

Quantifying soil salinity in areas invaded by *Tamarix* spp.

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ABSTRACT

Elevated soil salinity is often associated with *Tamarix* invasion; however, it's unclear whether soils are more saline because of *Tamarix* or other environmental factors. Surface soil salinity was investigated along a flow-regulated, arid river with dense *Tamarix* of varying age to determine which factors best explain soil salinity. Flooding was the most important predictor, reducing salinity by nearly 70%. Soils under *Tamarix* had lower salinity than adjacent areas without woody cover in non-flooded areas suggesting that evaporation in arid environments may contribute more surface salts than *Tamarix* or may exacerbate plant inputs. Under most conditions, higher salinities were found under *Tamarix* than natives. An exception to this pattern was that soils under the smallest trees were more saline for natives. Relationships between soil salinity and stem size suggest that salts increase over time under *Tamarix* unless they are removed by flooding. However, the most mature stands had lower salinity than expected, reflecting some additional mechanism. Soil texture and distance from the river were important, but interacted strongly with other factors. The observed relationships between surface soil salinity and *Tamarix* stem size, a predictor of aboveground age, suggest *Tamarix* plays an active role in floodplain salinization within the sampled area.

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1. Introduction

Tamarix spp. (*Tamarix ramosissima*, *Tamarix chinensis* and hybrids) invasion is considered a major threat to ecological health at both national and global levels, with potential impacts on soil chemistry. As the common name “saltcedar” implies, one of the most often cited mechanisms of ecosystem change by *Tamarix* lies in its ability to sequester salts in its tissues. This deciduous tree can extract salts from the groundwater, secrete these compounds from leaf tissue, and deposit them onto the soil surface through mature leaf senescence and exudation (Arndt et al., 2004; Berry, 1970; Thomson et al., 1969). Despite this ability to redistribute salts to the soil surface, some suggest that any positive relationships that have been observed between *Tamarix* and elevated soil salinity may

result from *Tamarix*'s known higher tolerance to salinity; that its presence may be the consequence rather than the cause of this condition (Stromberg et al., 2009).

Elevated floodplain salinity has undoubtedly contributed to the large-scale replacement of native riparian vegetation with *Tamarix* (Busch and Smith, 1995; Glenn et al., 1998; Ohmart et al., 1988; Stromberg, 2001). The most often cited cause of elevated soil salinity along streams and rivers is river regulation. Flow-regulated and channelized river stretches can develop saline streambanks and adjacent riparian zones because they are no longer subjected to periodic overbank flooding that dilutes and flushes salts from the soil (Busch and Smith, 1995; Stromberg, 2001). Soil salinity is typically exacerbated in flood-deprived arid regions due to a lack of sufficient rainfall that would leach and transport salt deposits, and high evaporation rates (Goodall et al., 1981). These factors tend to further concentrate salts in the surface soil horizons.

Tamarix salt secretion has led many authors to speculate that soil salinity may increase significantly below *Tamarix* canopies (Brotherson and Field, 1987; Busch and Smith, 1993; Sala et al., 1996; Shafroth et al., 1995). Studies are often cited for showing that *Tamarix* elevates soil salinity, but generally these studies simply correlate high salinity with the presence of *Tamarix* (Carman and Brotherson, 1982; Ladenburger et al., 2006). Others indicate that environmental variables such as distance from the river,

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flooding, capillary rise from the aquifer, and eolian deposition may be more influential on salt levels (Glenn et al. 2012; Stromberg, 1998; Taylor et al., 1999; Yin et al., 2010) or that *Tamarix* salt contributions do not elevate soil salinity above the tolerance range of native riparian vegetation (i.e. <4 mmhos cm^{-1} ; Lesica and DeLuca, 2004). Much of the published research on the subject was designed to address questions unrelated to evaluating *Tamarix* contributions to soil salinity, and thus sampling may not have been sufficient to support or refute a causal relationship (Bagstad et al., 2006; Brotherson and Winkle, 1986; Campbell and Dick-Peddie, 1964; Nagler et al., 2008; Sexton et al., 2006). To assess whether *Tamarix* is responsible for significant salt-loading in surface soils, other potential sources of environmental salts must be examined with sufficient replication.

