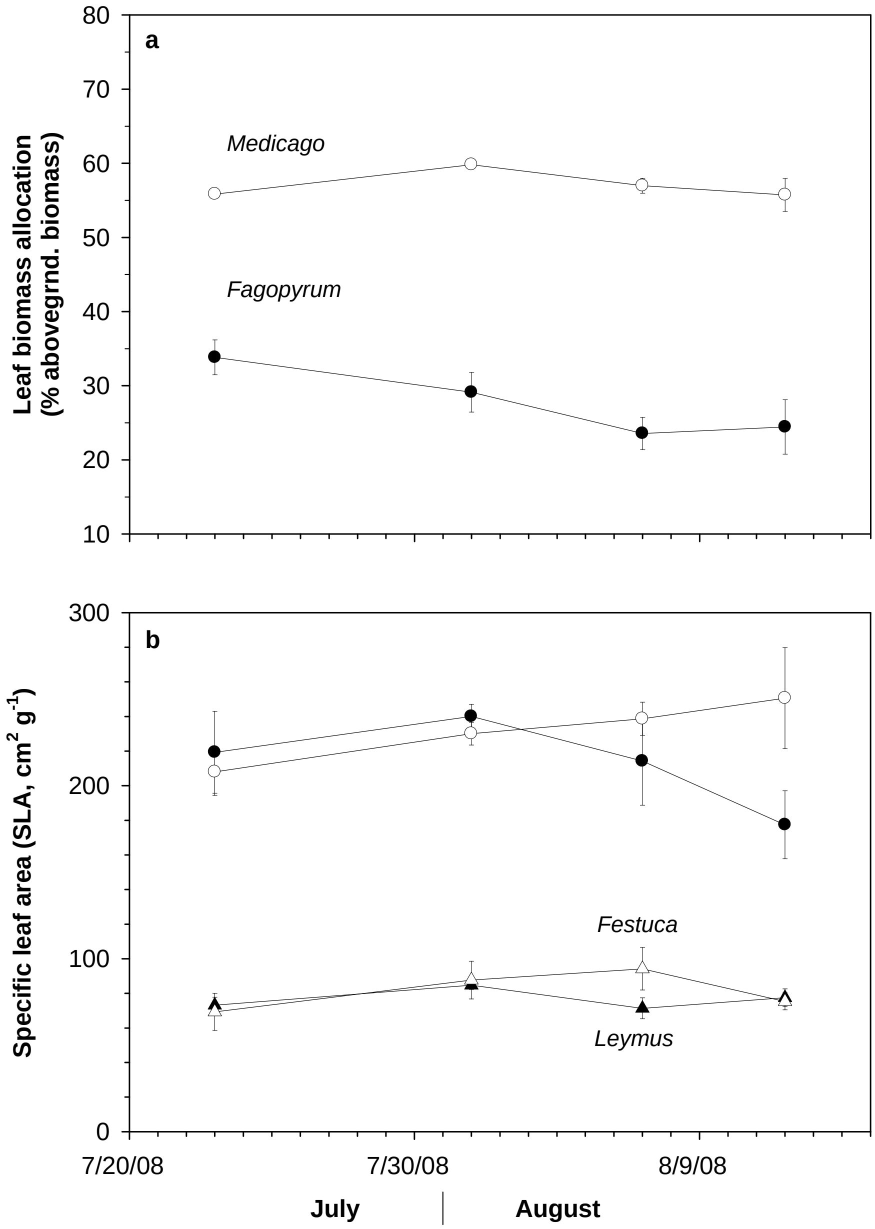

Figure 4. Time courses of growing season (**a**) leaf biomass allocation for the two continuously monitored forb species, *Medicago* and *Fagopyrum*; and (**b**) specific leaf area for all four continuously monitored test crop species (mean ± SE, n=4 to 6 experimental plots) measured in July and August 2008 at the 5C Cottonwood Ranch site in Mason Valley, Nevada, USA.

