Invasive Plant Science and Management 2012 5:139–147

Fire as a Tool for Controlling *Tamarix* spp. Seedlings

Michelle K. Ohrtman, Sharon A. Clay, David E. Clay, and Alexander J. Smart*

Fire is often used in northern grasslands to control invasive grass species but has unknown effects on *Tamarix* spp., more recent invaders. Temperature (using an oven as a fire surrogate) and duration combinations that would be most lethal to *Tamarix* seeds and seedlings were determined. *Tamarix* seeds were sown in soil-lined dishes, water added to saturation, and seedlings grown for 1 to 5 d. Seeds were also placed in water-saturated or dry soil just before temperature exposure (79 to 204 C [175 to 400 F]) by duration (1 to 5 min) treatments. After treatment, soil water loss was measured by weight difference, and surviving seedlings were counted for 6 d. *Tamarix* seedling establishment and survival decreased with increasing temperature and duration. The 5-d-old seedlings were the most affected. No 5-d-old seedlings survived 1- and 2-min exposures to 204 C, whereas 1-d-old seedlings had greater than 25% survival. If soils were saturated, two to four times more seedlings established following seed exposure to 177 and 204 C. Longer durations at lower temperatures were required to reduce *Tamarix* survival. Increasing duration from 2 to 5 min at 121 C decreased 5-d-old seedling survival from more than 80% to less than 10% and eliminated those seedlings at 149 C. Five minutes at 149 C decreased dry-soil seed viability to about 15%, whereas germination on saturated soils remained high (~75%). No seeds survived the exposure to 177 and 204 C. Soil moisture loss values associated with 90% mortality of 5- and 1-d-old seedlings were 1.7 and 2.2%, respectively. On saturated soils, 90% of seeds died with 2.5% water loss. Under suitable conditions, fire can decrease *Tamarix* seedling survival. Fire may be useful for controlling *Tamarix* seedlings in northern grasslands and should be considered for management of new invasions.

Nomenclature: *Tamarix* spp.: Chinese tamarisk, *Tamarix chinensis* Lour. TAACH; saltcedar, *Tamarix ramosissima* Ledeb. TAARA.

Key words: Temperature, duration, residence time, soil moisture, seed, seedling age.

Tamarix spp. (a.k.a saltcedar (*Tamarix ramosissima* Ledeb.) and Chinese tamarisk (*Tamarix chinensis* Lour. and hybrids) have been nominated as some of the 100 world's worst invasive weeds (GISD, 2010). This nonnative shrub/tree is the second most abundant riparian woody plant in the western United States, with the highest concentration of invasion located in the Southwest (Friedman et al. 2005; Morisette et al. 2006). *Tamarix* was introduced for ornamental and flood control purposes in the Northern Great Plains between 1930 and 1950 (Pearce and Smith 2007; R. Moehring, personal communication) and now forms dense, naturalized stands similar to those observed at southern latitudes (Lesica and Miles 2001; Pearce and Smith 2007). To date, northern *Tamarix* infestations occur primarily in riparian habitats on regulated (Bighorn, Cheyenne, Missouri, and Yellowstone) and unregulated (James, Powder, and White) rivers of Wyoming, eastern Montana, and the western Dakotas (Pearce and Smith 2007; R. Moehring, personal communication), but recent projections suggest this plant may invade new northern habitat types (Jarnevich et al. 2011; Morisette et al. 2006).

Tamarix habitat-suitability modeling predicts that about 35,000 km^2 (13,513 mi^2) of moderately to highly suitable *Tamarix* habitat exists in Montana, North Dakota, and South Dakota (Jarnevich et al. 2011), with grasslands expected to be two times more likely to support *Tamarix* than water areas (Morisette et al. 2006). Current maps of *Tamarix* infestations report presence, albeit in low numbers at few sites, in eastern South Dakota's Prairie Pothole region (South Dakota Department of Agriculture 2010). Those data provide evidence that *Tamarix* is establishing in moist-soil northern grassland habitats. Producers and land managers in the Northern Great Plains can take proactive measures to eliminate current *Tamarix* infestations and to stop its spread into new areas. Prescribed fires often are used to manage nonnative, invasive grass species in these

DOI: 10.1614/IPSM-D-11-00033.1

* Postdoctoral Research Associate, Professor, and Professor, Department of Plant Science, South Dakota State University, Brookings, SD 57007; Professor, Department of Natural Resource Management, South Dakota State University, Brookings, SD 57007. Corresponding author's E-mail: michelle.ohrtman@sdstate.edu

https://doi.org/10.1614/IPSM-D-11-00033.1 Published online by Cambridge University Press

Management Implications

Tamarix can invade moist-soil grasslands in the Northern Great Plains, and it is necessary to treat seedlings before they become well-established. Fire is an important management tool used to control nonnative grasses in northern grasslands, but this practice may also minimize *Tamarix* spread from seed. Although temperatures and durations associated with prescribed grassland fire are reported to be minimal, under appropriate conditions controlled burns in northern grasslands can provide soil surface temperatures and exposure periods lethal to most *Tamarix* seeds and developing seedlings. Deposited seeds are more likely to survive elevated temperatures than newly emerging seedlings but because seeds germinate rapidly upon wetting, fire will more likely encounter seedlings. To effectively control new infestations, *Tamarix* seedlings should be treated before they develop belowground perennating buds that generate new shoots following dormancy or disturbance. Repeated burning regimes are less likely to increase nonnative invasions in grasslands than other habitats suitable for *Tamarix* establishment because these ecosystems have evolved with this disturbance. Fire is, therefore, a viable option for *Tamarix* seedling control in northern grasslands, but burn programs should not target this species until more information is available.

rangelands (Higgins et al. 1989), and that practice may also reduce *Tamarix* invasion.

