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Effectiveness of Control Treatments on Young Saltcedar (*Tamarix* spp.) Plants

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Preventing the establishment of saltcedar in new areas requires early detection and rapid response. However, it is unclear when saltcedar develops perennating tissue and which treatments are most efficacious for young plants. The effectiveness of mowing, herbicide, and fire treatments, alone and in combination, was evaluated on saltcedar plants grown from seed to 4, 8, and 12 wk age in 2011 and 6 and 12 wk age in 2012. Plants were clipped to 2 cm height or remained intact. Plants were then exposed to no treatment (control), herbicide application (0.12 mg ae imazapyr), or treated with fire for 30 or 60 s. Six weeks after treatment, plant survival and tallest living shoot height were recorded and roots were dried and weighed for biomass comparison. Saltcedar survival increased with greater plant age. No 4-wk-old plants survived herbicide or fire treatments, whereas 6-wk-old plants were eliminated by fire. Clipping alone did not control plants of any age but clipping before fire was the most effective control for older plants. Herbicide alone did not kill 8- and 12-wk-old plants during the study period, but reduced plant vigor suggests that these applications may be effective in the long-term. Fire alone for 60 s was the most effective single treatment for 12-wk-old plants. Root biomass was reduced for all treatments relative to untreated plants with the lowest biomass typically associated with fire treatments. Resprouts were shortest for combined clipping and herbicide and clipping and fire treatments. Results indicate that saltcedar grown from seed can develop viable belowground reproductive tissues between 6 and 8 wk after germination. Multiple intensive control practices may be required to kill saltcedar plants ≥8 wk of age, whereas younger plants can be controlled by single, less-intensive treatments such as fire.

Nomenclature: Arsenal; imazapyr; saltcedar, *Tamarix ramosissima* Ledeb. TARA; *T. chinensis* Lour. TACH; *Tamarix* hybrids.

Key words: Age, clipping, fire, herbicide, management, vegetative reproduction.

Saltcedar (*Tamarix ramosissima* Ledeb., *Tamarix chinensis* Lour. and *Tamarix* hybrids) continues to expand its range at an unknown rate, occupying only a fraction of potentially suitable habitat in the northern U.S. (Jarnevich et al. 2011; Kerns et al. 2009) and Canada. Managed grasslands of the Northern Great Plains may be vulnerable to future saltcedar invasion (Morisette et al. 2006; Ohrtman et al. 2011) and it is important for land managers in this region to know the most effective methods for controlling young infestations.

Saltcedar's small seeds and mechanisms for long-distance dispersal by wind and water permit rapid colonization of new areas. Plants grow rapidly (Friederici 1995; Merkel and Hopkins 1957) and have the ability to develop perennating tissues in the first growing season. Northern saltcedar ecotypes have been shown to grow more roots at low temperatures than southern ecotypes, which may aid in overwinter survival in cold climates (Sexton et al. 2002). Once mature, saltcedar control can be labor-intensive and expensive (McDaniel and Taylor 2003). In addition, plants may have altered the ecosystem and abiotic processes (e.g. soil salt content) such that pre-invasion communities cannot be restored (Busch and Smith 1993; Estrella and Kneitel 2011; Kerns et al. 2009; Tomanek and Ziegler 1962). Therefore, the best defense against saltcedar is to identify and remove plants before they become well-established.

Greater control often is achieved at less expense when perennial weeds are treated as seedlings, immature plants, or in young stands (Estrella and Kneitel 2011; Smith et al. 2002; Westbrooks 2004) yet only a few control techniques are reported for young (a few weeks to one growing-season old) saltcedar plants. Flooding has been reported to control saltcedar plants between 4 and 10 wk old if completely submerged for >25 d (Gladwin and Roelle 1998; Horton et al. 1960; Sprenger et al. 2001). However, larger (>30 cm [12 in.] tall) or older (e.g. 12 wk old) plants were more resistant to inundation (Horton et al. 1960; Sprenger et al.

