Rangeland Ecology & Management 69 (2016) 390–398

Contents lists available at ScienceDirect

Rangeland Ecology & Management

journal homepage: http://www.elsevier.com/locate/rama

Forage Kochia and Russian Wildrye Potential for Rehabilitating Gardner's Saltbush Ecosystems Degraded by Halogeton☆,☆☆

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ARTICLE INFO

Article history:
Received 30 September 2015
Received in revised form 4 June 2016
Accepted 10 June 2016

Keywords:
establishment
forage
rangeland
rehabilitation
saline

ABSTRACT

Gardner's saltbush ecosystems are increasingly being invaded by halogeton (*Halogeton glomeratus* [M. Bieb.] C.A. Mey.), an annual halophyte that increases soil surface salinity and reduces plant biodiversity. Thus, a study was established in the Flaming Gorge National Recreation Area within the lower Green River Basin of Wyoming to evaluate the potential for rehabilitating halogeton-dominated Gardner's saltbush ecosystems with forage kochia (*Bassia prostrata* [L.] A.J. Scott), Russian wildrye (*Psathyrostachys juncea* [Fisch.] Nevski), tall wheatgrass (*Thinopyrum ponticum* [Podp.] Z.-W. Liu & R.-C. Wang), Indian ricegrass (*Achnatherum hymenoides* [Roem. & Schult.] Barkworth), and Gardner's saltbush (*Atriplex garneri* [Moq.] D. Dietr.). A seeding evaluation, with and without prior disking, was conducted to determine ability of these species to establish. A transplant evaluation determined the effect of established plants on halogeton frequency at four 10-cm intervals (10–20, 20–30, 30–40, and 40–50 cm) distal from transplants. Gardner's saltbush, tall wheatgrass, and Indian ricegrass did not establish in the seeded study or persist beyond the first year in transplant study. In contrast, Russian wildrye and forage kochia established and persisted, with Russian wildrye establishment higher ($P = 0.05$) in the disked treatment compared with no-till (4.5 and 1.7 plants m^{-2}, respectively) and no-till favoring ($P = 0.05$) forage kochia establishment (2.3 and 0.8 plants m^{-2}, respectively). Transplants of these two species reduced halogeton frequency by 52% relative to the control. Moreover, this interference of halogeton establishment by Russian wildrye and forage kochia had extended to 50 cm distal from transplant by the second year of the study. By the third year (2014), transplant survival and halogeton frequency were highly correlated ($r = -0.61$, $P = 0.0001$), indicating the importance of plant persistence. Results indicate that Russian wildrye and forage kochia can establish and reduce halogeton frequency, thereby providing an opportunity for rehabilitation of halogeton-invaded areas.

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Introduction

The semiarid and arid rangelands of the western United States provide a broad array of ecosystem services, including livestock forage, a diversity of native plants, pollinators, wildlife, and recreational activities. The salt desert shrub ecosystems found within these rangelands are particularly vulnerable to invasive species (Levine et al., 2003; Young and Clements, 2003) and as such, are experiencing a rapid increase in annual weeds such as halogeton (*Halogeton glomeratus* [M. Bieb.] C.A. Mey). Halogeton is a succulent annual halophyte and highly invasive species of Eurasian origin that was first reported near Wells, Nevada in 1934 (Dayton, 1951; Holmgren and Andersen, 1970; Young, 2002). By 1952, halogeton had spread to 0.6 million hectares encompassing deserts of the Great Basin, Colorado Basin (Utah and Colorado), and Wyoming (Tisdale and Zappetini, 1953) and is now found in all 11 western states, as well as South Dakota and Nebraska (USDA-NRCS, 2015).

Halogeton is a particularly difficult weed to manage, in part because of its seed (establishment) biology. Halogeton is a prolific seed producer (224–448 kg seed ha^{-1}), producing two types of seeds, easily identified by color (Cronin and Williams, 1966). Black seeds are viable for 1 yr and readily germinate with favorable soil moisture and temperature, whereas brown seeds are dormant and can remain viable in the soil for up to 10 yr (Cronin and Williams, 1966). Halogeton is also known for "salt pumping," which brings salt from the soil into the plant tissue and

☆ Research was funded in part by the Wyoming Landscape Conservation Initiative, USDA Forest Service, and USDA-ARS.
☆☆ Joint contribution of the USDA-ARS, the Utah Agricultural Experiment Station, and Utah State University, and approved as Utah Agricultural Experiment Station journal paper 8815. Mention of a trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the USDA or Utah State University and does not imply its approval to the exclusion of other products that may also be suitable.
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http://dx.doi.org/10.1016/j.rama.2016.06.001
1550-7424/Published by Elsevier Inc. on behalf of The Society for Range Management.

increases the salt concentrations at the soil surface as the plant senesces (Eckert and Kinsinger, 1960; Kinsinger and Eckert, 1961; Harper et al., 1996; Duda et al., 2003). As a result, the physical structure of the soil is altered, causing severe crusting and dramatically decreasing soil permeability (Eckert and Kinsinger, 1960). It has been hypothesized that the increase of sodium on the soil surface interferes with the germination and subsequent establishment and persistence of native grasses and forbs (Eckert and Kinsinger, 1960; Kinsinger and Eckert, 1961), thus allowing halogeton to spread and densities to increase (Duda et al., 2003).

In the lower Green River Basin of Wyoming (NRCS, 2011), Gardner's saltbush (*Atriplex gardneri* [Moq.] D. Dietr.), a valuable native shrub that provides a nutritious winter forage for wildlife and livestock, has been declining and subsequently replaced by halogeton (Goodrich and Zobell, 2011). For instance, Goodrich and Zobell (2011) reported that in one area, Gardner's saltbush declined from 26% to 0% canopy cover from 1993 to 2009, and afterwards it became predominately a monoculture of halogeton. The authors speculated that the decline in Gardner's saltbush was probably due to a combination of factors, including cattle grazing drought, and especially the effects of "salt pumping" by halogeton (Goodrich and Zobell, 2011). One of the major concerns about halogeton, wherever it is found, but particularly in this region, is that it accumulates toxic oxalates in its tissues that are often fatal to livestock when ingested, especially sheep (Tisdale and Zappetini, 1953; Cronin and Williams, 1966). Therefore the increase in halogeton and associated loss of perennial species like Gardner's saltbush not only result in potential degradation of the rangeland but also reduce the forage base in terms of quantity and quality.