Fire has not often been used to manage *Tamarix* in southwestern riparian ecosystems for several reasons. Well-established *Tamarix* plants can recover rapidly from fire by producing new shoots from buds on root crowns and buried stems (Busch and Smith 1993; McDaniel and Taylor 2003). High soil moisture in riparian areas reduces the likelihood that fires will occur at sufficient intensity to kill mature *Tamarix* vegetative reproductive tissues (Busch 1995). Desired native woody vegetation often exhibits poor fire recovery response, and thus, fire disturbance can lead to new *Tamarix* infestations from seed by removing vegetative competition (U.S. Fish and Wildlife Service 2002; Ohrtman et al. 2011). However, fire may be used in Northern Great Plains grassland areas to destroy *Tamarix* seeds (Ohrtman et al. 2011) with grasses quickly recovering.

To date, no studies have reported fire effects on *Tamarix* seedlings, to our knowledge, presumably because seedlings typically establish without competing vegetation required to fuel fire (Sher et al. 2000, 2002; Stromberg 1997). *Tamarix*, however, can establish in the presence of grassland vegetation, although in lower numbers and with reduced growth, and that vegetation is sufficient to fuel spring burns (Ohrtman et al. 2011). Given this opportunity for seedling establishment in grasslands, combined with potential seed longevity in northern climates (Lehnhoff et al. 2011), it is necessary to resolve if and how fire treatments can be used to control new infestations before they become well-established and fire-resistant. Indeed, if young plants have not developed vegetative propagules, postfire resprouting rates of shrub-type seedlings are often low or do not occur (Boudreau and Willson 1992; Hodgkinson 1998; Vesk 2006) resulting in excellent control. As these seedlings age, however, they are more likely to resprout from vegetative buds following disturbance (Hodgkinson 1998; Reyes et al. 2009).

Temperature and residence time (duration) of controlled burns are important factors that contribute to fire-induced plant mortality (Bova and Dickinson 2005), yet few studies have documented these fire conditions in northern grasslands. In a companion study conducted by our research group, controlled grassland spring burns performed biennially, which contained a mixture of dormant and green foliage, produced soil surface (~1 cm [0.4 in]) temperatures that exceeded 200 C for 2 min and 150 C for 5 min (author's unpublished data). These temperatures are well above 60 C, the suggested lethal level for nonresistant plant tissues (Whelan 1995), with tissue loss accelerated by longer durations of exposure (Bova and Dickinson 2005). Controlled burns in northern grasslands, therefore, provide sufficient heat to kill plants with actively growing tissues (Wright and Bailey 1982), and our study results suggest that residence times may be longer than previously reported (Fidelis et al. 2010; Stinson and Wright 1969). Other aspects to consider for successful fire management include burn timing (Drewa et al. 2002; MacDonald et al. 2001) and amount of thatch present, which is a function of prior fire and grazing management (Fidelis et al 2010; Savadogo et al. 2007).

In this study, we sought to identify specific temperatures and durations that would be most lethal to *Tamarix* seeds and young seedlings. Oven/furnace experiments are often used to test invasive plant propagule response to fire conditions (Abella and MacDonald 2000; Emery et al. 2011). However, no one has reported, to our knowledge, using this method to examine heat tolerance of weed seedlings. In addition, seeds were placed on dry and wet soils, and seedlings were grown in saturated soil to examine the potential of soil and water on heat-buffering capacity; factors more characteristic of field conditions. Results will provide baseline data needed to understand *Tamarix* seed and seedling fire response and can be used to develop multispecies management plans that reduce the abundance of exotic grasses and minimize the risk of *Tamarix* invasion.

Materials and Methods

A full factorial design was used to determine the influence of six temperatures (79, 93, 121, 149, 177, and 204 C) associated with controlled burns in northern grasslands at three durations (1, 2, and 5 min) on germination of *Tamarix* seeds, sown on saturated or dry soil and on young seedling survival (1, 2, 3, 4, and 5 d old) in saturated soils. Although prescribed grassland burn durations greater than 3 min are not reported in the

https://doi.org/10.1614/IPSM-D-11-00033.1 Published online by Cambridge University Press

literature, we selected a 5-min exposure time because data from a related study indicated that surface soil temperatures monitored at ~1 cm in controlled eastern South Dakota grassland fires were sustained at greater than 150 C for durations longer than 5 min (authors' unpublished data). Control treatments included seeds and seedlings of each age maintained at 25 C. There were six replicates for each treatment combination and 132 total treatments including controls.

Tamarix seeds were obtained from seven states (Arizona, California, Colorado, Montana, New Mexico, South Dakota, and Utah) in 2010 to compare seed viability of populations from different regions. Seeds were stored in a 3 C refrigerator before use (Merkel and Hopkins 1957; Zaman et al. 2009). Germination tests to determine seed viability before temperature exposure were done by applying 100 *Tamarix* seeds to wetted filter paper inside closed germination dishes held at 25 C with 8 h of light (Young et al. 2004). Root radical protrusion was visible within 12 h, and seedlings were counted every day for 5 d (Merkel and Hopkins 1957).

Aluminum weighing dishes (7 cm diameter by 2 cm deep and 70 ml capacity) were selected because the type, size, and depth of these containers were necessary to (1) withstand extreme heat exposures, (2) support *Tamarix* seedling growth for several days, and (3) facilitate the inclusion of a large number of samples. Containers were filled with 50 g of sandy clay loam topsoil collected from multiple sites near Brookings, SD, which had been passed through a 2-mm (.08-in) sieve. Twenty-five seeds were applied to the soil surface of each dish. Soils were wetted to complete saturation with deionized water to represent the saturated-soil conditions necessary for *Tamarix* seed germination. The saturated soil environment also served to reduce below-ground tissue exposure to potentially lethal heat (temperatures > 60 C rarely occur below 2 cm soil depth in grassland burns; Wright and Clarke 2008) and to more closely mimic moist-soil field conditions in riparian and wetland areas. Dishes were placed in 25 C growth chambers and watered daily until exposure to simulated fire temperatures.