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Interpretive Summary

Early detection and rapid response is the primary campaign for managing weeds in the United States, yet little is known about the best method for controlling new saltcedar infestations. Older saltcedar individuals are often difficult to control because of the presence of belowground reproductive tissues but when these structures become viable is poorly understood. This research found that young saltcedar response to control treatments is dependent on plant age and treatment. All plants treated with clipping between 4 and 12 wk of age were able to recover and produce robust plants. Destructive treatments such as fire eliminated 4- and 6-wk-old plants but 8- and 12-wk plants often regrew vigorous shoots from belowground buds following complete top-kill by fire. These results suggest that belowground reproductive tissues can become viable between 6 and 8 wk of age. Fire and herbicide alone resulted in younger plant mortality and reduced growth for older saltcedar but the use of these practices will depend on land management options. Clipping prior to herbicide or fire treatment was the most effective control and could be used to treat small populations or individual plants. Fire may be preferred over herbicide application in areas where vegetation is adapted to this disturbance and burn programs are already established. On the other hand, herbicide may be desired where saltcedar density is high, there is minimal herbicide-susceptible native vegetation, and/or the landscape is unsuitable for burning or other mechanical removal methods. Spot fire treatment to individual plants, rather than a large-scale field burn, may be another control option although this technique has not been field-tested.

2001; Tomanek and Ziegler 1962). Diminished water availability and river regulation limit the use of flooding for saltcedar management in many areas. Shallow discing (13 cm deep [5.1 in.]) was observed to remove about 70% of young saltcedar plants that were in their first year of growth (Smith et al. 2002). This method may not be feasible for small populations or desired for use in northern rangelands where vegetation cover is important for grazing and minimizing non-native plant invasions.

Recent research suggests that fire soon after seed deposition may reduce establishment and growth of newly emerging saltcedar seedlings by 75% (Ohrtman et al. 2011). In addition, the majority of saltcedar seeds and young seedlings (≤5 d old) were killed by exposure to oven-controlled temperatures and durations associated with spring grassland fire (Ohrtman et al. 2012). However, land managers are more likely to encounter plants >5 d old in the field and thus it is important to determine the response of older plants to a range of control techniques.

Control of saltcedar plants that are asexually reproductive is difficult, as new shoots can resprout from belowground reproductive buds following aboveground tissue injury (Busch and Smith 1993; Ellis 2001; Warren and Turner 1975) and begin re-infestation. For example, although all aboveground tissue was destroyed following two separate fires along the Rio Grande in New Mexico, over 50% of mature saltcedar plants resprouted (primarily from the root crown), irrespective of fire severity (Ellis 2001). Seventy days of inundation with nearly 1 m (39.3 in.)of water killed the shoots of mature saltcedar plants in Arizona but resprouts from the root crown occurred on plants that had tissues above the water level (Warren and Turner 1975). Saltcedar control would be more effective if treatments were applied before belowground perennating tissues are formed but to our knowledge, the time when vegetative reproductive tissues are developed and the effectiveness of various treatments occurring during this time have not been experimentally determined.

This study evaluated control of saltcedar plants ranging in age from 4 to 12 wk in replicated greenhouse studies using clipping, fire, and herbicide treatments alone and in combination (Clip + Fire; Clip + Herbicide). These treatments are likely to be accepted by producers to manage new weed infestations in northern rangelands. Results provide insight into when young saltcedar plants become vegetatively reproductive and can aid in developing management strategies for recently established saltcedar populations to minimize spread to new habitats and regions.

Materials and Methods

Saltcedar seeds were obtained from a population on Forest Service land near Wasta, SD on July 6, 2011 and July 3, 2012 and stored at 3 C. Seed germinability was evaluated from three sets of 100 seeds just prior to the first planting date each year. Seeds were placed on wetted filter paper inside closed germination dishes, incubated at 25 C for 5 d, and counted. Seed germination was >90% for each seed lot.

Seeding dates were staggered so that cohorts of plants on Oct 7, 2011 were 4, 8, and 12 wk old and on Oct 10, 2012 were 6 and 12 wk old. Saltcedar plants were grown by methods described in Ohrtman and Clay (2013) with plants thinned to one container^{-1} about 3 wk after germination. About 150 plants were grown for each cohort with the 72 most robust plants (determined by plant height) selected for treatment to minimize effects of pre-treatment height on treatment response, as plant size rather than age has been suggested to be related to plant stress response (Sprenger et al. 2001). The heights of five tallest plants age class^{-1} for each treatment (n=35) were measured before treatment to quantify the relationship between pre-treatment plant height and treatment response.