Forage kochia (*Bassia prostrata* [L.] A. J. Scott), a perennial chenopod shrub, is an important forage in its native environment of Eurasia, where it is used by sheep, goats, camels, and horses (Waldron et al., 2010). Waldron et al. (2011) recommended the use of forage kochia on western rangelands as it increases nutritional value, carrying capacity, and livestock performance on semiarid rangelands, especially for fall/winter grazing. Forage kochia has been reported to establish, compete, and persist with the annual weed downy brome (*Bromus tectorum* L.) (McArthur et al., 1990; Monaco et al., 2003) and is widely used to rehabilitate disturbed areas where frequent fire occurs and invasive annuals persist. The successful establishment of forage kochia is dependent on its peculiar seed biology, including late fall seed ripening, rapid loss of seed viability under normal storage conditions, inability to emerge from soil depths > 0.5 cm, and delayed, asynchronous germination of fresh seed during the moist cold months of winter (Waller et al., 1983; Kitchen and Monsen, 2001; Stewart et al., 2001; Creech et al., 2013). Forage kochia is well adapted to the semiarid and arid rangelands of the western United States, in part due to its high salt and drought tolerance. Forage kochia has been reported to be productive in soils approaching salinity electrical conductivity (EC) values of 20 dS m^{-1} (Francois, 1976; McFarland et al., 1990; Waldron et al., 2010). It also has an extensive root system, consisting of a taproot extending to 6.5 m in depth (Gintzburger et al., 2003) and fibrous lateral roots of 130–160 cm in length (Baylan, 1972) that enable it to compete for limited available water and enhance its drought tolerance (Romo and Haferkamp, 1988). These adaptive traits make forage kochia a strong candidate species to rehabilitate halogeton-infested semiarid rangelands. Stevens et al., (1990) reported that forage kochia had replaced halogeton 7 yr after seeding in a lower-elevation (1569 m) degraded shadscale salt desert shrub ecosystem in Utah. There are no published reports of forage kochia's adaptation and effect on halogeton in the Gardner's saltbush ecosystems of the lower Green River Basin.

Other candidate species for rehabilitation of halogeton-infested rangelands include Russian wildrye (*Psathyrostachys juncea* [Fisch.] Nevski), tall wheatgrass (*Thinopyrum ponticum* [Podp.] Z.-W. Liu & R.-C. Wang), Indian ricegrass (*Achnatherum hymenoides* [Roem. & Schult.] Barkworth), and Gardner's saltbush itself. Russian wildrye is considered to be extremely drought resistant, exceeding even crested wheatgrass (*Agropyron desertorum* [Fisch. Ex Link] Schultes) (Jensen et al., 2006), best adapted to loam and clay soils, and is moderately tolerant of saline-alkali soils (Asay and Jensen, 1996a). Tall wheatgrass is particularly noted for its capacity to produce forage and persist in areas too saline or alkaline for other forage crops and is adapted to semiarid rangelands that receive a minimum of 350 mm of annual precipitation (Asay and Jensen, 1996b). Indian ricegrass is a dominant native perennial grass in the low-elevation salt desert rangelands (Stubbendieck and Jones, 1996). It is valued for winter forage (Stubbendieck and Jone,s 1996) and is tolerant of slightly saline and sodic conditions and persists in areas receiving as low as 152 mm of average annual precipitation (USDA-NRCS, 2015). Gardner's saltbush is a native perennial shrub that is considered to be an important winter browse (Stubbendieck et al., 1997) and is widespread throughout salt desert shrub rangelands, where it most commonly inhabits saline, sodic, or clay soils with a pH of 7.8 − 8.6 (USU, 2015). Gardner's saltbush has been noted to be difficult to establish in seeded plantings due to germination requiring a complex interaction of after-ripening, scarification, leaching, and cold stratification (Ansley and Abernethy, 1985).

Therefore, two experiments were designed to compare the relative abilities of forage kochia, Russian wildrye, tall wheatgrass, Indian ricegrass, and Gardner's saltbush to establish, persist, and subsequently reduce halogeton establishment. The first experiment tested the hypothesis that if rehabilitation included a niche-creating soil disturbance that temporarily interfered with halogeton establishment long enough for favorable species to germinate and mature to juvenile plants, these species could persist and reduce halogeton frequencies. Given these assumptions, containerized-grown transplants were used in a systematic design to evaluate relative persistence and interference with halogeton establishment. The second experiment, conducted simultaneously, evaluated the relative ability of these species to actually establish from seed under field conditions and form a stand, with or without a niche-creating disturbance.

Materials and Methods

Study Site

The study area was located 11 km northeast of Manila, Utah within the Flaming Gorge National Recreation Area, Ashley National Forest in the lower Green River Basin (41°03.307'N, 109°36.410'W; elevation 1860 m), within the Cool Central Desertic Basins and Plateaus Major Land Resource Area (MLRA) D-34A. The mean calendar year annual precipitation (MCYAP; January 1–December 31) was 228 mm for a 104-yr period (1910–2015; based on Manila, Utah Western Regional Climate Center (WRCC, 2015) station number 425377 located 11.6 km southwest of the study area) (Fig. 1). Calendar year annual precipitation (CYAP) was 96%, 124%, 33%, 110%, and 107% of the MCYAP, in 2010, 2011, 2012, 2013, and 2014, respectively. The soils around the study area are dominated by Aridisols and Entisols. Soil tests conducted at the initiation of the research (Table 1) indicated that soil texture was a silt-clay-loam with up to 35% clay and would be considered a high pH soil (pH ≥ 7.8), approaching being sodic (SAR ≥ 13) with an SAR of 11.3; however, the 3–7 cm soil depth was considered sodic on the basis of an exchangeable sodium percentage > 15% of the soil's cation exchange capacity (CEC) (Davis et al., 2012). Our observations concurred with the soil test description, including soil physical properties as being variable to poor, with reduced infiltration and a tendency to crust (Davis et al., 2012). Plants commonly associated with MLRA D-34A are Gardner's saltbush, shadscale saltbush (*Atriplex confertifolia* [Torr. & Frém.] S. Watson), winterfat (*Krascheninnikovia lanata* [Pursh] A. Meeuse & Smit), bud sagebrush (*Picrothamnus desertorum Nutt.*), and Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young). Common grasses include bottlebrush squirreltail (*Elymus elymoides* [Raf.] Swezey), Indian ricegrass, and needle-and-thread grass (*Hesperostipa comata* [Trin. & Rupr.]

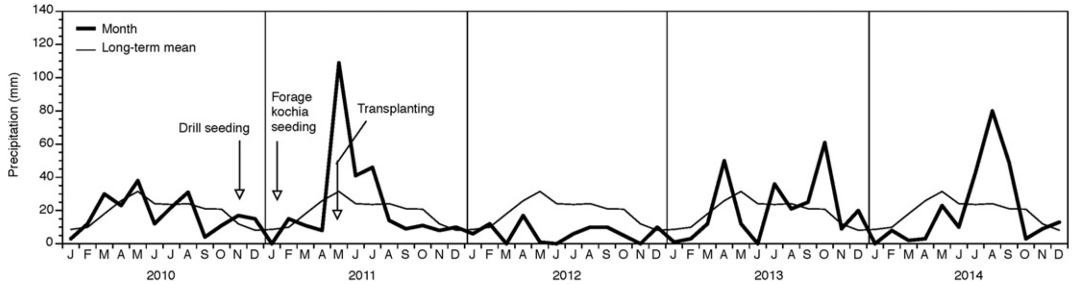

Figure 1. Monthly and long-term precipitation for the Wyoming lower Green River Basin study site (WRRC 2015). Monthly data from Manila, Utah (1935 M) located approximately 11 km southwest of the study site. The thin solid line represents the 104-yr norm and thick solid line represents monthly precipitation in the given year. Data last examined on 5 February 2015 at http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?utmani.