Many researchers have observed similar salt constituents in *Tamarix* leaves and the root environment (Berry, 1970; Sookbirsingh et al., 2010), but only recently has elemental composition of leaves and groundwater been compared with surface soils under *Tamarix*. Glenn et al. (2012) observed similar ratios of cations and anions in subtending groundwater, *Tamarix* leaves, and surface soils underneath trees, but these salt signatures were different than deeper soils and concentrations were higher than soils outside the plant canopy. These findings provide the most convincing evidence to date that *Tamarix* is redistributing salts to surface soils but it is still unclear which environmental factors are most important for understanding floodplain salinity.

If *Tamarix* does directly contribute to soil salinity, then we might expect that the magnitude of its impact would be related to stand features such as age, density, and cover. Stromberg (1998) found older *Tamarix* individuals to be associated with the highest levels of soil salinity along the San Pedro, a free-flowing river in Arizona. On the other hand, the oldest *Tamarix* stands along a regulated river reach of the Middle Rio Grande in central New Mexico have been observed to have surprisingly low surface soil salinity (<4 mmhos cm^{-1} ; K. Lair, unpublished data). Sexton et al. (2006) reported that soil salinity did not change with age of *Tamarix* along three rivers in southern Montana. This discrepancy suggests that soil salinity underneath *Tamarix* may depend on interactions between age and other environmental factors.

The objective of this research was to fill the critical gaps in understanding salt-loading by *Tamarix* with a quantitative study of soil salinity in *Tamarix*-infested locations in the field. Specifically this research sought to determine which environmental factors or combinations of factors, including hydrologic and climatic factors, are critical for explaining soil salinity in *Tamarix*-invaded areas along an arid river. Results were examined in the context of *Tamarix* aboveground age (as reflected by basal stem size), cover, and density to determine how these stand features affect soil salt loads.

2. Materials and methods

2.1. Study sites

The study area focused on an approximate 100-km reach of the Middle Rio Grande from State Highway 60 near Bernardo, south to the Fort Craig Bridge (Fig. 1a and b). The study area along the Middle Rio Grande is associated with an arid climate with a mean maximum daily temperature of nearly 40 °C during summer months and an average of 217 mm of precipitation annually (WRCC, 2011, Bosque del Apache weather station 291138). Summer monsoon thunderstorms deliver about half of the annual precipitation in brief high-intensity events. The sampling reach of the Middle Rio Grande contains a system of levees or barriers to flood flow. *Tamarix* has a strong presence in both the distal historic floodplain (i.e. outside the levees and deprived of flooding) as well as the proximal active