Eight treatments (including untreated controls) were applied to the plants as a laboratory exercise for a weed science course at SDSU on October 7, 2011 and October 10, 2012 (Ohrtman and Clay 2013). Treatments were (1) no treatment (Control); (2) herbicide application; (3) fire for 30 s; (4) fire for 60 s; (5) plants clipped to 2 cm height (Clip) (to simulate mowing); and the combination treatments of (6) Clip + Herbicide; (7) Clip + Fire for 30 s; (8) Clip + Fire for 60 s. In 2011, treatments were replicated twice in time with four or five plants of each age per replication whereas in 2012, treatments were replicated three times in time on three plants of each age (n=9 age^{-1} treatment^{-1} year^{-1}). Four additional treatments (four or five plants treatment^{-1} with replication in time) were performed in 2011 using combinations of clipping and no clipping with fire for 120 s and a double herbicide (2X) rate. These treatments are unrealistic for field application and were not repeated in 2012.

The herbicide spray solution contained 3% isopropyl amine salt of Imazapyr (22.6% acid equivalent or 240 g ae L^{-1} [32 oz ae gal^{-1}]) (Arsenal®, BASF Corp., Research Triangle Park, NC) with 0.25% Chemsurf 90 non-ionic surfactant (Chemorse, LTD, Urbandale, IA) which is similar to field treatments that have achieved 95% control of mature saltcedar in South Dakota (R. Moehring, personal communication). Herbicide was applied with a boom speed of 0.8 kph [0.5 mph] and 206 kPa pressure that delivered 238 L ha^{-1} [25 gal acre^{-1}] using a flat fan nozzle. Based on spray deposition, the calculated herbicide dose was 0.12 mg ae plant^{-1}.

Clipped and unclipped plants were treated with fire using a blow torch. Three fire durations were tested in 2011 (30, 60, and 120 s). Fire temperatures were monitored at the soil surface of each plant using a Type K thermocouple attached to a data logger (TC Direct, Hillside, IL). Experimental fire temperatures were targeted to be near 200 C because a mixture of dormant and actively growing grassland fuels were observed to exceed this temperature for more than 60 s during spring prescribed burns in the Northern Great Plains (authors' unpublished data). However, actual soil surface burn temperatures ranged between 150 and 300 C. The temperature at the 1-cm soil depth was monitored in a similar manner for selected longer duration treatments and never exceeded 40 C.

Six wk after treatment, the number of surviving saltcedar plants (those with green tissue or regrowth) and the height of the tallest living stem were recorded by treatment. Plants were excavated and soil was carefully removed from roots. Roots and shoots were separated, dried at 60 C for 72 hr and weighed for biomass comparisons. Root length measurements from the base of the plant to the end of the longest root were recorded in 2012 prior to drying. Very large plants that were minimally stressed by a treatment and untreated plants had roots that overgrew the container. In these cases, the container was removed from the tub and entwined roots were separated carefully and assigned to the contributing plant.

A two-way ANOVA was used to analyze treatment effects and young saltcedar age on root biomass and tallest living shoot height 6 wk after treatment. Fixed effects were assigned to treatment and random effects were assigned to replication and year using JMP-In software (version 10.2, SAS Institute, Cary, NC). The response among plants of similar age within a year and treatment was similar among runs so results were pooled by treatment. Shoot and total biomass were not analyzed because some treatments required shoot removal and other treatments had remaining dead shoots that could have weighed more than new growth. ANOVA was also used to examine the relationship between pre-treatment height for 12-wk-old plants and the measured response variables. Log10 transformation was used to normalize data distribution for root biomass in both models but non-transformed data are reported.