Barkworth) (NRCS, 2011). Canopy cover at the study site was primarily composed of Gardner's saltbush before the invasion of halogeton (Goodrich and Zobell, 2011), but at the time of the study it had a nearly uniform monoculture stand of halogeton. A 1-acre enclosure was fenced to keep out livestock/wildlife, and both experiments were conducted within the enclosure.

Plant Materials

The same plant materials were used in both experiments and consisted of representative entries of forage kochia, Russian wildrye, tall wheatgrass, Indian ricegrass, and Gardner's saltbush. Forage kochia entries were representative of three ploidy levels (diploid, tetraploid, and hexaploid) and two subspecies, consisting of the cultivars Immigrant (diploid, ssp. *virescens*) (Stevens et al., 1985) and Snowstorm (tetraploid, ssp. *grisea*) (Waldron et al. 2013) and the breeder population KZ6XSEL (hexaploid, ssp. *grisea*) (Waldron et al., 2001). Forage kochia entries had been previously evaluated for salt tolerance according to the greenhouse methods of Peel et al. (2004), where the data indicated that the higher the ploidy level, the greater the salt tolerance (data unpublished). Three cool-season grass species used in this study were Russian wildrye (cv. Bozoisky II) (Jensen et al., 2006), tall wheatgrass (cv. Alkar) (Schwendiman, 1972), and Indian ricegrass (cv. Rimrock) (Jones et al., 1998). Bozoisky II Russian wildrye was developed from Bozoisky-Select (Asay et al., 1985) and is noted for its increased seedling establishment and persistence on alkaline soils (Jensen et al., 2006). Alkar tall wheatgrass was derived from germplasm (PI98526) obtained from the N.I. Vavilov Institutes of Plant Industry in 1932 and has been shown to be adapted to alkali soils (Hafenrichter et al., 1968; Schwendiman, 1972). Rimrock Indian ricegrass was originally collected in 1960, north of Billings, Montana (PI478833) and released for revegetating and restoring rangelands, as well as a winter forage for livestock and wildlife (Jones et al., 1998). A commercial source of Gardner's saltbush (variety not stated; VNS) was used in this study.

Experiment #1—Effect of Established Plants on Halogeton Density (Transplant Study)

Experimental Design

This experiment tested the hypothesis that established seedlings of the evaluated perennial species could persist and reduce or displace halogeton. The assumption was made that prior rehabilitation efforts temporarily reduced halogeton, creating a niche for the perennial species to germinate and establish. Given these assumptions, containerized transplants were placed in a systematic design to evaluate relative survivability and effect on subsequent halogeton frequency. Containerized-grown plants of the aforementioned entries of forage kochia, Russian wildrye, tall wheatgrass, Indian ricegrass, and Gardner's saltbush plants were started from seed in a greenhouse in Logan, Utah. Seeds were planted on 18 January 2011 in Stuewe & Sons SC10 super container cells, which are 3.8 cm in diameter and 21 cm in depth. The media type used was a 3:1 ratio of perlite based soil and sphagnum peat moss mix. Greenhouse temperatures from mid-January to the first of May were kept at a mean temperature of 22°C. Plants were watered (2.5 cm day^{-1}) by an overhead sprinkler system with Peter's 20-20-20 water soluble fertilizer injected into the system at a rate of 1:100 ratio of fertilizer to water.

The containerized-grown juvenile plants were transplanted to the study site on 3 May 2011 into systematically designed evaluation plots. A plot consisted of a 4 × 4 grid of 16 transplants arranged such that plant density was 2 plants m^{-2} (e.g., 4 rows of 4 plants with 0.5 m between plants within the row and 1 m between rows). Plots consisted of monocultures of each entry, or as binary mixtures, in an alternating pattern of Gardner's saltbush with either forage kochia or grass. The overall dimension of each plot was 2 m × 4 m for a total area of 8 m^2. Control plots of the same size without any transplants were included within the experiment.

The study was arranged in a randomized complete block design (RCBD) with four replications of the seven monocultures, six mixtures, and one control, for a total of 56 plots. The plot area had been previously tilled with a Howard tiller on 10 November 2010 to simulate a niche-creating soil disturbance that would reduce initial halogeton stands and soil-surface salinity and to prepare for transplanting. Maintenance of the plots consisted only of mowing transplants in late summer of 2012 and 2013 before forage kochia reaching seed maturity. This was done so that forage kochia did not produce seed and recruit new seedlings within the plot area.

Data Collection and Statistical Analyses

Data were collected on 29 June 2012, 10 July 2013, and 29 October 2014. Halogeton frequency (%) was determined using the frequency grid protocol described by Vogel and Masters (2001) by laying a grid

Table 1
Soil characteristics for the halogeton-degraded Gardner's saltbush area in the Wyoming lower Green River Basin study site 11 km northeast of Manila, Utah. Soil tests were completed before the beginning of the study in 2010

Soil Depth	Soil Texture (% clay)	pH	EC	SAR	Soluble Na	Exchangeable Na	CEC
cm			dS m^{-1}		meq $^{-L}$		meq $^{-100\ g}$
0-3	Silt clay loam (32%)	8.3	3.5	11.3	10.0	4.5	31.8
3-7	Silt clay loam (34%)	8.4	2.1	6.9	6.3	5.5	31.1
7-16	Silt clay loam (35%)	8.6	1.5	7.3	6.4	3.8	29.9

consisting of 80 10 × 10 cm quadrants between plot rows. Each quadrant containing one or more halogeton plants (at the point of rooting) was scored as present (versus absent). The grid was placed between plants 2 and 3 within the row and between rows 1 and 2, 2 and 3, and 3 and 4. Furthermore, the grid was designed so that frequency was scored in four 10-cm intervals increasingly distal from the transplants (e.g., 10 quadrants each at 10–20, 20–30, 30–40, and 40–50 cm intervals and repeated on both halves of the 1 m inter-row space). The mean of the six subsamples (60 quadrants) per interval was used for analysis. Transplant survival was determined each time halogeton frequency was measured, with the number of transplants of each species scored as dead or alive.

Halogeton frequency and transplant survival data were first analyzed across years using the MIXED procedure of SAS, (SAS Institute Inc., Version 9.3, Cary, NC) with entry, interval, and year as fixed effects, and replication considered random. Year was considered a repeated measure and the best covariance models for each trait were determined and used in the analyses (Littell et al., 2006). Due to a significant Interval × Year interaction, the halogeton frequency data were subjected to analysis of covariance (ANCOVA) within years using the MIXED procedure of SAS and following the strategy outlined in Littell et al. (2006). In brief, ANCOVA was initially performed to test if the slope of response between intervals was equal to zero. It was determined to be zero in 2013 and 2014 (e.g., no differences between interval distances), and, thus these data were then analyzed and mean comparison tests were completed within year using the average halogeton frequency across all interval distances. Conversely, the data from 2012 were further analyzed with ANCOVA to determine if a common slope for all entries was appropriate. The response was found to differ significantly among the entries, so the intercepts and slopes for each entry in 2012 were determined. Transplant survival was also analyzed within years. The correlations between transplant survival and halogeton frequency (at each interval distance and on average) were determined using the CORR procedure of SAS (SAS Institute Inc., Version 9.3, Cary, NC). Mean comparisons were made between treatments using the Tukey-Kramer honest significant difference (HSD) test at the $P = 0.05$ (experiment-wise) level of probability.