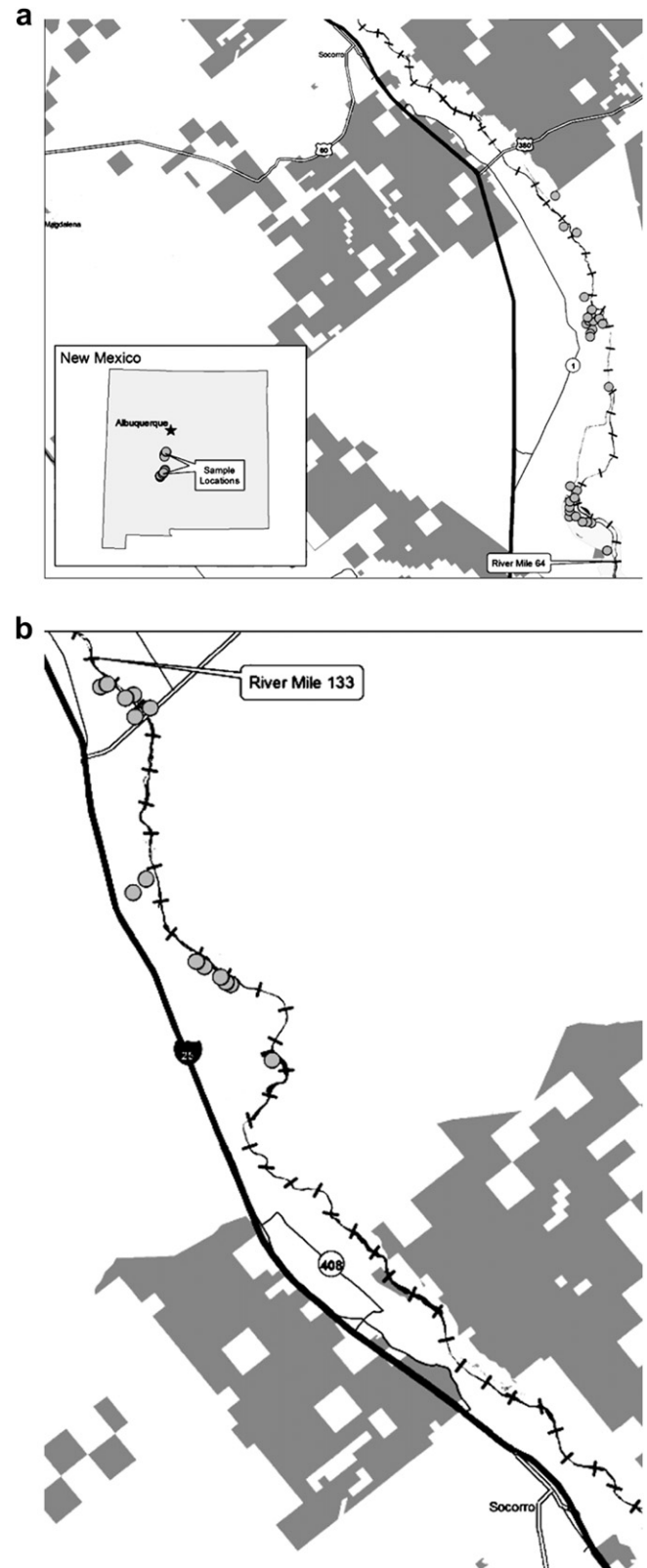


Fig. 1. Location map for research sites (gray circles) along the Middle Rio Grande, NM. a) Sites south of Socorro managed by Bureau of Reclamation and United States Fish and Wildlife Service used for models relating environmental variables to surface soil salinity and for comparison of open and closed-canopy surface soil salinity. b) Sites north of Socorro managed by Department of Game and Fish and Middle Rio Grande Conservancy District used for comparison of open and closed-canopy surface soil salinity only.

floodplain (i.e. inside the levees and exposed to overbank flooding). The river floods the area between the levees, on average, every five to seven years (Hink and Ohmart, 1984). Sites were located on flooded and non-flooded lands managed by the United States Fish and Wildlife Service (Bosque del Apache and Seville National Wildlife Refuges), Bureau of Reclamation, New Mexico Department of Game and Fish, and Middle Rio Grande Conservancy District.

A total of 50 sites within 40 stands (continuous blocks of similar vegetation in terms of age, cover, and density) were sampled for vegetation and soils between May and August of 2007. Stands greater than 5 ha were sampled in more than one location to account for variability across larger areas. Selected stands were composed of monotypic *Tamarix* vegetation; mixed vegetation (native riparian overstory and *Tamarix* understory); and restored native vegetation (planted native riparian species following *Tamarix* removal). Restored native stands were selected because there were no available native relict stands along this river reach. Stands either received seasonal flooding (i.e. within the levees) or managed emulation of flooding using irrigation, or were deprived of surface flows (i.e. outside the levees). Because mixed stands were only present in the active floodplain, only monotypic *Tamarix* and restored native stands were associated with both flooded and non-flooded conditions.