Results and Discussion

Conditions Associated with Young Saltcedar Control Treatments. Saltcedar stems for all plant ages were herbaceous with reddish coloring at the base of stems for older plants. Plant height was influenced by age. Saltcedar pre-treatment shoot height averaged 3.6 ± 0.2 cm (4 wk), 8.3 ± 0.3 cm (6 wk), 16.9 ± 0.8 cm (8 wk) and 42.2 ± 1.2 cm (12 wk). In addition, the staggered planting dates affected overall plant growth. For example, plants from seed sown in late August and September for the 4 and 6 wk cohorts were about 50% smaller and had fewer branches than plants at the same age when seeds were sown in July and early August. The growth differences during the pre-treatment interval most likely were photoperiod induced. Indeed, saltcedar has been reported to have a photoperiod response with maximal shoot and root growth under 14-hr light periods and similar among plants subjected to 8 and 11 hr of light (Wilkinson 1966). Daylight (sunrise to sunset) hrs in Brookings, SD were about 15, 13, and 12 for the July, August, and September planting dates, respectively.

Saltcedar Aboveground Response and Survival. Older plants showed the greatest resilience, with more plants surviving (e.g. maintaining or producing new aboveground green tissue) following severe treatments. Sixty-five percent of 12-wk-old plants (excluding untreated control plants) were observed to have living tissue 6 wk after treatments whereas only 46, 44, and 15% of 8, 6, and 4-wk-old plants were alive, respectively. Four-wk-old plants survived clipping only. Some plants at least 6 wk old survived clipping and herbicide treatments, and some plants at least 8 wk old survived fire treatments. More 12-wk than 8-wk-old plants survived fire for either duration and only 12-wk-old plants survived the Clip + Fire for 30 s, with no plants of any age group surviving Clip + Fire for 60 s. The 2011 treatments of 2X Herbicide and fire for 120 s, with and without clipping, killed all 4-wk-old plants and most 8- and 12-wk plants (data not shown) however these

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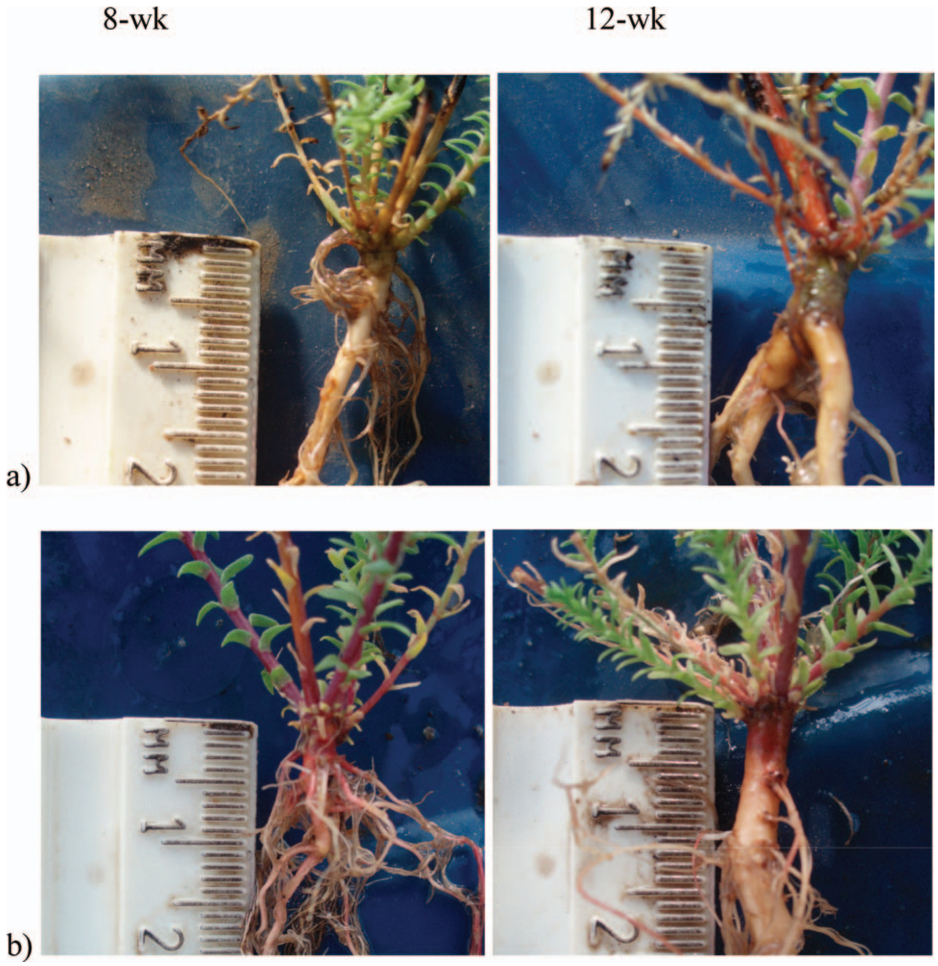