Three-week-old *Tamarix* plants have been observed to have roots longer than 1.5 cm with the slowest phase of growth occurring in the first week (Merkel and Hopkins 1957). To ensure roots did not incur heat damage from contact with the base of the aluminum containers, which conducts heat better than soil, we did not grow seedlings beyond 5 d before heat exposure. *Tamarix* seedlings between 1 and 5 d old were used to determine whether heat tolerance varied by seedling age. Immediately before temperature tests, three additional treatments were initiated with seeds sown onto soil as described above and soil remaining dry (one treatment) or with water added (two treatments). Dry-soil treatments were included to represent *Tamarix* seeds that had not made contact with surface soil moisture. Soils for the dry treatment were placed in aluminum dishes 1 wk before temperature exposure and set in a greenhouse to evaporate soil water. Following seed application, dry-soil dishes were wrapped with aluminum foil to prevent seed loss during treatment. One of the water-added treatments was exposed to experimental temperature and duration combinations, as described for seedlings, and the second treatment was used as a 25 C control.

Because of the extreme variability in the behavior of field fire (using a drip-torch method to start and maintain fire) and simulated fire (using a blow-torch method in the greenhouse), a Thelco oven (Model 130DM, Precision Scientific/Napco, Winchester, VA) was used, which gave a more controlled environment to obtain plant response. Sensors spotted with six different Tempilaq (Tempil, South Plainfield, NJ) thermo-sensitive paints, which melted at specific temperatures, were placed in the oven for each trial to verify oven temperature-gauge accuracy. Dishes containing water-saturated soils were weighed at both pretemperature and posttemperature exposures (five replicates), and the difference was used to calculate water loss; that information is required to determine the relationships among soil water, seed viability, and seedling survival. Water was added to resaturate soils following temperature treatment, and dishes were placed in 25 C growth chambers. Seedlings were counted every other day for 6 d.

ANOVA models were used to test the effects of temperature and duration on *Tamarix* seedlings and seeds. Percentage of seedling survival relative to control treatments for each seedling age and seed treatment were used as the response variables. The 2-, 3-, 4-, and 5-d-old seedling responses were similar for all treatment combinations, so results are presented for 5-d-old seedlings only. Log_{10} transformation was used to normalize the distribution of the percentage of *Tamarix* seed/seedling survival data, but nontransformed averages are reported. An ANOVA and scatterplot matrix was used to determine the strength of the linear relationship between the percentage of soil water loss and the temperature and duration of heat. Percentage of mortality was calculated, and an inverse prediction was used to determine the critical percentage of soil water loss values associated with 90% mortality of saturated soil seeds and 1- and 5-d-old seedlings. Statistical analyses were performed in JMP-In software (version 5.1.1, SAS Institute, Cary, NC).

Results and Discussion

***Tamarix* Germination Tests.** Northern *Tamarix* populations (i.e., Montana and South Dakota) had low germination (average of 55%) compared with southern samples (100%) (data not shown). A *Tamarix* population with high viability was selected for further study (1) to ensure high seedling numbers with minimal replication; (2)

https://doi.org/10.1614/IPSM-D-11-00033.1 Published online by Cambridge University Press

Table 1. ANOVA to test the effects of temperatures associated with grassland fires and three exposure durations on *Tamarix* seedling survival relative to controls (25 C). Data are presented for 1- and 5-d-old seedlings ($N = 216$; $R^2 = 0.71$; F ratio = 15.98; $P < 0.0001$). Log_{10} transformation was used to normalize the distribution of the data.

Parameter	df[a]	Sum of squares	F ratio
Temperature	5	81.44	73.74**
Duration	2	16.15	36.57**
Seedling age	1	6.76	30.60**
Temperature × duration	10	13.50	6.11**
Temperature × seedling age	5	0.84	0.76
Duration × seedling age	2	0.01	0.03
Temperature × duration × seedling age	10	4.83	2.19*

[a] Abbreviation: df, degrees of freedom.

Significance levels, **< 0.0001; *< 0.05.

to be able to easily distinguish differences among seed treatments, rather than dealing with the confounding influence of low germinability; and (3) to determine temperature effects on the most robust population sampled. *Tamarix* seeds used for temperature tests originated from Riverside County near Blythe, CA, and were collected by Dr. Bertin Anderson in April 2010. Although phenotypic differences have been observed between southern and northern *Tamarix* ecotypes, these traits develop in individuals over the course of several months (Friedman et al. 2008; Sexton et al. 2002) to years (Friedman et al. 2011). Sample location is not likely to influence individual growth response of 1- to 11-d-old seedlings at 25 C, although it should be noted that seed and seedling heat tolerance may vary by latitude.

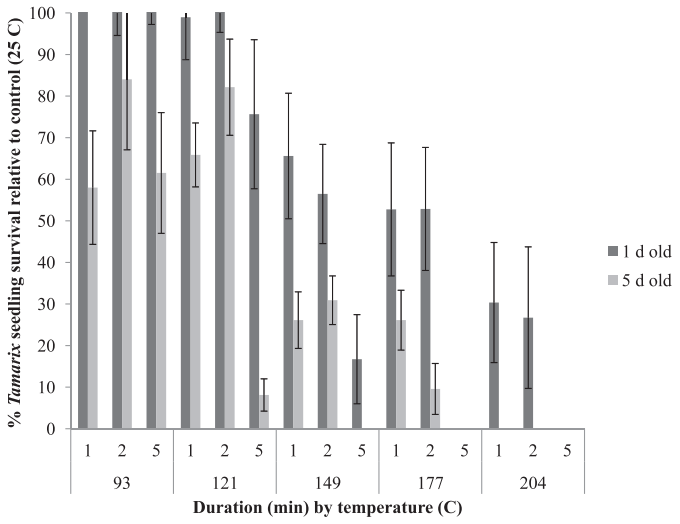


Figure 1. Average percentage of 1- and 5-d-old *Tamarix* seedlings that survived temperatures associated with grassland fires when compared with controls (25 C) for 1-, 2-, and 5-min durations (ANOVA, $N = 216$; F ratio = 2.19; $P = 0.02$; mean ± SE). Percentages above 100% represent the establishment of more seedlings in temperature treatments than controls. Seedling survival was high for 1- and 5-d-old treatments at 79 C, irrespective of duration, so data are not shown.