2.2. Vegetation characteristics

Vegetation was sampled along two 100-m line transects that were established 50 m apart (0.5 ha area). These lines ran parallel to the river in a north-south direction because soils and vegetation features tend to be more variable perpendicular to the river. Point-intercept was used to determine cover for each woody species along the line transects; these values were calculated by adding up the total number of occurrences (sampled at every m) by vegetation layer (lower and upper canopy) and dividing by 100 (the total number of sample points along each transect) (Cummings and Smith, 2000). Nearest neighbor woody vegetation data was collected at every 10 m along each transect using the Point-Centered Quarter Method (Bonham, 1989). Each woody plant with a stem size greater than or equal to 2 cm diameter was identified to species and the largest basal stem diameter was measured at 30 cm above the soil surface (Brotherson et al., 1984, 1983). These data were used to calculate tree density (i.e. the number of woody individuals per ha) and *Tamarix* stem age. The relationship between *Tamarix* stem diameter and age was previously determined along this river section in areas deprived of seasonal flooding by counting annual growth rings for 94 individuals across a gradient of stem sizes (between 2 and 40 cm diameter) (Ohrtman, 2009). Because *Tamarix* is able to resprout after disturbance and tolerate sediment deposition, younger stem ages are typically present at the ground surface than at the root crown, or original germination point (Friedman et al., 2005; Scott et al., 1997). Aboveground age can be very different from the age of the genet and therefore the relationship between *Tamarix* stem diameter and soil salinity only represents conditions since the most recent disturbance episode.

2.3. Soils characteristics and groundwater depth

Surface soil samples (upper 30 cm) were collected representing the zone that exhibits the greatest impact on co-occurring plant species. Because salt levels can vary dramatically in the surface profile, soil samples were separated into two depths: upper surface (0–15 cm) and lower surface (15–30 cm). Soils were sampled along each transect from underneath the canopy of woody plants receiving vegetation measurements. Samples were extracted 1 m from the base of the primary plant stem of known diameter. When the

canopy of an individual plant was less than 1 m from the base, soil samples were collected as far from the primary stem as possible while still underneath the canopy. Soil samples were therefore directly related to an individual plant canopy. Composite surface soil samples were extracted (for both depths) under each plant using a hand auger with a 5-cm bit. For sites with more sparse woody vegetation, composite soil samples were collected within the nearest open area (>50 m² area containing no woody vegetation canopy cover) to compare soils underneath *Tamarix* canopies with those associated with non-canopied areas having greater solar radiation exposure in an arid climate. Soil samples were sent to the Colorado State University Soil and Water Analysis Laboratory for analyses. Soil salinity was quantified based on the electrical conductivity (EC) of the soil-saturated paste (Richards, 1954). Texture was estimated using methods described by Theim (1979). In total, nearly one thousand soil samples were used to quantify the relationship between the presence of *Tamarix* and soil salinity within the sampled area.

Groundwater monitoring wells (3.25 m length by five cm-diameter PolyVinyl Chloride pipes) were installed along transects within 26 sites. Groundwater depth was measured in July and November 2007 and January and May 2008 to document groundwater fluctuation throughout the year.