Figure 1. Resprouts on 8- and 12-wk-old saltcedar plants treated with (a) fire for 60 s and (b) clipping. Plants are 14 and 18 wk old at the time of photo. (Color for this figure is available in the online version of this paper.)

treatments were unrealistic for field application and not tested in 2012.

The greater survival of older saltcedar plants following treatments may be related, in part, to the development of vegetative buds. Removal or death of the apical meristems that inhibit lateral bud development often facilitates growth of lateral shoots and, if present, sprouting of vegetative propagules. For example, saltcedar exposed to fire and flooding have been observed to produce new growth within the first month following the disturbance event (Ellis 2001; Sprenger et al. 2001; Tomanek and Ziegler 1962). We observed new growth 1 wk after treatment on all clipped plants, 6-, 8-, and 12-wk-old imazapyr-treated plants, and 8 and 12-wk-old fire-treated plants. Herbicide injury developed about 10 d following treatment and was observed as leaf chlorosis and stunted growth, which is typical of acetolactate synthesis (ALS) inhibitor herbicides. It was determined at the end of the post-treatment growth period that new shoots originated primarily from the base of the stem between the soil surface and 0.5 cm below the surface irrespective of plant age and treatment (Figure 1). However, the maximum depth of vegetative reproductive tissue development was not determined.

Saltcedar Plant Height, Root Biomass, and Root Length. Treatment effects on young saltcedar shoot height and root biomass were dependent on plant age at the time of treatment ($P < 0.0001$; Table 1). Treatment effects on shoot biomass were not examined for all treatments because shoots (and therefore biomass) were decimated by fire and clipping treatments, unlike the herbicide treatment, which would have had greater biomass, but mostly dead tissue.

Twelve-wk-old plants had greater root biomass than all other ages. Six wk after treatment in 2011, untreated 12-wk-old saltcedar (now 18 wk) had four times more roots than 8-wk plants (14 wk); these ages had 35 and 10 times more root tissue than 4-wk-old plants (10 wk), respectively (Figure 2). In 2012, 12-wk controls had eight times more roots than untreated 6-wk plants at the end of the growth period. Although root biomass following treatments for

Table 1. ANOVA models for effects of treatments and age on saltcedar root biomass (n = 360, R^2 = 0.89, P < 0.0001), and shoot height (n = 360, R^2 = 0.87, P < 0.0001) measured 6 wk after treatment. Twelve-wk plants in 2011 and 2012 differed in biomass and height and were separated in the models.

	Root biomass		Shoot height	
Parameter	DF	F ratio	DF	F ratio
Treatment	7	158.0*	7	223.8*
Plant age	4	292.9*	4	74.5*
Treatment×plant age	28	24.7*	28	20.8*

* Significance level, P < 0.0001.

plants treated at 12 wk was higher in 2012 than 2011, biomass of untreated plants was similar for both years.

Clipping reduced root biomass (Figure 2) and height of the tallest living shoot (Figure 3) for 6-, 8-, and 12-wk-old plants relative to untreated plants with new shoots produced after clipping similar in height across age groups. Mowing may temporarily set back older saltcedar plants but this treatment was the least destructive of those tested. All other treatments for all age groups had less biomass and were shorter in stature than the clipped plants (Figure 2 and 3). Destructive methods that result in injury to both above- and belowground tissue (e.g. shallow discing) may be more successful at removing saltcedar plants in the field. In this study, average root lengths observed for untreated 12- and 18-wk plants (6 and 12 wk at the time of treatment) extended 20 and 35 cm, respectively (data not shown). This root length is beyond the 13-cm discing depth used by Smith et al. (2002) to kill young saltcedar plants in the field, although the depth for vegetative bud development was not determined in either study.