***Tamarix* Seedling Responses to Temperature Treatments.** Seedling survival decreased with increasing temperature, duration, and seedling age (Table 1). The 5-d-old *Tamarix* seedlings were less heat tolerant than were 1-d-old seedlings at almost all temperatures and durations (Figure 1). Survival of 1-d-old seedlings declined compared with nontreated seedlings when exposed to 121 C for 5 min or when exposed to higher temperatures, regardless of duration. At 204 C, the highest temperature tested, about 30% of the 1-d-old seedlings survived when durations were 1 or 2 min. The 5-d-old seedlings were more sensitive to heat, with declines in survival evident at the second to lowest tested temperature (93 C), even with a 1-min duration, and these older seedlings did not survive when exposed to 149 or 177 C for 5 min or to 204 C for any duration.

Fire temperature and duration depends on the quantity and type of aboveground biomass and the amount of actively growing foliage (Bond and van Wilgen 1996; Vermeire and Rinella 2009), which can vary considerably in grasslands, depending on climate, species diversity, and management (Bernhardt-Römermann et al. 2011). Grassland fire intensity in areas with only dormant vegetation can produce temperatures that exceed 700 C for up to 2 min (Stocks et al. 1996; Stronach and McNaughton 1989). However, grassland fires in areas with mixed dormant and growing vegetation are typically lower in intensity, with low average temperatures, rapid rates of spread, and short durations (Fidelis et al. 2010; Morgan 1999; Stinson and Wright 1969); prescribed fires generally have even lower intensity because managers select milder burning conditions to facilitate more predictable fire behavior (DeBano et al. 2005). However, our research showed that controlled, spring, grassland fires in areas that

https://doi.org/10.1614/IPSM-D-11-00033.1 Published online by Cambridge University Press

Table 2. Average percentage of soil moisture loss by temperature and duration for treatments with saturated soils (ANOVA, $N = 90$; $R^2 = 0.88$; F ratio $= 38.95$; $P < 0.0001$).

	Time (min)		
Temperature (C)	1	2	5
79	0.4	0.5	0.8
93	0.4	0.5	1.4
121	0.5	0.6	1.2
149	0.6	1.2	1.8
177	1.1	1.0	2.1
204	0.7	1.5	4.3

had a mix of dormant and growing vegetation maintained elevated temperatures for durations similar to experimental test conditions (2 min at 200 C and 5 min at 150 C) (authors' unpublished data). These results suggest that prescribed grassland fires have the potential to reduce, but not to eliminate, newly established *Tamarix* seedlings because soil temperatures may not be high enough or durations may not be long enough for complete control.

Survival of 1-d-old seedlings in this study (i.e., 55% at 149 C and 25% at 204 C for 2 min durations) was higher than the 5% survival reported when *Tamarix* seeds were exposed to fire 24-h after deposition on soil cores taken from a grassland and observed 21 d after treatment (Ohrtman et al. 2011). The 5% survival of the young seedlings may be more akin to what occurs in fire-treated grasslands because *Tamarix* does not compete well with established vegetation (Ohrtman et al. 2011; Sher et al. 2000, 2002; Stromberg 1997). On the other hand, reduction of sod-forming, cool-season, exotic grasses with fire may initially create more openings for *Tamarix* establishment in early summer (Ohrtman et al. 2011).

High levels of soil water have been observed to reduce soil heating during grassland fire (Wright and Clarke 2008) and may protect young *Tamarix* seedlings from exposure to lethal temperatures. Heat duration and soil water loss were positively correlated ($r = 0.72$; $P < 0.0001$), suggesting that increased water loss was a direct result of longer periods of temperature exposure (Table 2). Based on water loss and seedling mortality data, soil water losses of 1.7 and 2.2% resulted in 90% mortality of 5- and 1-d-old seedlings, respectively, and further suggest that less energy was required to kill 5-d-old seedlings. *Tamarix* preferentially establishes in riparian and wetland habitats that contain high levels of soil water. Higher fire temperatures and longer durations would be necessary to evaporate soil water and to kill *Tamarix* seedlings in moist environments. Less-intense fires would likely be effective at drier sites or during periods of low surface soil water, although *Tamarix* is less likely to establish under those conditions.

Fire is more likely to meet older *Tamarix* seedlings than those used in our studies in field conditions. Research performed on other fire-resistant species suggests that 2-wk-old (MacDonald et al. 2001) to several week-old (Boudreau and Willson 1992) seedlings may succumb to heat. However, northern *Tamarix* plants have been observed to die back each year (Lesica and Miles 2001), suggesting that subsurface vegetative buds develop before the end of the first growing season. Ultimately, survival of young *Tamarix* plants will depend on fire intensity, plant maturity, and the presence and depth of perennating, belowground tissue (Pyke et al. 2010). If vegetative buds develop at depths > 2 cm, grassland fire may not be an effective management tool because lethal temperatures are not observed below that depth (Wright and Clarke 2008; author's unpublished data).

***Tamarix* Seed Viability and Seedling Establishment Following Temperature Treatments.** Seed survival decreased with greater temperature and duration and was dependent on soil condition (wet vs. dry) (Table 3). Seedlings established in greater numbers in saturated soil compared with dry soil when exposed to 177 and 204 C for

Table 3. ANOVA to test the effects of temperatures associated with grassland fires and three durations of exposure on *Tamarix* seedling establishment relative to controls (25 C). Tests were performed on seeds sown on saturated and dry soils ($N = 208$; $R^2 = 0.77$; F ratio $= 20.38$; $P < 0.0001$). Log_{10} transformation was used to normalize the distribution of the data.

Parameter	df[a]	Sum of squares	F ratio
Temperature	5	57.51	87.56*
Duration	2	9.11	34.69*
Seed treatment	1	6.59	50.20*
Temperature × duration	10	8.46	6.44*
Temperature × seed treatment	5	4.33	6.59*
Duration × seed treatment	2	0.20	0.75
Temperature × duration × seed treatment	10	7.33	5.58*

[a] Abbreviation: df, degrees of freedom.