Experiment #2—Establishment into Halogeton Monoculture (Seeded Study)

Experimental Design

This experiment, conducted simultaneously with the containerized transplant study, evaluated the relative ability of these species to actually establish from seed, with or without a niche-creating soil disturbance. Seed of the forage kochia, Russian wildrye, tall wheatgrass, Indian ricegrass, and Gardner's saltbush entries were planted as a fall/winter dormant seeding as monocultures, and as binary mixtures with Gardner's saltbush. The grass entries and Gardner's saltbush were drilled on 17 November 2010 and the forage kochia entries were broadcast on 12 January 2011. Even though Ansley and Abernethy (1985) recommend scarifying Gardner's saltbush seed prior to seeding, our seed was not scarified inasmuch as a preliminary in-house laboratory test indicated that scarifying this particular seed lot did not improve germination. All plots were seeded at a rate of 300 pure live seeds (PLS) m^{-2}. Mixture plots received 150 PLS m^{-2} of Gardner's saltbush and 150 PLS m^{-2} of the other entry in the binary mix. The rate of 300 PLS m^{-2} resulted in an "Immigrant" forage kochia seeding rate of 3.8 kg ha^{-1} and "Bozoisky II" Russian wildrye being seeding rate of 12.0 kg ha^{-1}, which is within the recommended rate for planting forage kochia and grasses on harsh rangelands (USDA-NRCS, 2015).

Seeded plots were 1.5 m wide × 3.0 m long. Drilled entries were planted with a Hege Model 1000 6-row seeder with 25.4-cm spacing between rows at a depth of 0.6 cm. Broadcast entries were planted with a Hege Model 1000 with the disk openers raised above the soil. Two soil treatments were applied before seeding to determine the effect of tillage on seedling establishment within a halogeton infestation. One-half of the plots were disturbed with an offset disk at a depth of 12 cm to turn the soil over. This niche-creating disturbance was used to reduce initial halogeton stand and in an attempt to reduce the effect of "salt-pumping" (e.g., accumulated salts on the soil surface) on the establishment of the perennial species. The other half were no-till planted, which was possible as there were no live perennial plants (e.g., Gardner's saltbush) remaining in the plot area. The experiment was arranged as a split-plot design with tillage as the whole plot and entry as the subplot. It included six replications of the 13 monoculture/mixtures plus a control (e.g., not seeded) per soil treatment, for a total of 168 plots.

Establishment Data Collection and Statistical Analysis

Establishment data on the seeded study were collected on 2 August 2011, 10 July 2013, and 29 October 2014. Data were not collected in 2012 due to the severity of drought (Fig. 2) and resulting lack of seedling growth/establishment. Seedling establishment was measured as plant frequency (%) in 2011, or as plant density (plants m^{-2}) in 2013 and 2014. Frequency was determined using the grid system described by Vogel and Masters (2001) by laying a grid of 42 12.5 × 12.5 cm quadrants over the drilled rows and determining the percentage of quadrants containing at least one seedling (at the point of rooting). If a plant occurred in every quadrant, establishment frequency was considered to be 100%. Two subsamples (e.g., 84 quadrants) were measured in each plot. Establishment data in 2013 and 2014 were measured by taking total plant counts within the plot area. Halogeton establishment within the plots was also determined by taking total seedling counts in 2011 and 2013. Individual plants of halogeton could not be counted in 2014 due to above-average precipitation (see Fig. 1) and subsequent high levels of germination/growth of halogeton. Therefore, a visual score of halogeton canopy cover (score of 1–9; 9 ≥ 90% cover, 5 = 50% cover, and 1 ≤ 10% cover) was used to measure the halogeton stand.

Entry and halogeton frequency, density, or visual rating scores were analyzed within years using the MIXED procedure of SAS (SAS Institute Inc., Version 9.3, Cary, NC) with entry and tillage (disk or no-till) as fixed effects and replication considered random. Data were analyzed as a split-plot design with tillage being the whole plot and entry the subplot. The Entry × Tillage interaction was significant, therefore, Entry × Tillage treatment means were compared using the Tukey-Kramer honest significant difference (HSD) test at the $P = 0.05$ (experiment-wise) level of probability as calculated using the standard error of the Entry × Tillage treatment means.

Results

Experiment 1—Effect of Established Plants on Halogeton Density (Transplant Study)

Transplant Survival

The Entry × Year interaction was significant for transplant survival ($P = 0.0001$) and reflective of successive reductions each year in survival of the entries, with the exception of forage kochia and Russian wildrye, which persisted throughout the study (Table 2). One year after transplanting (2012), all entries except the Indian ricegrass/Gardner's binary mix had 100% survival (see Table 2). However, by the next year (2013), while forage kochia and Russian wildrye monocultures had transplant survival near 100%, persistence of Gardner's saltbush, Indian ricegrass, tall wheatgrass, and their respective binary mixtures with Gardner's had declined to values approaching complete plot mortality (see Table 2). In contrast, forage kochia/Gardner's binary mixtures had approximately 50% survival, reflective of near-complete mortality of all Gardner's saltbush transplants by the second year after transplanting (see Table 2). These 2013 trends were repeated in 2014, with just slightly overall lower survival (see Table 2). Comparison among individual entries revealed that in 2013 and 2014, Bozoisky II Russian wildrye was numerically the most persistent entry, but not