2.4. Statistical analyses

A nested ANOVA, with site nested within stand and stand nested within presence or absence of flooding, was used to determine which of the measured environmental variables (or combinations of variables) best explain soil salinity within the study reach. Log₁₀ transformation was used to normalize the data for soil EC. Comparisons were made between soils collected under native woody species (*Populus deltoides* ssp. *wislizeni*, *Salix exigua*, *Salix goodingii*, *Prosopis glandulosa*, *Prosopis pubescens*, *Baccharis glutinosa*, *Atriplex canescens*, and *Lycium berlandieri*) and *Tamarix* across a gradient of cover values and densities and across three stem size categories (<5, 5–10, and >10 cm diameter, determined by data distribution) to determine how these factors relate to surface salt-loading. Stem size classifications related to approximately <11, 11–22, and >22 years of aboveground *Tamarix* age for individuals sampled in non-flooded areas (Ohrtman, 2009). Age determinations were not made for native woody individuals and therefore comparisons between *Tamarix* and natives were done using stem diameter but results related to *Tamarix* are often discussed using estimated stem age. Student's *t*-tests were used to compare sample means. Statistical comparisons were separated in the model by upper (0–15 cm) and lower (15–30 cm) soil depths. Only six native woody individuals and four *Tamarix* individuals with primary stems >10 cm diameter were sampled at higher latitudes, suggesting that there may be location effects with latitude that influence salinity. As a result, sites north of Socorro, NM (Fig. 1b) were excluded from salinity models. Matched pairs analysis was performed on pairwise open and closed-canopy soil samples collected in areas without flooding throughout the entire sampling reach (i.e. sites north and south of Socorro, NM; Fig. 1a and b) to determine the impact of evaporation and increased solar radiation on surface soil salinity. Samples collected in seasonally flooded areas were excluded from open and closed-canopy comparisons because of an insufficient sample size. An independent ANOVA was used to determine the importance of groundwater depth in predicting salinity along the sampled river section. Groundwater depth measurements for January (the month with highest water levels) were compared to an average of four composite surface soil samples collected in July on the transect containing the corresponding well. All statistical analyses were performed in JMP version 5.1.1 (SAS Institute, Inc., 2003).

3. Results

Of the nearly 90 variables measured in this study, those that created the best model for explaining soil salinity included: sampling location (i.e. stand or site), presence or absence of flooding, stem size class, and soil texture (Table 1). Species (native woody or *Tamarix*) and distance from the river were only found to influence salinity when interacting with other environmental variables. Woody species cover and density were not important variables for understanding surface soil salinity in the study area. Relationships between the measured parameters were similar for the 0–15 and 15–30 cm soil depths, however average soil EC was greater for the top 15 cm of soil (4.5 ± 0.3 mmhos cm^{-1}) compared with the lower depth (3.6 ± 0.2 mmhos cm^{-1}). Because upper surface soils appear to be the zone of highest salt concentration and the most important for establishment of co-occurring native species, the following results are restricted to the 0–15 cm soil depth.

3.1. The role of flooding and climate in soil salinization

Stand nested within flooding status had the greatest influence on surface soil salinity within the study area (i.e. 68 and 63% of the total sums of squares for the 0–15 and 15–30 cm depths, respectively) (Table 1). Salt levels also varied by sites within larger stands containing similar vegetation features (i.e. species composition, age, density, and cover) providing further evidence of the dynamic nature of this system.

Sites deprived of periodic flooding had more than three times higher mean surface soil EC than flooded sites (6.7 ± 0.6 vs. 2.1 ± 0.3 mmhos cm^{-1}). Other variables within the salinity model were found to interact strongly with flooding status because few variables significantly explained salinity trends in areas exposed to

overbank flooding. The absence of woody vegetation also impacted soil salinity, with surface soils in open areas having higher EC when compared directly with adjacent closed-canopy soils for both 0–15 cm (14.7 ± 1.6 mmhos cm^{-1} vs. 11.2 ± 1.1 mmhos cm^{-1} ; t -ratio = -3.7 , $P = 0.0004$) and 15–30 cm depths (12.1 ± 1.6 mmhos cm^{-1} vs. 9.8 ± 1.1 mmhos cm^{-1} ; t -ratio = -3.0 , $P = 0.002$).

3.2. *Tamarix* and soil salinity

Elevated floodplain salinity was related to presence of *Tamarix*, but only in the absence of overbank flooding, and only for individuals with basal stem diameters greater than 5 cm (Fig. 2a). The highest salinity in flood-deprived areas was observed under *Tamarix* canopies with stems between 5 and 10 cm diameter, with lower salt levels recorded under plants with smaller and larger primary stems. The lowest salt concentrations recorded were associated with the largest *Tamarix* trees growing in seasonally flooded zones (Fig. 2b). The highest salinities observed in flooded areas were those associated with the smallest native individuals.