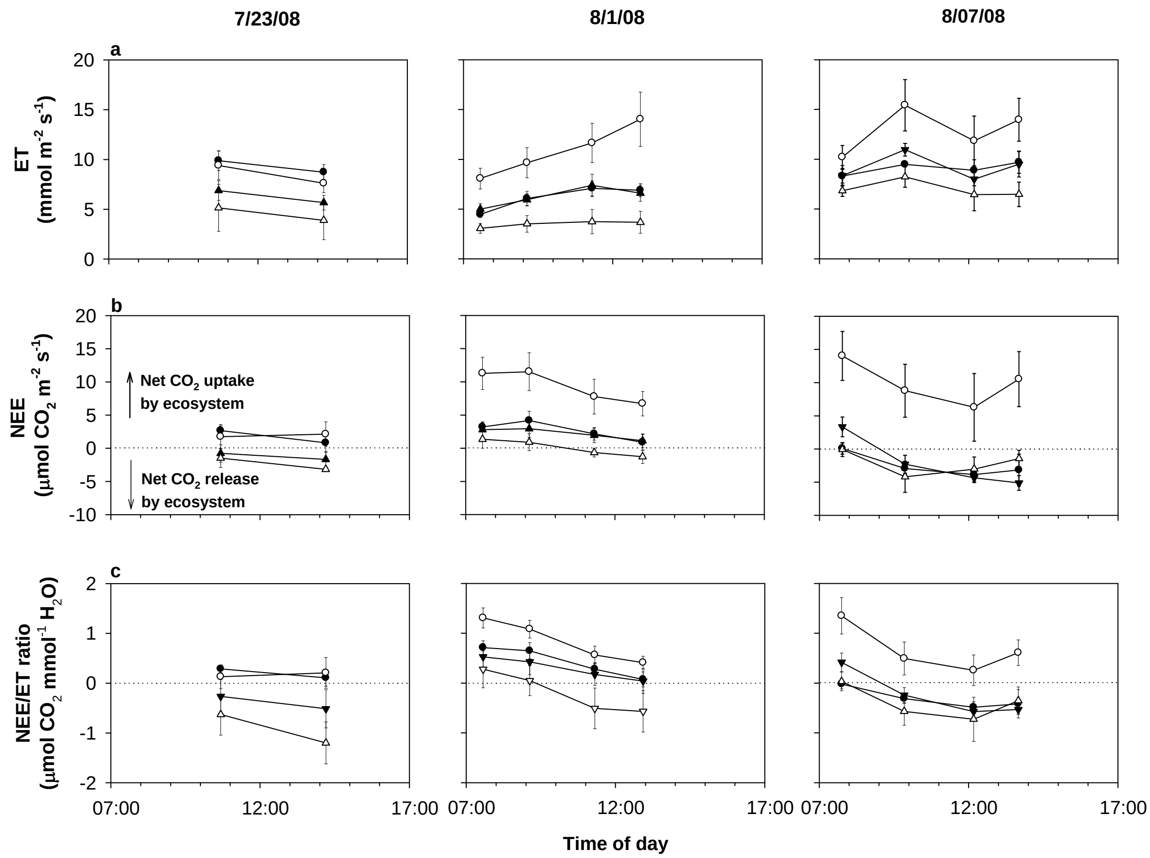

Figure 5. Diurnal time courses for each sampling date of (**a**) ecosystem ET; (**b**) net ecosystem CO_2 exchange—positive values indicate net CO_2 uptake by ecosystem/crop; and (**c**) ecosystem NEE:ET ratio (mean±SE, n=4 to 6 experimental plots) for the four continuously monitored test crop species measured in July and August 2008 at the 5C Cottonwood Ranch site in Mason Valley, Nevada, USA. Open circles, *Medicago*; closed circles, *Fagopyrum*,; open triangles, *Festuca*; close triangles, *Leymus*.