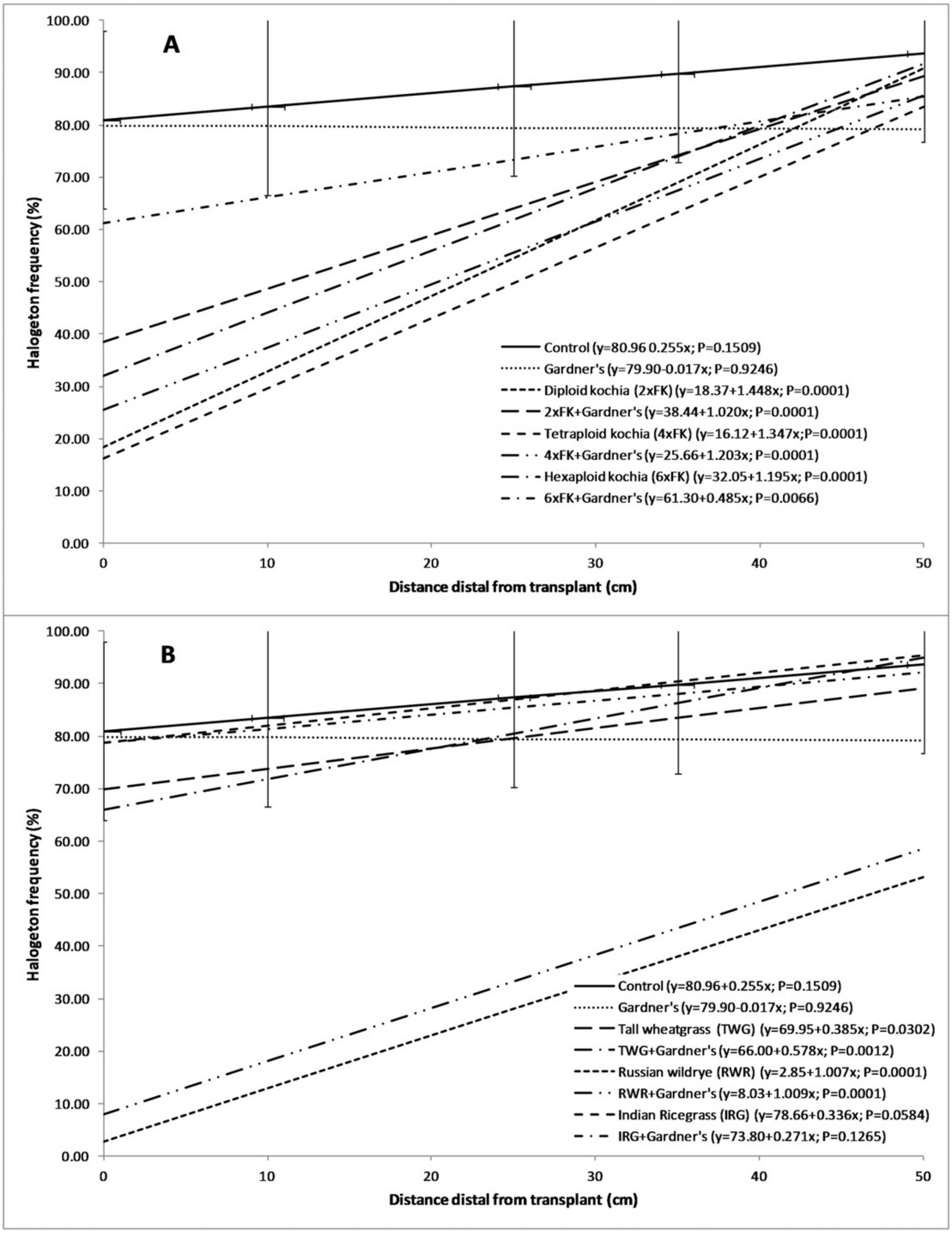

Fig. 2. Response in halogeton frequency across four intervals (10–20, 20–30, 30–40, and 40–50 cm) distal from plants in a containerized transplant study established in 2011 at a Wyoming lower Green River Basin study site 11 km northeast of Manila, Utah. Data are from 2012, the year following establishment. A, Response of halogeton frequency in relation to diploid, tetraploid, and hexaploid forage kochia entries in monoculture and binary mixtures with Gardner's saltbush in comparison to the control and the Gardner's saltbush monoculture. Similarly, B is a graph of the halogeton frequency response in relation to grass species included in study. Bars on the control regression line represent the Entry Tukey-Cramer HSD ($P = 0.05$) value of 15.3.

significantly more so than the forage kochia entries (see Table 2). Furthermore, there were no differences in survival among the ploidy levels of forage kochia (see Table 2).

Although there was no overall correlation between transplant survival and halogeton frequency, there were variable and highly significant correlations within years and intervals. In 2012, there were no correlations between survival and halogeton at any interval. Conversely, in 2013, there was a moderate negative correlation at the closest 10–20 cm interval ($r = -0.41$, $P = 0.0098$) but no correlations between survival and halogeton density at the other more distal intervals. In contrast, by 2014 survivorship had stabilized (see Table 2), resulting in moderately high negative correlations ($r = -0.57$ to -0.61, $P = 0.0001$ for all) across all intervals.

Halogeton Frequency in Transplant Plots

In 2013, average halogeton frequency dropped ($P = 0.0001$) to 16% as compared with 69% and 54% in 2012 and 2014, respectively. Although this reduction in halogeton contributed to a significant Entry × Year interaction ($P = 0.0001$), it was mainly in magnitude as ranking of entries was fairly consistent across years (Table 3). The low 2013

Table 2
Annual and 3-yr mean survival of containerized-grown transplants systematically transplanted in 2011 to measure effect on halogeton density at a Wyoming lower Green River Basin study site 11 km northeast of Manila, Utah

Entry[1,2]	2012[3]	2013	2014	3-Yr mean
	% Survival			
Russian wildrye (RWR)	100 a	98 a	92 a	97 a
Tetraploid forage kochia (4xFK)	100 a	94 a	90 a	95 a
Hexaploid forage kochia (6xFK)	100 a	90 a	88 a	92 a
Diploid forage kochia (2xFK)	100 a	79 ab	75 a	85 ab
RWR + Gardner's	100 a	54 bc	44 b	66 b
6xFK + Gardner's	100 a	50 bc	48 b	66 b
4xFK + Gardner's	100 a	50 bc	44 b	65 b
2xFK + Gardner's	100 a	46 c	42 b	63 b
Indian ricegrass (IRG)	100 a	10 d	6 c	39 c
Gardner's saltbush	100 a	8 d	6 c	38 c
TWG + Gardner's	100 a	13 d	0 c	38 c
Tall wheatgrass (TWG)	100 a	0 d	0 c	33 c
IRG + Gardner's	67 a	6 d	4 c	26 c
SEM[4]	9.2	6.2	4.9	4.7

[1] Gardner's saltbush had near-complete mortality after 2012; therefore, the survivors in the binary mixtures in 2013 and 2014 were primarily the other species component of the mixture.
[2] Entries were transplanted into systematically designed 16-plant plots with a density of 2 plants m^{-2} as monocultures or binary mixture with Gardner's saltbush.
[3] Values within each year followed by different letters are significantly different as determined by Tukey-Kramer HSD ($P = 0.05$).
[4] SEM; standard error of the means.

halogeton frequency was most likely due to the 2012 drought (33% of normal precipitation, see Fig. 1), which probably would have resulted in less seed produced in 2012 and subsequent lower germination and seedlings in 2013. It is even possible that many of the 2013 halogeton seedlings originated from the residual seedbank of dormant brown seeds produced in previous years (Cronin and Williams, 1966).

The Interval × Year interaction was also found to be significant ($P = 0.0001$) for halogeton frequency. Thus, as explained in the Methods section, analyses were performed within years using ANCOVA to investigate the relationship between interval distance and halogeton frequency. The ANCOVA analyses revealed that in 2012, there were significant ($P = 0.0001$) differences in halogeton frequency among interval distances (e.g., regression slope across interval distances not equal to zero); whereas in 2013 and 2014, interval distance had no effect ($P = 0.1527$ and 0.7844) on halogeton frequency (e.g., slopes equal to zero). Further analyses of the 2012 data determined an unequal slope model (Littell et al., 2006) was appropriate ($P = 0.0001$), and the regression responses (intercept and slope) of each entry to interval distance were estimated (see Fig. 2). All entries, except the control, Gardner's saltbush, Rimrock Indian ricegrass, and Gardner's + Indian ricegrass mixture, had significant regression responses ($P = 0.0584 - 0.0001$) to increased interval distance (see Fig. 2), indicating that in 2012 the effect on halogeton establishment was reduced as the interval became more distal from transplant. This was verified by only two entries having significantly less halogeton than the control at the most distal interval of 40–50 cm, as compared with five, seven, and eight significant entries at the 30–40, 20–30, and 10–20 cm intervals, respectively (see Fig. 2).