Significance level, *< 0.0001.

https://doi.org/10.1614/IPSM-D-11-00033.1 Published online by Cambridge University Press

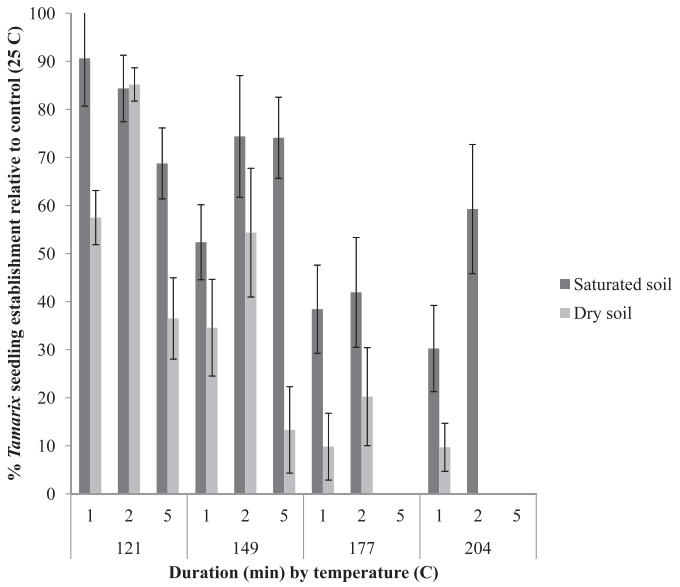


Figure 2. Average percentage of *Tamarix* seedling establishment (relative to 25 C controls) for seeds on saturated and dry soil exposed to temperatures associated with grassland fire for 1-, 2-, and 5-min durations (ANOVA, $N = 208$; F ratio $= 5.58$; $P < 0.0001$; mean $\pm$ SE). Results for 79 and 93 C exposure were similar for saturated and dry soil treatmens, so data are not shown.

1- or 2-min durations and for 5 min at 121 and 149 C (Figure 2). These results provide further evidence that soil water buffers temperature effects. When soils contain water, the temperature does not exceed water's boiling point (100 C) until the water evaporates (DeBano et al. 1976; Scotter 1970). Temperatures can increase more rapidly and be higher in dry soils because heat is not dissipated (Campbell et al 1995). Wet soils conduct heat better than dry soils (DeBano et al. 2005), but because of the small soil volume, shallow soil depth, and soil exposure to heat from all surfaces (i.e., not only from a surface treatment) used for our experimental treatments, dry soils are expected to reach higher temperatures than wet soils, especially when exposed to temperatures greater than 100 C. The dry soil used in this experiment may have provided some temperature buffering because some water is present in air-dried soil.

Although germination tests showed reduced viability of *Tamarix* seeds sown on soil (85%) vs. filter paper (100%) at 25 C, seeds exhibited moderate heat tolerance. *Tamarix* seed viability decreased at temperatures $\geq$ 121 C, irrespective of duration and soil water conditions (Figure 2). Nearly 15% of dry seeds and 75% of seeds in saturated soil survived 5 min exposures to 149 C, but that duration eliminated all seeds (dry and saturated) at 177 and 204 C. Germination rates for seeds exposed to high temperatures in dry soil and then wetted were surprising when the small size of *Tamarix* seeds is considered. *Tamarix* seeds typically measure 0.1 mm by 0.5 mm and have half the thickness of seed coats protecting some fire-resistant pine (*Pinus* spp.) species (Little 1968; Merkel and Hopkins 1957; Vander Wall and Balda 1977). Seeds of invasive Scotch broom [*Cytisus scoparius* (L.) Link.], which are up to 30 times larger than *Tamarix* seeds and can survive in the soil for several years, were eliminated when exposed to temperatures greater than 150 C for more than 2 min (Bossard 1993).

As expected, *Tamarix* seed was more resilient to high temperature exposure than developing seedlings. Soil water loss that caused 90% mortality of seed on saturated soils was 2.5%, which was 12 and 33% more water loss than was needed to induce 90% mortality of 1- and 5-d-old seedlings, respectively. The greater amount of energy required to kill nongerminated *Tamarix* seeds confirms that, although these seeds are small, they possess a protective barrier against heat damage. Differences between the heat tolerance of the southern ecotype used in this study and the northern ecotypes were not investigated.

Survival of *Tamarix* seeds applied to dry soil and exposed to 204 C for 1 min suggests that seeds may be able to withstand grassland fires when soil water is low; a condition more typical of upland areas or drought conditions. Rapid germination upon wetting and low, long-term seed viability reduces the likelihood that fire would encounter *Tamarix* seeds in the field. However, seeds from a Montana *Tamarix* accession were observed to maintain viability for several weeks to months at warm and cold temperatures (30 d at 35 C and 180 d at 20 C, 5 C, and -14 C) (Lehnhoff et al. 2011), suggesting that, under dry conditions, *Tamarix* seeds may have some longevity.

Using Fire to Control *Tamarix* Seeds and Seedlings. Results of this study suggest that prescribed grassland fires can decrease new *Tamarix* infestations by reducing seed viability and killing young seedlings. However, there are limitations and disadvantages of using fire to manage *Tamarix* seedlings.

Prescribed fire must be above threshold temperatures and durations to optimize control, with longer durations needed when fire temperature is low. Fires in areas with wet soils and low vegetative cover, typical of disturbed riparian areas where *Tamarix* commonly establishes, are unlikely to produce these conditions, whereas fires in grassland areas can provide favorable control conditions (authors' unpublished data). Frequency (i.e., burn recurrence) and timing (i.e. spring vs. summer vs. fall burn) of grassland fires could influence its effectiveness for *Tamarix* management.

Grassland ecosystems have evolved with frequent fire, but repeated annual treatments that may be required to control *Tamarix* in the long term can have undesirable effects. For example, annual burning has been found to

https://doi.org/10.1614/IPSM-D-11-00033.1 Published online by Cambridge University Press

reduce species diversity (Abrams and Hulbert 1987) and biomass (Higgins et al. 2007) in grasslands. Losses in cover could increase the potential for *Tamarix* establishment (Ohrtman et al. 2011) although the risk for *Tamarix* seedling establishment immediately after spring fire in northern grasslands is low because seed release occurs after vegetation has recovered. A biennial spring burning regime is required for effective control of the cool-season exotic Kentucky bluegrass (*Poa pratensis* L.) (Gibson et al. 1993; Hartnett et al. 1996), so fire programs established for this species would already incur environmental costs associated with frequent burning.