Herbicide treatments were more effective at reducing young saltcedar growth than clipping. Root biomass for 4-, 6-, and 8-wk-old plants treated with herbicide was three times less than clipped plants whereas root biomass for 12-wk plants was similar between these treatments (Figure 2). Twelve-wk plants treated with herbicide had three (2012) and 10 (2011) times lower root biomass than untreated plants but shoot height was not reduced (Figure 2 and 3). Although shoot biomass was not collected for all treatments, it was found that the average shoot biomass for 12-wk herbicide-treated plants was less than one-third that of untreated plants (0.7 ± 0.1 g vs. 2.3 ± 0.1 g). Although most 6-, 8-, and 12-wk plants survived herbicide applications, observed reductions in above- and below-ground growth following treatment suggest that these plants may not survive in the long-term, especially if challenged with competitive and climatic stressors associated with field conditions. Reduced vigor also suggests that 0.12 mg ae imazapyr plant^{-1} (0.53 kg ae ha^{-1}[0.47 lb ae a^{-1}]) may be an effective treatment for first-year saltcedar growth. This rate is similar to applications used to successfully control saltcedar plants in mature stands (plants growing in an area with last disturbance 50 yr prior to treatment) (McDaniel and Taylor 2003). It should be noted that control of young saltcedar using herbicide may not be

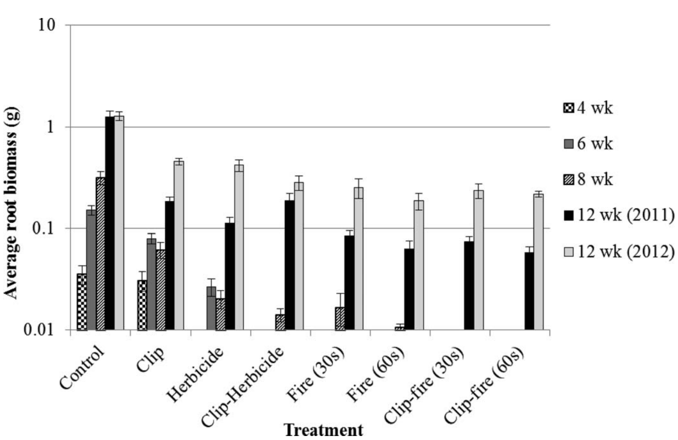

Figure 2. Average root dry weight 6 wk after treatment for saltcedar plants treated at 4, 6, 8, and 12 wk (2011 and 2012) of age (ANOVA, n = 360, F ratio = 24.7, P < 0.0001). Root biomass values lower than 0.01 g were not obtained.

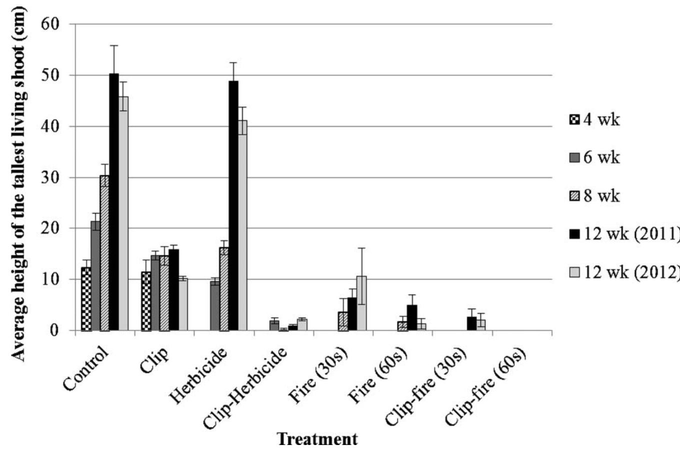

Figure 3. Average height of the tallest living shoot 6 wk after treatment for saltcedar plants treated at 4, 6, 8, and 12 wk (2011 and 2012) of age (ANOVA, n= 360, F ratio = 20.8, P < 0.0001).

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desired in some areas because of immediate and residual impacts on associated communities.