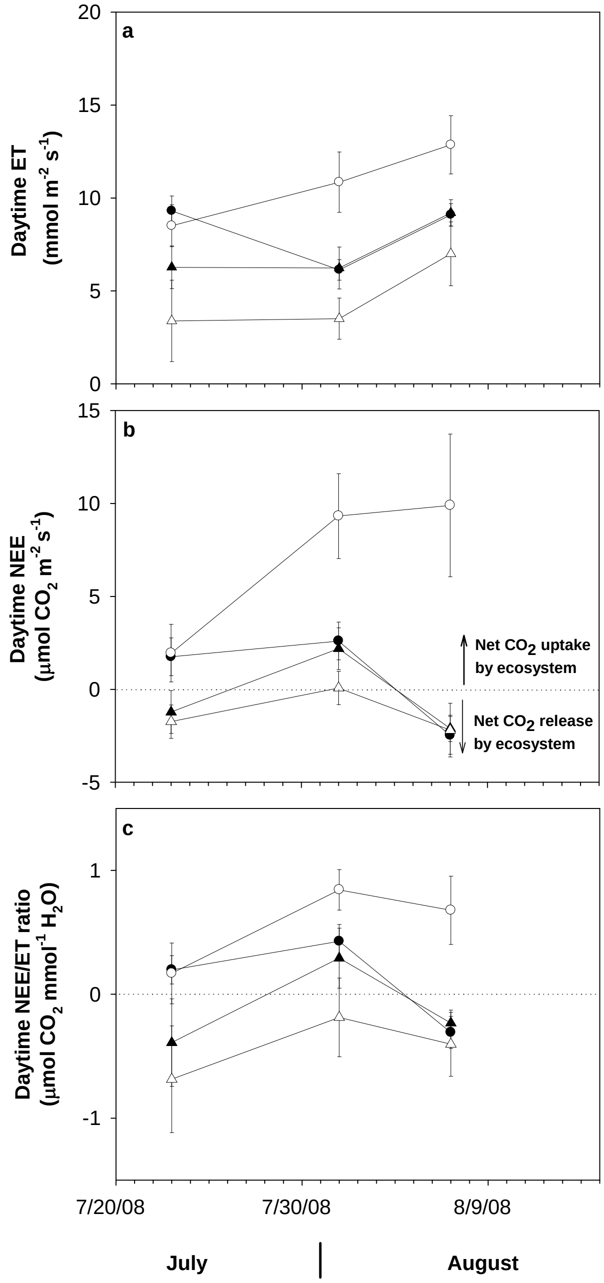

Figure 6. Time courses of growing season (**a**) daytime ecosystem/crop ET; (**b**) daytime NEE; and (**c**) daytime NEE:ET ratios for the four continuously monitored test crop species (mean ± SE, n=4 to 6 experimental plots) measured in July and August 2008 at the 5C Cottonwood Ranch site in Mason Valley, Nevada, USA. Open circles, *Medicago*; closed circles, *Fagopyrum*,; open triangles, *Festuca*; close triangles, *Leymus*.

Diurnal patterns in NEE, and differences observed among plots planted with the four continuously monitored species (Figure 4b), were generally the same as those observed for ET. However starting at the 1 August sampling, NEE of *Medicago* plots increase above NEEs measured in plots containing the other three species (Figure 4b). Daytime NEE in plots containing *Medicago* was strongly positive (ca. 10 µmol CO_2 m^{-2} s^{-1} on 7 August), whereas NEE of plots containing the other three species actually dropped below zero (ca. -2 µmol CO_2 m^{-2} s^{-1}) by the third sampling date (they were only slightly positive on 23 July and on 1 August). Thus plots containing the other three species were net emitters of CO_2 even during the daytime. NEE of plots with these three species were similar to each other (Figure 4b).

As a consequence of the patterns in ecosystem ET and NEE, patterns calculated for the daytime NEE/ET ratio (Figure 4c) tended to reflect the patterns observed in NEE (Figure 4b). No differences were observed in NEE/ET ratios between plots containing the four different species on 23 July. On 1 August, *Medicago* showed NEE/ET ratios that were significantly greater than NEE/ET ratios of only *Festuca*. On 7 August, NEE/ET ratios of *Medicago* exceeded those of all of the other three continuously monitored species.

When WUE was expressed as aboveground biomass yield at harvest per mean pre-harvest daytime ET measured with the chamber, *Fagopyrum* (24.0±2.7 g biomass $liter^{-1}$ daytime ET-H_2O) exceeded the three other continuously monitored species by factors of 1.7 to 2.8 (black bars, Figure 5). When water use was expressed as water consumption per unit LAI, *Medicago* showed lower consumption rates than *Fagopyrum* and *Leymus* but rates that were statistically indistinguishable from those of *Festuca* (white bars in Figure 5; no data available for *Eragrostis*). No differences in water consumption rates (per unit leaf area) were detected between *Fagopyrum*, *Leymus*, and *Festuca*. Regressions of total aboveground biomass yield on WUE (expressed as g biomass $liter^{-1}$ mean daytime ET-H_2O) calculated for 7 August across all continuously monitored species were highly significant and strong with species having higher WUE also exhibiting higher biomass yields and those with lower WUE showing lower biomass yields (Figure 7a, 7b).