Table 3
Halogeton frequency between rows of containerized-grown transplants in a study established in 2011 at a Wyoming lower Green River Basin study site 11 km northeast of Manila, Utah. Values are the yearly (2012, 2013, and 2014) halogeton frequency averaged over four intervals (10–20, 20–30, 30–40, and 40–50 cm) distal from transplants

Entry[1,2]	2012[3]	2013	2014	3-Yr mean
	%			
Control	89 a	22 a	84 a	65 a
Indian ricegrass (IRG)	89 a	23 a	83 a	65 a
TWG + Gardner's	83 ab	23 a	86 a	64 a
Tall wheatgrass (TWG)	82 abc	17 ab	67 ab	55 ab
Gardner's saltbush	79 abc	16 ab	67 ab	54 ab
IRG + Gardner's	82 abc	16 ab	53 bcd	50 bc
6xFK + Gardner's	76 abcd	13 ab	61 abc	50 bc
2xFK + Gardner's	69 bcde	11 b	40 bcde	40 cd
Hexaploid forage kochia (6xFK)	68 cde	11 b	40 bcde	39 cd
4xFK + Gardner's	62 de	8 b	38 cde	36 d
RWR + Gardner's	38 f	23 a	42 bcde	34 d
Diploid forage kochia (2xFK)	62 de	7 b	29 de	33 d
Russian wildrye (RWR)	33 f	16 ab	45 bcd	31 d
Tetraploid forage kochia (4xFK)	57 e	11 b	21 e	30 d
SEM[4]	3.3	2.5	6.2	3.1

[1] Gardner's saltbush had near-complete mortality after 2012; therefore the survivors in the binary mixtures in 2013 and 2014 were primarily the other species component of the mixture.
[2] Entries were transplanted into systematically designed 16-plant plots with a density of 2 plants m^{-2} as monocultures or binary mixture with Gardner's saltbush.
[3] Values within each year followed by different letters are significantly different as determined by Tukey-Kramer HSD ($P = 0.05$).
[4] SEM indicates standard error of the means.

Averaged across intervals, a significant species effect on halogeton establishment was evident with some entries having less ($P = 0.05$) halogeton density than the control (see Table 3). Russian wildrye transplants had the greatest interference on halogeton establishment in 2012, with the least halogeton frequency. However, by 2014, tetraploid forage kochia had surpassed Russian wildrye with the least ($P = 0.05$) halogeton frequency, whereas diploid and hexaploid forage kochia were equal to Russian wildrye (see Table 3). Indian ricegrass never had an effect on halogeton frequency as compared with the control, in contrast to tall wheatgrass and Gardner's saltbush plots, which had a trend toward less halogeton than control plots in both 2013 and 2014 (see Table 3).

Experiment #2—Establishment into Halogeton Monoculture (Seeded Study)

Analyses revealed that Entry, Soil Treatment, and Entry × Soil Treatment were all significant factors in the establishment of seeded entries. The significant Entry × Soil Treatment interaction ($P = 0.0017$, 0.0001, and 0.0001 for 2011, 2013, and 2014, respectively) primarily was the result of rank changes that occurred as grass entries established better within the disked treatment. Forage kochia entries had greater establishment under the no-till treatment (Table 4). For instance, Bozoisky II Russian wildrye final plant density was 4.5 and 1.7 plant m^{-2} compared with the average forage kochia monoculture establishment of 0.8 and 2.3 plants m^{-2} in the disked and no-till treatments, respectively. Furthermore, none of the forage kochia entries established in the disked treatment (e.g., greater than control), as compared with the no-till treatment where the diploid forage kochia established (e.g., establishment greater than the control), and a trend of greater establishment than the control was observed for the tetraploid and hexaploid forage kochia entries (see Table 4).

Initial establishment in 2011 was comparatively poor, with only the Alkar tall wheatgrass and Bozoisky II Russian wildrye/disked treatments having > 25% stand frequency (see Table 4). However, by 2013, there was 100% mortality in tall wheatgrass plots, whereas the Russian wildrye/disked combination remained as one of the most successful treatments throughout the study. Bozoisky II Russian wildrye (disked) (4.5 plants m^{-2}) and Immigrant diploid forage kochia (no-till) (3.6 plants m^{-2}) had greater ($P = 0.05$) establishment than all other entries (see Table 4). The Indian ricegrass/disked treatment showed some initial establishment in 2011 but by 2014 did not differ from the control (see Table 4). Gardner's saltbush did not establish via seed (see Table 4).

Entry × Soil Treatment and, for the most part, Entry effects (except in 2014, $P = 0.0001$) were not significant for halogeton establishment. In contrast, Soil Treatment had an initial influence on halogeton establishment, with 2011 halogeton density in the disked treatment (13.6 plants m^{-2}) 50% less ($P = 0.0001$) than the no-till (28.7 plants m^{-2}), but this effect dissipated by 2014 such that there was no difference ($P = 0.2170$)

Table 4
Establishment of seeded plots in a halogeton-degraded Gardner's saltbush study area in the Wyoming lower Green River Basin 11 km northeast of Manila, Utah. Study was planted in 2010/2011. There were two soil treatments (disk and no-till) and values are the Entry × Soil Treatment means for the 3 yr following planting

Entry[2,3]	Soil Treatment	Seeded Plot Establishment[1] 2011	2013	2014
		Frequency (%)	— Density (plants m^{-2}) —	
Russian wildrye (RWR)	Disk	27.6 a	3.6 a	4.5 a
Diploid forage kochia (2xFK)	No-till	8.5 bcd	3.3 ab	3.6 ab
2xFK + Gardner's	No-till	6.0 cd	2.1 abc	2.2 bc
6xFK + Gardner's	No-till	2.6 d	1.7 bcd	2.1 bcd
Hexaploid forage kochia (6xFK)	No-till	2.2 d	1.7 bcd	1.8 bcd
RWR + Gardner's	Disk	10.7 bc	1.6 cd	1.8 bcd
Russian wildrye (RWR)	No-till	15.9 abc	1.3 cd	1.7 bcd
Tetraploid forage kochia (4xFK)	No-till	2.4 d	1.4 cd	1.5 bcd
Diploid forage kochia (2xFK)	Disk	1.8 d	1.1 cd	1.1 cd
RWR + Gardner's	No-till	8.1 bcd	0.4 cd	1.0 cd
4xFK + Gardner's	No-till	1.4 d	0.9 cd	0.8 cd
Hexaploid forage kochia (6xFK)	Disk	1.2 d	0.9 cd	0.8 cd
2xFK + Gardner's	Disk	1.6 d	0.5 cd	0.5 cd
Tetraploid forage kochia (4xFK)	Disk	1.0 d	0.3 d	0.4 cd
4xFK + Gardner's	Disk	0.4 d	0.2 d	0.3 cd
6xFK + Gardner's	Disk	0.2 d	0.3 d	0.2 cd
Indian ricegrass (IRG)	Disk	11.3 bcd	0.2 d	0.2 cd
IRG + Gardner's	No-till	4.2 cd	0.0 d	0.0 cd
Gardner's saltbush	No-till	0.0 d	0.0 d	0.0 cd
IRG + Gardner's	Disk	9.3 bcd	0.3 d	0.0 d
Tall wheatgrass (TWG)	Disk	28.0 a	0.0 d	0.0 d
TWG + Gardner's	Disk	19.2 ab	0.0 d	0.0 d
Tall wheatgrass (TWG)	No-till	16.3 abc	0.0 d	0.0 d
TWG + Gardner's	No-till	11.9 bcd	0.0 d	0.0 d
Indian ricegrass (IRG)	No-till	6.2 cd	0.0 d	0.0 d
Gardner's saltbush	Disk	0.0 d	0.0 d	0.0 d
Control	Disk	0.0 d	0.0 d	0.0 d
Control	No-till	0.0 d	0.0 d	0.0 d
SEM[4]	–	2.3	0.3	0.4