3.3. Salinity relationships with soil texture and distance from the river

Texture was found to be a strong predictor of surface soil salinity, but the effects of this factor varied by woody vegetation stem size (Table 1). When samples collected under *Tamarix* and natives were pooled, clay soils had similar average EC across all

Table 1

ANOVA model to explain variance in upper (0–15 cm; $N = 271$, $R^2 = 0.87$, F -ratio = 31.91, $P < 0.0001$) and lower (15–30 cm; $N = 273$, $R^2 = 0.82$, F -ratio = 22.46, $P < 0.0001$) surface soil EC relationships with sampled variables along the Middle Rio Grande. Factors that were found to be the best predictors of salinity (i.e. highest R^2) included presence or absence of flooding, woody species (e.g. *Tamarix* or native), stem size class (<5 cm, 5–10 cm, and >10 cm diameter), texture (clay or sandy loam), and distance from the active river channel. Log₁₀ transformation was used to normalize the distribution of the data.

Parameter	df	0 to 15 cm depth		15 to 30 cm depth	
		Sum of squares	F-ratio	Sum of squares	F-ratio
Stand [Flooding]	25	7.91	10.75 ^c	7.65	8.24 ^c
Site[Stand]	8	0.96	4.07 ^b	0.72	2.41 ^a
Flooding	1	0.28	9.51 ^b	0.93	24.91 ^c
Species	1	0.02	0.82	0.00	0.08
Stem size class	2	0.42	7.17 ^b	0.25	3.35 ^a
Texture	1	0.02	0.56	0.74	19.88 ^c
Distance	1	0.00	0.15	0.03	0.69
Flooding*species	1	0.07	2.52	0.01	0.25
Flooding*stem size class	2	0.26	4.35 ^a	0.24	3.29 ^a
Flooding*texture	1	0.08	2.85	0.01	0.16
Flooding*distance	1	0.06	2.16	0.07	1.86
Species*stem size class	2	0.35	5.92 ^b	0.33	4.39 ^a
Species*texture	1	0.01	0.39	0.06	1.55
Species*distance	1	0.09	3.01	0.06	1.71
Stem size class*texture	2	0.38	6.41 ^b	0.33	4.50 ^a
Texture*distance	1	0.01	0.19	0.11	2.98
Flooding*species*	2	0.30	5.03 ^b	0.35	4.74 ^b
stem size class					
Flooding*species*	1	0.24	8.13 ^b	0.12	3.12
distance					
Flooding*texture*	1	0.17	5.90 ^a	0.01	0.24
distance					

Significance levels: ^a<0.05, ^b<0.01, ^c<0.0001.