In northern regions, *Tamarix* seed is released between July and September (S. Burnette, personal communication; Pearce and Smith 2003), and, therefore, spring fires will only encounter *Tamarix* seedlings if seeds remain viable over winter and germinate in colder soils (Lehnhoff et al. 2011). *Tamarix* may establish in early summer if spring fire programs decrease cover of sod-forming, cool-season grasses (Ohrtman et al. 2011). Summer fire programs could coincide with early summer *Tamarix* seed release and be used to improve productivity of native grasses (Copeland et al. 2002; Towne and Kemp 2008). However, summer fires traditionally are not used because of increased wildfire risk.

If summer seeds make contact with moist soils, fall fire treatments can encounter first-year Tamarix growth. Burn areas should be monitored to identify and treat *Tamarix* seedlings before their leaves senesce and they harden-off for winter, which, for northern ecotypes, occurs in mid-October (Friedman et al. 2011). Fall burns, under some conditions, may be desirable, although temperatures and burn durations have not been monitored for northern grasslands.

Timing and amount of rain determine whether fire can even be used in an area. For example, areas near Brookings, SD, from September 1 through October 31, 2011, when fall burning often occurs, received less than 2 cm of rain (normal, 11.6 cm), and prescribed burns were not permitted because of the very dry conditions. In addition, depending on seasonal rainfall, older plants with perennating buds may need to be controlled, and to date, the effect of grassland fires on older plants has not been reported. Based on these limitations and information gaps, fire programs designed specifically to control *Tamarix* seedlings over large areas are not advised at this time.

Spot fire treatments may be a better option for targeting new *Tamarix* infestations because of the potential adverse effects of prescribed burning. Spot-burning using a propane torch has been successfully demonstrated to control invasive seedlings in several Michigan preserves (Tu et al. 2001). This method does not require vegetation for fuel and can be used at any time during the growing season when conditions are favorable with less concern about large-scale effects on vegetation community dynamics. However, this method may not be feasible across large expanses and has not been tested on *Tamarix*.

Population explosions in western South Dakota, along the Cheyenne River, and recent habitat-suitability modeling suggest that *Tamarix* may spread to suitable habitats (e.g., sites with prolonged periods of surface soil moisture) in the Prairie Pothole region, where prescribed burns are already used to manage nonnative grasses. Fire is an effective tool for managing invasive plants, but this practice has not been considered a principal method for *Tamarix* control because of this plant's propensity for vigorous vegetative reproduction (Busch and Smith 1993; DiTomaso et al. 2006). Research findings reported here suggest that there may be opportunities to use fire for *Tamarix* seedling control but the effectiveness of this technique is dependent on the temperature and duration of the burn. In this study, plants were watered soon after exposure to high temperatures, if a dry period followed high-temperature treatments, less seedling survival may have been observed. Seedlings were not monitored beyond 6 d, and susceptibility to pathogens and other effects of heat exposure could cause mortality beyond this observation period.

This research provides the framework for beginning to understand fire effects on *Tamarix* seeds and seedlings, but more information is needed about older seedling fire response, especially in northern regions where invasion is relatively new and exposure to cold temperatures may increase the effectiveness of fire control. Presently, there is insufficient evidence to suggest that burns should be implemented specifically for control of *Tamarix*, but fire programs designed to manage other species have the potential to minimize *Tamarix* invasion. In light of the potential environmental problems associated with prescribed fire, new *Tamarix* management practices, such as spot burning, should be examined. In addition, prefire or postfire herbicide and mechanical treatments, which have been shown to effectively control mature *Tamarix* in other regions (McDaniel and Taylor 2003), may provide novel disturbances in northern grasslands and should be evaluated before use.

Acknowledgments

This research was supported by a grant from U.S. Department of Agriculture– Cooperative State Research, Education, and Extension Service Rangeland (award 00486094). Additional funding was provided by South Dakota Agricultural Experiment Station and South Dakota Cooperative Extension Service. Many thanks to Stephanie Hansen and Carrie Werkmeister for project assistance and materials. Additional thanks to Stephanie Hansen for manuscript review. Thanks to Dennis Ruhlman and the South Dakota State University Seed Technology Laboratory for use of the growth chambers and supplies. Thanks to Leo Schleicher and the South Dakota State University Horticulture

https://doi.org/10.1614/IPSM-D-11-00033.1 Published online by Cambridge University Press

Department for providing the soil. Special thanks to the following individuals for regional *Tamarix* seed collection: Bertin Anderson (Revegetation and Wildlife), Gina DelloRusso (Bosque del Apache National Wildlife Refuge), Steven Gonzales (Bureau of Reclamation, Socorro Field Office), Hisham Elwaer (University of Denver), Diana Stuart (Maricopa County Flood Control District), Justin King (Bureau of Land Management, Roswell Field Office), Erik Lehnhoff (Montana State University), Sarah Burnette (U.S. Geological Survey/South Dakota State University), Stacy Kolegas (Tamarisk Coalition), and Caleb R. M. Affuso and Max Alderidge (Utah Bureau of Land Management).

Literature Cited

Abella, S. R. and N. W. MacDonald. 2000. Intense burns may reduce spotted knapweed germination. Ecol. Restor. 18:203–205.

Abrams, M. D. and L. C. Hulbert. 1987. Effect of topographic position and fire on species composition in tallgrass prairie in northeast Kansas. Am. Midl. Nat. 117:442–445.

Bernhardt-Römermann, M., C. Römermann, S. Sperlich, and W. Schmidt. 2011. Explaining grassland biomass—the contribution of climate, species and functional diversity depends on fertilization and mowing frequency. J. Appl. Ecol. 48:1088–1097.

Bond, W. J. and B. W. van Wilgen. 1996. Fire and Plants. London: Chapman and Hall. 20 p.