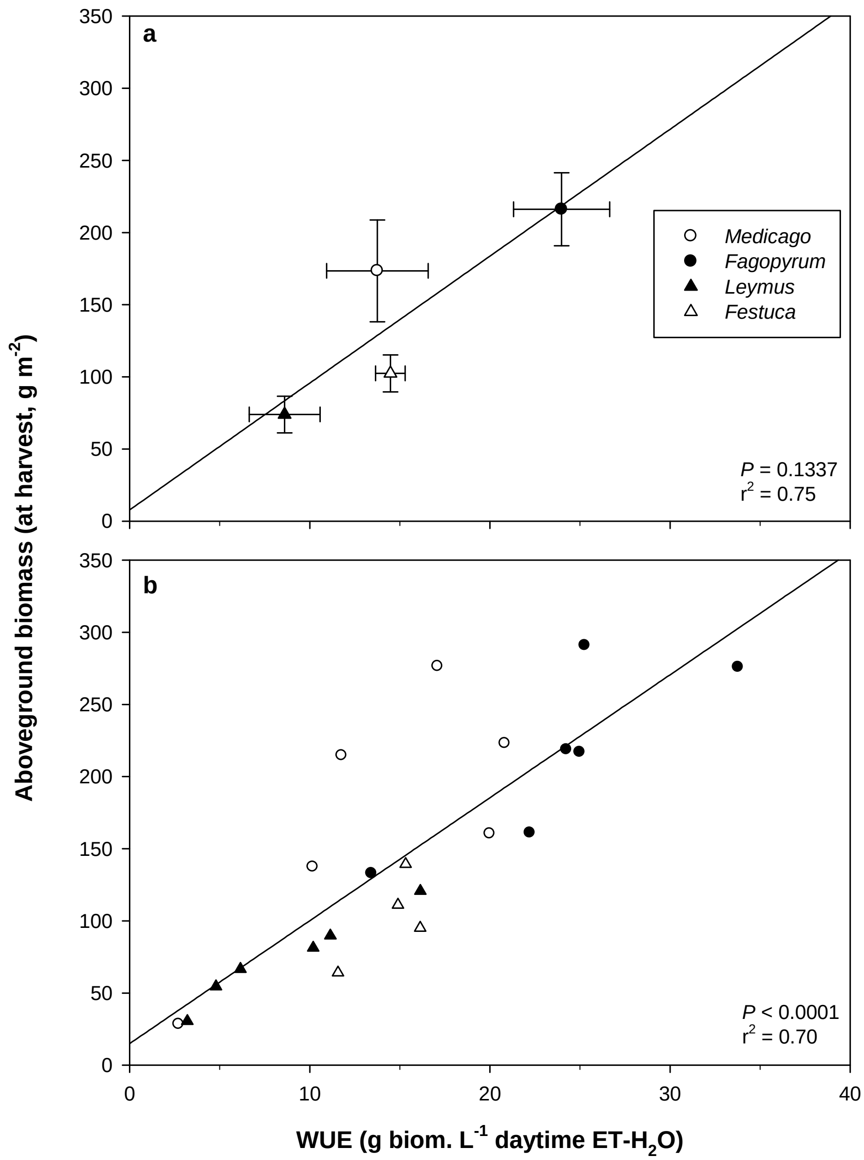

Figure 7. Linear regression relationships between (**a**) mean ± SE aboveground biomass yield at harvest and corresponding mean ± SE daytime water use efficiency calculated at the end of the growing season; and (**b**) plot-level aboveground biomass yield at harvest and corresponding plot-level daytime water use efficiency calculated at the end of the growing season for the four continuously monitored test crop species measured in August 2008 at the 5C Cottonwood Ranch site in Mason Valley, Nevada, USA.