[1] Values within each year followed by different letter are significantly different as determined by Tukey-Kramer HSD ($P = 0.05$).
[2] Entries were seeded into 4.5 m^{-2} plots as monocultures or in a binary mixture with Gardner's saltbush.
[3] Gardner's saltbush did not establish from seed; therefore seedlings in the binary mixtures were entirely the other species component of the mixture.
[4] SEM indicates standard error of the entry by soil treatment means.

between the average halogeton canopy cover rating of the disked (rating = 7.4) and no-till (rating = 7.1) treatments.

Discussion

Experiment 1—Effect of Established Plants on Halogeton Density (Transplant Study)

The objective of this experiment was to determine, if a niche-creating event allowed perennial species to be reestablished, what would happen afterwards in terms of perennial species persistence and subsequent halogeton density. Inasmuch as nearly 100% of transplants remained alive 1 yr after transplanting (see Table 2), there is evidence that the assumption was met and perennial species were established (e.g., they did not die from transplant shock). However, by the third year, transplant survival was highly correlated ($r = -0.61$, $P = 0.0001$) with average (across intervals) halogeton frequency, and, thus, it is critical to first discuss entry persistence in subsequent years in this harsh environment before the effect of individual entries on halogeton establishment. Initial successful transplant survival was in part due to the above-average precipitation during establishment (May through July, 2011; see Fig. 1), but the study site experienced a severe drought in 2012 (33% of normal) (see Fig. 1), which appeared to have a varying impact on plant mortality. In this study, we observed a high survivorship of Russian wildrye and forage kochia and nearly complete plot mortality of Indian ricegrass, tall wheatgrass, and Gardner's saltbush (see Table 2). Although Gardner's saltbush is considered both salt and drought tolerant (Nord et al., 1971), our results were consistent with the recent lack of persistence of Gardner's saltbush at this site. Duda et al. (2003) and Harper et al. (1996) provide evidence that halogeton alters the microbiotic conditions in the rhizosphere and offered this as an alternative explanation of how halogeton can replace and exclude otherwise adapted perennial shrubs such as winterfat. Although not measured here, a halogeton-altered rhizosphere may also be a contributing factor for the rapid mortality of established Gardner's saltbush plants in the study (0%−92% mortality in 1 yr) and as a possible causal factor in the decline of Gardner's saltbush in the general area over recent decades. Given the implications concerning the future restoration of Gardner's saltbush to this site, further research is necessary to elucidate the possible differential effect of a halogeton-altered rhizosphere on these species.

There were no detectable differences in survival among forage kochia entries (see Table 2). In a previous study, hexaploid and tetraploid forage kochia (both within subspecies *grisea*) had higher salt tolerance than diploid forage kochia, which is subspecies *virescens* (unpublished data). Thus, we had hypothesized that increased salt tolerance in the recently released tetraploid *grisea* entry, Snowstorm, may result in higher survival than Immigrant. However, this was not observed. The difference in survival between Russian wildrye and tall wheatgrass (see Table 2) suggests that drought had a larger effect than salinity on persistence in this environment. Tall wheatgrass is considered one of the most salt-tolerant perennial cool-season grasses and is often included as a check in salt experiments (Rauser and Crowle, 1962). In this study, Alkar tall wheatgrass had no surviving transplants by the second year, as compared with nearly 100% survival of Bozoisky II Russian wildrye. During the establishment year of 2011, precipitation was 124% of the long-term normal; however, annual precipitation was only 76.7 mm, or just 33% of normal in 2012 (see Fig. 1). Undoubtedly, this drought had an effect on the survival of both Indian ricegrass and tall wheatgrass, both of which are considered moderately drought tolerant (Jensen et al., 2001), as compared with the highly drought-tolerant Russian wildrye (Asay et al., 2003) and forage kochia species (Waldron et al. 2010). Similar to our study, Cook (1965) reported that over a 6-yr period, Russian wildrye stands increased while tall wheatgrass essentially died out in salt-desert shrub ecosystems in northwestern Utah. Cook (1965) attributed Russian wildrye's better persistence to being more adapted to low precipitation areas than tall wheatgrass, in addition to having moderate salt tolerance allowing it to persist on saline-alkali soils.

The ANCOVA analysis allowed us to evaluate the effect of plant proximity to the halogeton, resulting from a low-density planting of perennial species, on subsequent halogeton establishment. By the second year (2013), the effect of the entries on reducing halogeton establishment had extended to the maximum distance of 50 cm distal from transplants. Thus, our results suggest that after the first year, differences among entries were more biologically important in reducing halogeton establishment than the proximity of plants to the halogeton. Indian ricegrass transplants did not persist and had no effect on halogeton density. Conversely, tall wheatgrass and Gardner's saltbush transplants also did not persist past the first year, but there was a trend toward less halogeton than the control in subsequent years (see Table 3). This possible residual interference on halogeton establishment, by two species that did not persist, may suggest that future management plans could use seeded annuals to reduce halogeton frequency for a short time.

Diploid and tetraploid forage kochia and the Russian wildrye transplants had the greatest effect on halogeton establishment, with an average 52% reduction in halogeton frequency, in comparison with the control (see Table 3). Interestingly, among the forage kochia entries, the hexaploid, highly salt-tolerant line (KZ6XSEL) had a trend toward lesser effect than the diploid (Immigrant—least salt tolerant) or tetraploid Snowstorm (intermediate salt tolerance), on halogeton recruitment (see Table 3). These results further suggest that once a threshold level of salt tolerance is reached, other adaptive traits including drought tolerance will be important for plants used to rehabilitate halogeton-degraded rangelands. In comparison, Stevens et al. (1990) reported a similar trend in a 7-yr study in which halogeton plant density (plants m^{-2}) was reduced by 69% of the control by establishment of forage kochia. Their research, in a lower elevation (1569 m as compared to 1860 m at our site) Utah shadscale salt desert shrub ecosystem, measured the halogeton recruitment within seeded plots with higher forage kochia density (54 plants m^{-2}) than our spaced-plant study (2 plants m^{-2}). In another study, Russian wildrye significantly reduced halogeton density over 6 yr as compared with an increase of halogeton within tall wheatgrass plots (Cook, 1965), further verifying the differences between these grasses to rehabilitate halogeton-degraded rangelands.