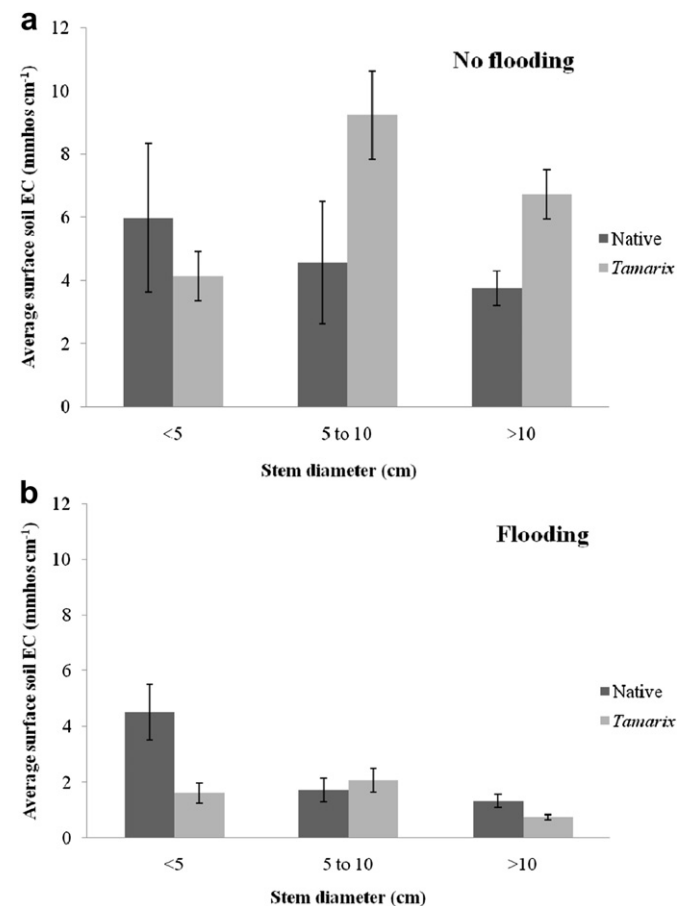


Fig. 2. Average EC of surface soils (0–15 cm) underneath *Tamarix* and native individuals sampled along the Middle Rio Grande by stem size class (ANOVA, $N = 271$, F -ratio = 5.03, $P = 0.007$, mean \pm 1 SE) for a) non-flooded and b) flooded sites.

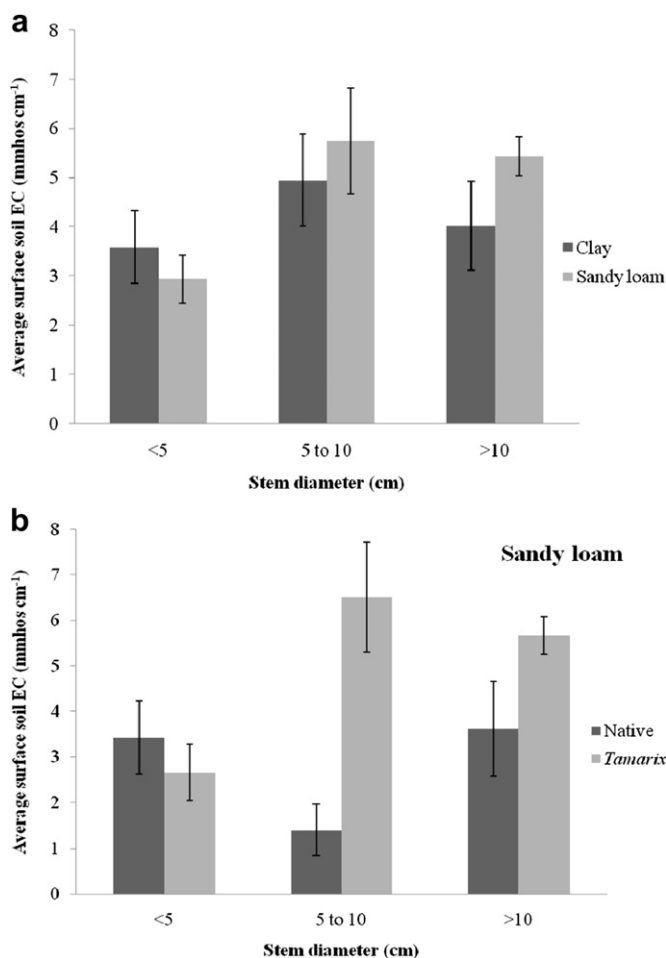


Fig. 3. Average EC of surface soils (0–15 cm) along the Middle Rio Grande by stem size class for a) sandy loam and clay textures averaged for all woody species (ANOVA, $N = 271$, F -ratio = 6.41, $P = 0.002$, mean \pm 1 SE), and b) sandy loam samples averaged separately for *Tamarix* and natives.

stem size classes (Fig. 3a). However, in sandy loam soils, salt levels associated with 5–10 cm diameter stems were 50% higher than those under plants with stems <5 cm diameter. Salinity of sandy loam soils under *Tamarix* showed similar results as the pooled data, i.e. EC increased between the smallest and intermediate stem sizes (Fig. 3b). Conversely, EC of sandy loam soils under natives decreased when stem size increased from <5 to 5–10 cm diameter. These results suggest that salt levels by woody stem size in sandy loam soils are strongly influenced by the presence of *Tamarix*.