DISCUSSION

Temporal patterns in canopy green cover, aboveground biomass or LAI of the four continuously monitored species indicate that most species had already reached their peaks by the time we began measurements, while especially *Medicago* was continuing toward its peak (Figure 2). Continued growth of *Medicago* between 23 July and 1 August 2008 suggests that this species was still exploiting available soil water (and nutrients) and aboveground (light) resources. However, *Fagopyrum* peaked much earlier and yielded as much biomass as *Medicago* by harvest time (Figure 2b). The absence of significant changes in *Leymus* and *Festuca* growth parameters over the observation period suggests either that soil resources may have limited their growth or that these species and varieties may not be well adapted to relatively dry spring and summer conditions.

The reasons for better growth performance of the two forb species, relative to that of the grass species, are unclear but may have to do with the greater ability of the forbs to produce leaves at multiple layers in the canopy, and thus to better exploit photosynthetically active radiation than the grasses could (e.g., Larcher 2003). Other potential explanations for the differences in crop growth between the forbs and grasses include: (1) lower VPDs, (Figure 1) created within canopy atmospheric micro-environments by the higher lateral density of leaves and stems present in plots containing forb species that allowed leaf stomata to remain open for longer periods—and thus assimilate more CO_2—than may have been possible in the relatively open, higher VPD canopies of the *Leymus*, *Festuca* and *Fagopyrum* plots where stomatal conductance and photosynthetic CO_2 assimilation may have been more limited (cf. Arnone et al. 2008; Bunce 1982; Körner 1994; Oren et al. 1999 particularly in graminoid dominated systems—Grace et al. 1998; Novick et al. 2004; Vourlitis et al. 1999; Wever et al. 2002—we did not directly measure leaf stomatal conductance in any species.); (2) in the case of *Medicago*, symbiotic nitrogen fixation in its root nodules enhancing plant nitrogen availability above levels than were possible for the other non-nitrogen fixing species (e.g., Arnone and Gordon 1990; Hebeisen et al. 1997; Newton et al. 1994; Soussana and Hartwig 1996; Zanetti et al. 1996); or (3) lower SLAs measured in grass species may have contributed to lower relative growth rates (Garnier 1992; Marañón and Grub 1993; Poorter and Remkes 1990;). However, higher leaf biomass allocation (leaf mass ratios—Lambers et al. 1998) of *Medicago*, relative to that measured in *Fagopyrum*, appear not to have contributed to higher relative growth rate in *Medicago* (Marañón and Grub 1993).

Higher plant WUE by *Fagopyrum* and *Medicago*, and lower water consumption per unit leaf area, may also help explain better biomass yield performance of forbs relative to the grasses *Leymus* and *Festuca* (Figure 3c). The apparent growth strategy (or inherent genetic plasticity) employed by *Fagopyrum* was a lower growth allocation to leaves (ca. 30%; Figure 4a), relative to that observed in *Medicago* (ca. 57%). Thus, two divergent growth strategies produced the same aboveground biomass yield, suggesting that aboveground biomass allocation may not be as functionally important in defining yield as we had originally hypothesized. However, lower leaf biomass allocation in the forb species *Fagopyrum* may confer ecological benefits to this species via improved WUE, expressed as aboveground biomass produced per unit of water lost through ET, when compared to higher leaf allocation and lower WUE measured in *Medicago* (Figure

4a, Figure 3c). Higher SLAs in forb species (ca. 210 cm^2 g^{-1}), compared to SLAs in grasses (ca. 90 cm^2 g^{-1}; Figure 3b), likely reflect commonly occurring inherent differences between plant functional types. It is unclear, however, how lower SLAs observed in *Fagopyrum* by harvest time, relative to those observed in *Medicago*, may confer higher WUE but also higher calculated water consumption per unit leaf area (Figure 3c). Regardless of the possible plant physiological mechanisms that may explain relative species performances, it is very clear that plant species with higher WUEs perform significantly better than those with lower WUEs (Figure 7).

Two to six-fold higher final aboveground biomass yields for plots with the grass *Eragrostis*, relative to plots of the other four species, indicate that WUE of this species may have also been highest among all five species tested (Figure 3a, Figure 7). If this were the case, then the pattern of higher forb species' performance, relative to grass species' performance, would be difficult to explain. At harvest, LAIs of *Eragrostis* appeared to be greater (we did not measure LAI in *Tef*) than LAIs of any of the other test species in our study—including *Medicago* and *Fagopyrum*, which also may have contributed to its superior performance.