Fire often resulted in the lowest root biomass, particularly at longer durations and in combination with clipping (Figure 2). Resprout height 6 wk following fire treatment typically decreased with increasing fire duration and was shortest for plants clipped before fire exposure (Figure 3). Therefore, fire may be an effective control method in habitats where this management is used, depending on fire temperature and duration of exposure. Field burns will likely kill more plants than observed in this study because of the presence of competing vegetation and greater environmental variability (e.g. fuel loads, fuel and soil moisture). Even in a controlled environment (e.g. saturated soils, no vegetation fuels) plants were exposed to a wide range of fire temperatures (150 to 300 C). Although we attempted to account for this variability with a larger sample size, field burns would produce a wider range of temperatures.

Combined treatments were the most effective for controlling the oldest experimental saltcedar plants (Figure 2 and 3). For example, clipped 12-wk-old plants were two to three times more likely to succumb to fire and herbicide than unclipped plants in 2011. In 2012, all 12-wk plants survived the Clip + Herbicide treatment but these plants had 50% fewer roots than the Herbicide only treatment (Figure 2). Clipping exposed internal plant tissues that are more sensitive to heat and herbicide exposure than protective epidermal tissues. However, these techniques are not likely to be practiced at large scales in the field because (1) clipping vegetation before burning removes fuels that are needed to carry fire (unless clippings are left on site as fuels), and (2) removing saltcedar top-growth will make it difficult to identify plants for spot herbicide treatments. Clipping before spot herbicide application or spot burning is more realistic for small populations or individual plants and will likely increase the effectiveness of these controls.

Effects of Pre-Treatment Saltcedar Height on Control. It has been suggested that saltcedar plant height may be more important than age for predicting control treatment survival (Sprenger et al. 2001). In this study, height of 12-wk-old saltcedar plants before treatment did not influence plant response (measured by root biomass and tallest shoot post-treatment) to control treatments ($P = 0.44$ and 0.52, respectively). Larger plants did not always experience greater rates of survival. In many cases, the tallest plant exposed to fire, herbicide, and combined treatments died where shorter plants prevailed. Although plant age is an important factor affecting plant resilience to control treatments, plant height within an age group does not appear to impact susceptibility to the control treatments examined in this study. Fire resistance is often attributed to the thickness of the bark layer in woody plants. Although 12-wk-old saltcedar plants did not appear woody, the thickness of the epidermal layer may be a better measure of plant resistance to control treatments than height. However, we did not collect these data.

This is the first study to quantify first-season saltcedar response to clipping (mowing), herbicide, and fire injury. Similar to field studies using mature saltcedar, multiple intensive control practices were required to kill older plants in this study whereas younger plants could be controlled by single less-intensive treatments. Saltcedar seeds are produced throughout the growing season and therefore establishing populations will likely contain plants of multiple ages. Intensive treatments may be required for multi-age stands to ensure effective control. The slower growth of plants started later in the growing season relative to plants started earlier suggests that late-season cohorts may be more susceptible to control treatments, although these data were not collected. In addition, response of older plants may be under-estimated in this study because roots of the 12-wk untreated plants were pot-bound by 18 wk. Therefore survival, root biomass, and shoot height values may be greater than reported for plants that are not restricted by pot size. Regardless of these experimental constraints, young saltcedar plants in the field would be exposed to greater environmental variability and competitive stress that may lead to greater mortality and reduced growth following treatment.

Fire has not been considered a method for saltcedar removal because of (1) saltcedar's vegetative reproductive capacity, and (2) the difficulty of using fire where saltcedar typically establishes. This research showed that young saltcedar ($\leq$12 wk of age) can be nearly eliminated by conditions associated with spring grassland burns in the Northern Great Plains but to our knowledge, temperatures and residence times associated with fall burns in this system have not been monitored. Because of the potential adverse effects of fire on plant and animal populations, it is not recommended that burn programs be designed for the sole purpose of saltcedar control. However, spot fire applications may be useful for removing individual plants or small populations with reduced environmental impacts but this practice has not been tested on saltcedar infestations in the field.

Another factor that may be important to young saltcedar survival following any treatments is time of germination. It was observed that plants grown from seed in July and early August were more robust (larger size and greater shoot production) than those of the same age when seeded in late August or September. If the early seeded plants were treated at 4 wk, it is unclear if these more robust plants would respond in a similar manner to the treatments as the 4-wk-old plants used in this study. If the two cohorts responded differently, there may be further implications for field treatments.

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