Binary mixtures with Gardner's saltbush were established to determine if Russian wildrye and forage kochia could help in restoration of saltbush by competing with halogeton and thus promote Gardner's saltbush growth and reproduction. As reported earlier, the Gardner's saltbush transplants in these binary mixtures plots had near-complete mortality after 1 yr, resulting in 35% versus 52% reduction in halogeton frequency as compared with the forage kochia monocultures. Inasmuch as monoculture plots of Gardner's saltbush also died, we cannot make conclusions from this study regarding the compatibility between these species and their ability to coexist in this test environment.

Overall, these results indicate that once established, forage kochia and Russian wildrye can persist in this degraded Gardner's saltbush environment and interfere with halogeton establishment, even at distances up to 50 cm distal from the established perennial plants. Snowstorm tetraploid forage kochia had slightly better survival than Immigrant diploid forage kochia, but both equally reduced halogeton density. We did not want to affect halogeton seed production and subsequent establishment, so we did not conduct destructive sampling of the halogeton biomass. However, there were observable differences in halogeton biomass in the forage kochia and Russian wildrye plots as compared with the control, and future studies should examine the effect of these species on halogeton biomass and seed production. Overall, our results are in agreement with previous studies (Miller, 1956; Cook, 1965; Stevens et al., 1990) and further support that forage kochia and Russian wildrye may be management options for rehabilitation of halogeton-invaded salt-desert shrub rangelands.

Experiment 2—Establishment into Halogeton Monoculture (Seeded Study)

Establishment into arid/saline sites typical of halogeton is often a difficult and slow process (Newhall et al. 2004), and this study was no exception with only 6, 3, and 3 of the possible 26 entry × soil treatment combinations having greater seeded establishment than the control (e.g., zero establishment) in 2011, 2012, and 2014, respectively (see Table 4). By 2014, Bozoisky II Russian wildrye in the disked soil (4.5 plants m^{-2}) and Immigrant diploid forage kochia in the no-till treatment (3.6 plants m^{-2}) had greater establishment than all other entry/soil treatments combinations (see Table 4). Immigrant is subspecies *virescens* and is adapted to the fine textured/poor permeability soils common of highly alkali areas (Harrison et al., 2000). Both the tetraploid and hexaploid forage kochia entries were from the *grisea* subspecies and overall had 46% to 55% less establishment than the diploid Immigrant; they were not significantly greater than the control (see Table 4). The *grisea* subspecies of forage kochia have been reported to be better adapted to gravelly and sandy environments (Waldron et al., 2005), perhaps explaining why the tetraploid (Snowstorm) and hexaploid (KZ6XSEL) entries had lower establishment, even though they have been shown to be more salt tolerant than Immigrant (diploid) (unpublished data). Previous authors have also reported that Immigrant forage kochia is one of few species that can establish on salt-desert shrublands in the presence of noxious annual weeds, including cheatgrass and halogeton (Stevens and McArthur 1990; Monaco et al., 2003; Newhall et al., 2004; Waldron et al., 2010), but these authors did not compare Immigrant with subspecies *grisea* or with tetraploid and hexaploid entries of forage kochia. In contrast, McArthur et al. (1996) reported that while Immigrant had greater establishment than several tetraploid- and hexaploid-*grisea* forage kochia populations, at least one tetraploid-*grisea* forage kochia population had greater establishment than Immigrant at two saltbush/halogeton salt desert shrub sites in Utah. These contrasting results might suggest location differences but more likely indicate variation in adaptive traits within the subspecies and ploidy levels of forage kochia. Our study tested the only current cultivars of forage kochia (Snowstorm and Immigrant) available to land managers, and thus the information is relevant for rehabilitation management decisions.

It is probable that the initial low establishment (mostly < 4 plants m^{-2}) and the immaturity of the few perennial seedlings resulted in the lack of an Entry effect on halogeton recruitment in 2011 and 2013. However, as seedlings progressed to more mature plants, they began to reduce halogeton frequency, as evidenced by successive correlations between seeded entry establishment and halogeton recruitment of 0.07 ($P = 0.3812$), -0.35 ($P = 0.0001$), and -0.58 ($P = 0.0001$) in 2011, 2013, and 2014, respectively. Given this trend and combined with the results from our spaced-plant study, it could be expected that as Russian wildrye and forage kochia plants/stands mature, they will likely have a greater impact on halogeton frequencies and densities. Previous studies had indicated that Russian wildrye and forage kochia may establish and reduce halogeton stands (Miller, 1956; Cook, 1965; Stevens and McArthur 1990), but our study also uniquely documented the plant density needed by these species to have an effect on halogeton establishment. It is of interest to note that the plant density of our transplant study (2 plants m^{-2}) was similar to the low density achieved by these species in the seeded study (2.3 and 4.5 plants m^{-2}, for forage kochia/no-till and Russian wildrye/disk treatments, respectively), further validating their potential to be used in rehabilitation of halogeton-degraded rangelands even when establishment is difficult. In contrast, the loss of a Soil Treatment effect over time (change from the disked treatment having 50% less halogeton frequency in 2011, compared with no-till, to no significant differences between the two soil treatments in 2014) suggests that tillage can reduce initial halogeton stands, but this effect may be short-lived without the rapid and successful establishment of perennials.

Our research covered a span of 4 yr but was relatively short term given the harshness of the environment, as evidenced by the continuing year-to-year change in species establishment in the seeded study. This suggests the need to follow up at this site and to conduct longer-term studies to validate our findings. Overall, our results indicate that rehabilitation of halogeton-infested Gardner's saltbush sites will require using the hardiest, easiest to establish plant materials available. The complete failure of Indian ricegrass and Gardner's saltbush to establish via seed further suggests that an intermediate step of reestablishing perennials like forage kochia and Russian wildrye may be necessary before Gardner's saltbush can be restored to its native rangeland.

Management Implications

A previous study (Stevens and McArthur 1990) indicated that forage kochia can reduce halogeton density in a Utah shadscale salt desert environment; however, this is the first published report on forage kochia's effect on halogeton outside of Utah and in a Gardner's saltbush ecosystem. We have shown that both released cultivars, Immigrant and Snowstorm, established (seeded study) and persisted and reduced halogeton establishment (transplant study) in this degraded Gardner's saltbush site. Bozoisky II Russian wildrye, known for being highly drought tolerant and moderately salt tolerant, also established, persisted, and reduced halogeton frequency. Two years following transplanting, the effect of forage kochia and Russian wildrye on reducing halogeton frequency had extended to 50 cm distal from the transplants. This indicates that even the low density of forage kochia and Russian wildrye plants achieved in our seeded study (2.3 − 4.5 plants m^{-2}), which is typical of many rangeland plantings, can substantially reduce halogeton once the seeded plants reach maturity. Forage kochia demonstrated a slight advantage over Russian wildrye in the no-till planting, whereas Russian wildrye establishment was more successful when disking occurred before planting. These results support the recommendation that forage kochia and Russian wildrye can be used to rehabilitate halogeton-degraded Gardner's saltbush sites in the lower Green River Basin of Wyoming, thereby restoring palatable forage production for livestock and wildlife. In contrast, Indian ricegrass, tall wheatgrass, and Gardner's saltbush do not appear to be options for initial rehabilitation efforts.

EC indicates electrical conductivity; CEC, cation exchange capacity; sodium absorption ration (SAR).

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