Aboveground biomass (forage) yields measured in our study for *Medicago*, and *Festuca*, were generally much lower than yields reported in other studies. We were only able to find data on grain yields for *Fagopyrum* and no data on *Leymus*. Average *Medicago* forage yield in our study was 19 to 88% lower than yields reported in several other studies (Guitjens and Mahannah 1975; Hanson et al. 2007; McCormick and Myer 1958; Neyshabouri 1976; Tovey 1963; Tuteur 1976; Staubitz 1978; Wilcox 1978). When our single-harvest yields for *Medicago* are compared to first-harvest yields in other studies (e.g., Hanson et al. 2007), or to yields measured under deficit irrigation, differences were smaller (-19% to -44%; -68% to +19%). Not surprisingly the literature on yields of *Medicago* generally indicates that aboveground productivity increases with increasing water supply (irrigation or rain; e.g., Guitjens 1993; Hanson et al. 2007; Kimbell et al. 1990; Putnam et al. 2000; Robinson et al. 1994), suggesting that yields in our study were severely constrained by water availability. For example, yields of *Festuca* in our study (100±20 g m^{-2}) under 451±94 mm of irrigation water (based on rain gauge data) were 85% lower than yields reported for *Festuca* irrigated with 1067 mm (Davison 1993). Limited data available on yields of *Festuca* and *Leymus* indicate that high yields are possible in arid regions if these crops are provided adequate water and nitrogen (Davison 1993).

We were only able to find data on crop WUE expressed as g biomass yield $liter^{-1}$ H_2O lost through ET for *Medicago*. Values measured in our study were about five times greater than values calculated for *Medicago* growing in mesic climates (Grimes et al. 1992: 2.3 g biomass yield $liter^{-1}$ H_2O; Smeal et al. 1992: 1.8 g biomass yield $liter^{-1}$ H_2O; Wright 1988; 1.7 g biomass yield $liter^{-1}$ H_2O;) where greater precipitation and irrigation may have led to either a higher proportion of water losses occurring via evaporation or an actual depression of plant/crop WUE when water was more abundant.

Quantification of the relative potential of the ecosystems planted with the four continuously monitored crops to sequester C—assessed by measuring daytime NEE (Figure 6b)—suggests that a *Medicago* crop may surpass the other crops, but only if the aboveground biomass is allowed to remain on the site and contribute to the soil organic matter accumulation—which would not occur when the crop is removed from the site as it normally would be. Also, this estimate of potentially higher C-sequestration for *Medicago* does not include the likelihood of higher nighttime net ecosystem CO_2 losses to the atmosphere in these systems that contain more phytomass, and higher quality litter (cf. Arnone et al. 2008; Hirschel et al. 1997; Jasoni et al. 2005; Verburg et al. 2005), relative to the other test crops. Measurement of nighttime NEE over the entire growing season, and even during the fallow period, is required in order to quantitatively and accurately assess true ecosystem C sequestration potential by alternative crop species (e.g., Jasoni et al. 2005). It is unclear why plots containing *Medicago* indicated net CO_2 uptake during the day prior to harvest and the other three species did not.

Together, the results of our study indicate that (1) water losses through ET differ between alternative crop species indicating the potential for improved water savings and reduced irrigation requirements; (2) improvements in overall water use by some alternative crops correspond to enhanced water use efficiencies—expressed as aboveground biomass production per unit of water lost through ET or per unit of water applied—and higher ecosystem CO_2 uptake per unit of water lost through ET; and (3) alternative crop species demonstrating higher WUEs may achieve this by allocating less shoot growth to leaves, by producing leaves with lower C investment per unit area (i.e., higher SLAs), or by creating closed plant canopies, even at low water availability, that reduce atmospheric incursions into the canopy and allow VPDs to remain below levels that cause stomata to close and reduce leaf CO_2 assimilation. Thus, data from this study demonstrate the potential for large water savings by substituting high WUE forage/biomass species for traditional forage species such as alfalfa. Whether or not alternative crops will be used will however also depend on economic potential of these crops, which is also depends on the quality (e.g. nutrient content, grain chemistry) of the crop.

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