Bossard, C. C. 1993. Seed germination in the exotic shrub *Cytisus scoparius* (Scotch broom) in California. Madrono 40:47–61.

Boudreau, D. and G. Willson. 1992. Buckthorn research and control at Pipestone National Monument (Minnesota). Restor. Manag. Notes 10:94–95.

Bova, A. S. and M. B. Dickinson. 2005. Linking surface-fire behavior, stem heating, and tissue necrosis. Can. J. Forest Res. 35:814–822.

Busch, D. E. 1995. Effects of fire on southwestern riparian plant community structure. The Southwest. Nat. 40:259–267.

Busch, D. E. and S. D. Smith. 1993. Effects of fire on water and salinity relations of riparian woody taxa. Oecologia 94:186–194.

Campbell, G. S., J. D. Jungbauer, Jr., K. L. Bristow, and R. D. Hungerford. 1995. Soil temperature and water content beneath a surface fire. Soil Sci. 159:363–374.

Copeland, T. E., W. Sluis, and H. F. Howe. 2002. Fire season and dominance in an Illinois tallgrass prairie restoration. Restor. Ecol. 10: 315–323.

DeBano, L. F., D. G. Neary, and P. F. Ffolliott. 2005. Soil physical properties. Pages 29–51 *in* D. G. Neary, K. C. Ryan, and L. F. DeBano, eds. Wildland Fire in Ecosystems—Effects of Fire on Soil and Water. Ogden, UT: Rocky Mountain Research Station, USDA Forest Service General Technical Report RMRS-GTR-42-vol.4.

DeBano, L. F., S. M. Savage, and D. A. Hamilton. 1976. The transfer of heat and hydrophobic substances during burning. Soil Sci. Soc. Am. J. 40:779–782.

DiTomaso, J. M., M. L. Brooks, E. B. Allen, R. Minnich, P. M. Rice, and G. B. Kyser. 2006. Control of invasive weeds with prescribed burning. Weed Technol. 20:535–548.

Drewa, P. B., W. J. Platt, and E. B. Moser. 2002. Fire effects on resprouting of shrubs in southeastern longleaf pine savannas. Ecology 83:755–767.

Emery, S. M., J. Uwimbabazi, and S. L. Flory. 2011. Fire intensity effects on seed germination of native and invasive Eastern deciduous forest understory plants. Forest Ecol. Manag. 261:1401–1408.

Fidelis, A., M. D. Delgado-Cartay, C. C. Blanco, S. C. Muller, V. D. Pillar, and J. Pfadenhauer. 2010. Fire intensity and severity in Brazilian campos grasslands. Interciencia 35:739–745.

Friedman, J. M., G. T. Auble, P. B. Shafroth, M. L. Scott, M. F. Merigliano, M. D. Freehling, and E. R. Griffin. 2005. Dominance of non-native riparian trees in western USA. Biol. Invasions 7:747–751.

Friedman, J. M., J. E. Roelle, and B. S. Cade. 2011. Genetic and environmental influences on leaf phenology and cold hardiness of native and introduced riparian trees. Int. J. Biometeorol. 55:775–787.

Friedman, J. M., J. E. Roelle, J. F. Gaskin, A. E. Pepper, and J. R. Manhart. 2008. Latitudinal variation in cold hardiness in introduced *Tamarix* and native *Populus*. Evol. Appl. 1:598–607.

Gibson, D. J., T. R. Seastedt, and J. M. Briggs. 1993. Management practices in tallgrass prairie: large- and small-scale experimental effects on species composition. J. Appl. Ecol. 30:247–255.

[GISD] Global Invasive Species Database. 2010. *Tamarix ramosissima* (shrub, tree). http://www.issg.org/database/species/ecology.asp?si=72&fr=1&sts=sss&lang=EN Accessed: November 27, 2011.

Hartnett, D. C., K. R. Hickman, and L.E.F. Walter. 1996. Effects of bison grazing, fire, and topography on floristic diversity in tallgrass prairie. J. Range Manag. 49:413–420.

Higgins, S. I., W. J. Bond, E. C. February, A. Bronn, D.I.W. Euston-Brown, B. Enslin, N. Govender, L. Rademan, S. O'Regan, A.L.F. Potgieter, S. Scheiter, R. Sowry, L. Trollope, and W.S.W. Trollope. 2007. Effects of four decades of fire manipulation on woody vegetation structure in savanna. Ecology 88:1119–1125.

Higgins, K. F., A. D. Kruse, and J. L. Piehl. 1989. Effects of fire in the Northern Great Plains. Jamestown, ND: Northern Prairie Wildlife Research Center Online, U.S. Fish and Wildlife Ser. Coop. Ext. Ser., South Dakota State University, Brookings, South Dakota Extension Circular 761. http://www.npwrc.usgs.gov/resource/habitat/fire/index.htm Accessed: March 10, 2011.

Hodgkinson, K. C. 1998. Sprouting success of shrubs after fire: height-dependent relationships for different strategies. Oecologia 115:64–72.

Jarnevich, C. S., P. Evangelista, T. J. Stohlgren, and J. Morisette. 2011. Improving national-scale invasion maps: tamarisk in the western United States. West. N. Am. Nat. 71:164–175.

Lehnhoff, E. A., F. D. Menalled, and L. J. Rew. 2011. Tamarisk (*Tamarix* spp.) establishment in its most northern range. Invasive Plant Sci. Manag. 4:58–65.

Lesica, P. and S. Miles. 2001. Tamarisk growth at the northern margin of its naturalized range in Montana, USA. Wetlands 21:240–246.

Little, E. L. Jr. 1968. Two new pinyon varieties from Arizona. Phytologia 17:329–342.

MacDonald, N. W., P. J. Bosscher, C. A. Mieczkowski, E. M. Sauter, and B. J. Tinsley. 2001. Pre- and post-germination burning reduces establishment of spotted knapweed seedlings. Ecol. Restor. 19:262–263.

McDaniel, K. C. and J. P. Taylor. 2003. Saltcedar recovery after herbicide-burn and mechanical clearing practices. J. Range Manag. 56:439–445.

Merkel, D. L. and H. H. Hopkins. 1957. Life history of salt cedar (*Tamarix gallica* L.). Trans. Kansas Acad. Sci. 60:360–369.

Morgan, J. W. 1999. Defining grassland fire events and the response of perennial plants to annual fire in temperate grasslands of south-eastern Australia. Plant Ecol. 144:127–144.

Morisette, J. T., C. S. Jarnevich, A. Ullah, W. Cai, J. A. Pedelty, J. E. Gentle, T. J. Stohlgren, and J. L. Schnase. 2006. A tamarisk habitat suitability map for the continental United States. Front. Ecol. Environ. 4:11–17.

Ohrtman, M. K., S. A. Clay, D. E. Clay, E. M. Mousel, and A. J. Smart. 2011. Preventing saltcedar (*Tamarix* spp.) seedling establishment in the Northern Prairie Pothole Region. Invasive Plant Sci. Manag. 4: 427–436.

Pearce, C. M. and D. G. Smith. 2003. Saltcedar: distribution, abundance, and dispersal mechanisms, northern Montana, USA. Wetlands 23:215–228.

Pearce, C. M. and D. G. Smith. 2007. Invasive saltcedar (*Tamarix*): its spread from the American Southwest to the Northern Great Plains. Phys. Geogr. 28:507–530.

https://doi.org/10.1614/IPSM-D-11-00033.1 Published online by Cambridge University Press

Pyke, D. A., M. L. Brooks, and C. D'Antonio. 2010. Fire as a restoration tool: a decision framework for predicting the control or enhancement of plants using fire. Restor. Ecol. 18:274–284.
Reyes, O., M. Casal, and F. Castro Rego. 2009. Resprouting ability of six Atlantic shrub species. Folia Geobot 44:19–29.
Savadogo, P., D. Zida, L. Sawadogo, D. Tiveau, M. Tigabu, and P. C. Odén. 2007. Fuel and fire characteristics in savanna-woodland of West Africa in relation to grazing and dominant grass type. Int. J. Wildl. Fire 16:531–539.
Scotter, D. R. 1970. Soil temperatures under grass fires. Aust. J. Soil Res. 8:273–279.
Sexton, J. P., J. K. McKay, and A. Sala. 2002. Plasticity and genetic diversity may allow saltcedar to invade cold climates in North America. Ecol. Appl. 12:1652–1660.
Sher, A. A., D. L. Marshall, and S. A. Gilbert. 2000. Competition between native *Populus deltoides* and invasive *Tamarix ramosissima* and the implications for reestablishing flooding disturbance. Conserv. Biol. 14:1744–1754.
Sher, A. A., D. L. Marshall, and J. P. Taylor. 2002. Establishment patterns of native *Populus* and *Salix* in the presence of invasive nonnative *Tamarix*. Ecol. Appl. 12:760–772.
South Dakota Department of Agriculture. 2010. South Dakota Department of Agriculture. 2010. South Dakota Saltcedar Distribution Map. http://www.sdda.sd.gov/Ag_Services/Plant-Protection/PDF/2010%20SALTCEDAR.pdf Accessed: September 9, 2011.
Stinson, K. J. and H. A. Wright. 1969. Temperatures of headfires in the southern mixed prairie of Texas. J. Range Manag. 22:169–174.
Stocks, B. J., B. W. van Wilgen, W.S.W. Trollope, D. J. McRae, J. A. Mason, F. Weirich, and A.L.F. Potgieter. 1996. Fuels and fire behavior dynamics on large-scale savanna in Kruger National Park, South Africa. J. Geophys. Res. 101:23,541–23,550.
Stromberg, J. C. 1997. Growth and survivorship of Fremont cottonwood, Goodding willow, and salt cedar seedlings after large floods in central Arizona. Great Basin Nat. 57:198–208.
Stronach, N.R.H. and S. T. McNaughton. 1989. Grassland fire dynamics in the Serengeti ecosystem, and a potential method of retrospectively estimating fire energy. J. Appl. Ecol. 26:1025–1033.
Towne, E. G. and K. E. Kemp. 2008. Long-term response patterns of tallgrass prairie to frequent summer burning. Rangeland Ecol. Manag. 61:509–520.
Tu, M., C. Hurd, and J. M. Randall. 2001. Weed Control Methods Handbook, The Nature Conservancy. http://tncweeds.ucdavis.edu Accessed: November 14, 2011.
U.S. Fish and Wildlife Service. 2002. Southwesternn Willow Flycatcher Recovery Plan. Albuquerque, NM. i–ix + 210 p., Appendices A–O.
Vander Wall, S. B. and R. P. Balda. 1977. Coadaptations of the Clark's nutcracker and the pinyon pine for efficient seed harvest and dispersal. Ecol. Monogr. 47:89–111.
Vermeire, L. T. and M. J. Rinella. 2009. Fire alters emergence of invasive plant species from soil surface-deposited seeds. Weed Sci. 57: 304–310.
Vesk, P. A. 2006. Plant size and resprouting ability: trading tolerance and avoidance of damage? J. Ecol. 94:1027–1034.
Whelan, R. J. 1995. The Ecology of Fire. Cambridge University Press. Cambridge, UK. 346 p.
Wright, B. R. and P. J. Clarke. 2008. Relationships between soil temperatures and properties of fire in feathertop spinifex (*Triodia schinzii* (Henrard) Lazarides) sandridge desert in central Australia. Rangeland J. 30:317–325.
Wright, H. A. and A. W. Bailey. 1982. Fire ecology: United States and southern Canada. New York: John Wiley and Sons. 501 p.
Young, J. A., C. D. Clements, and D. Harmon. 2004. Germination of seeds of *Tamarix ramosissima*. J. Range Manag. 57:475–481.
Zaman, S., S. Padmesh, N. R. Bhat, and H. Tawfiq. 2009. Germination characteristics and storage behavior of *Tamarix aucheriana* (Decne.) seeds. European J. Sci. Res. 26:532–538.

Received April 22, 2011, and approved December 13, 2011.

https://doi.org/10.1614/IPSM-D-11-00033.1 Published online by Cambridge University Press