The relationship between soil texture and *Tamarix* stem size differed for flooded and non-flooded areas. Without flooding, sandy loam soils harbored larger *Tamarix* individuals (12.9 ± 1.0 cm diameter) than clay soils (9.9 ± 0.9 cm diameter). The opposite was observed in flooded areas; clay soils were associated with greater average *Tamarix* stem diameter (6.6 ± 0.5 cm) than sandy loams (2.9 ± 0.8 cm), and trees were generally smaller. A similar pattern of stem size by soil texture and flooding was observed for native woody plants.

Significant interactions between flooding, distance from river, and species were primarily due to salinity peaks between 800 and 1200 m from the river in sites with no flooding under *Tamarix* trees, irrespective of texture (Fig. 4a and c). Otherwise, surface soil salinity generally increased with greater distance from the river, at a somewhat greater rate for *Tamarix* than for native trees (Fig. 4a

and b), and in slightly different ways for clay versus sandy loam soils (Fig. 4c and d).

3.4. Soil salinity and groundwater depth

Irrespective of flooding, EC of the 0–15 cm soil layer decreased significantly with increasing depth to groundwater (Table 2, Fig. 5a). For the 15–30 cm soil depth, this relationship was only observed for sites exposed to flooding (Fig. 5b). Minimum water table depth for the 18 wells monitored within lower latitude sites was between 0.3 and 2.7 m and maximum groundwater depth rarely exceeded 3 m.

4. Discussion

Research results support previous assertions that flow-regulated and channelized river stretches can develop saline soils because they are no longer subject to periodic flooding that removes salts (Ohmart et al., 1988; Stromberg et al., 2009). Sites deprived of flooding had salinities three times that of seasonally flooded areas, suggesting that flooding may be one of the most important factors for determining floodplain salinity.

Lower surface soil salinity under *Tamarix* canopies (11.2 mmhos cm⁻¹) relative to adjacent open areas (14.7 mmhos cm⁻¹) suggests that *Tamarix* cover is important for minimizing salinization of surface soils along the Middle Rio Grande. Woody vegetation can slow the evaporation-driven capillary rise of salts in the soil profile by: 1) plant roots extracting rising water before it reaches surface soils (Tamea et al., 2009), and 2) reducing the amount of solar radiation reaching the soil surface (Yang et al., 1999). These factors explain why soils underneath *Tamarix* had significantly lower EC when compared with adjacent open areas for this study and other research performed along this river (Taylor et al., 1999). A study performed along the lower Colorado River, another arid southwestern river, found soils under dense *Tamarix* stands with higher leaf area indices and greater rates of transpiration had lower surface soil salinity relative to less dense growth. The authors attributed this difference to reduced upward movement of salts in the soil profile by greater plant water extraction for the denser growth (Glenn et al., 2012). Studies comparing soils under *Tamarix* with soils outside plant canopies in Montana (Lesica and DeLuca, 2004) and Wyoming (Ladenburger et al., 2006) found higher soil salinity under *Tamarix*. Perhaps the lower temperatures and greater precipitation associated with these semi-arid locations negated the influence of *Tamarix* cover and root water extraction on reduction of surface soil salinity. Soil salinity under *Tamarix* in Montana was less than 4 mmhos cm⁻¹ (Lesica and DeLuca, 2004), about one-third of that observed under *Tamarix* canopies in this study which suggests that salt redistribution by *Tamarix* may be accelerated in arid climates. Our results suggest that for the sampled arid riparian system, capillary rise of salts elevates surface soil salinity more than *Tamarix* and high surface evaporation may exacerbate salt contributions by *Tamarix* leaf exudates.

Whereas there is a complex network of environmental variables and interactions that can contribute to soil salinity in riparian areas, this research found that *Tamarix* presence and stem size (a predictor of aboveground age; Ohrtman, 2009) were among the most critical predictors of salinity along the Middle Rio Grande. Under most but not all conditions, higher salinities were found under *Tamarix* trees than under native species: in flooded sites, salinity increased at a greater rate under *Tamarix* with increasing distance from the river, and in non-flooded sites, the highest salinities were associated with *Tamarix*. An important exception to this pattern was that soils under the smallest trees were more

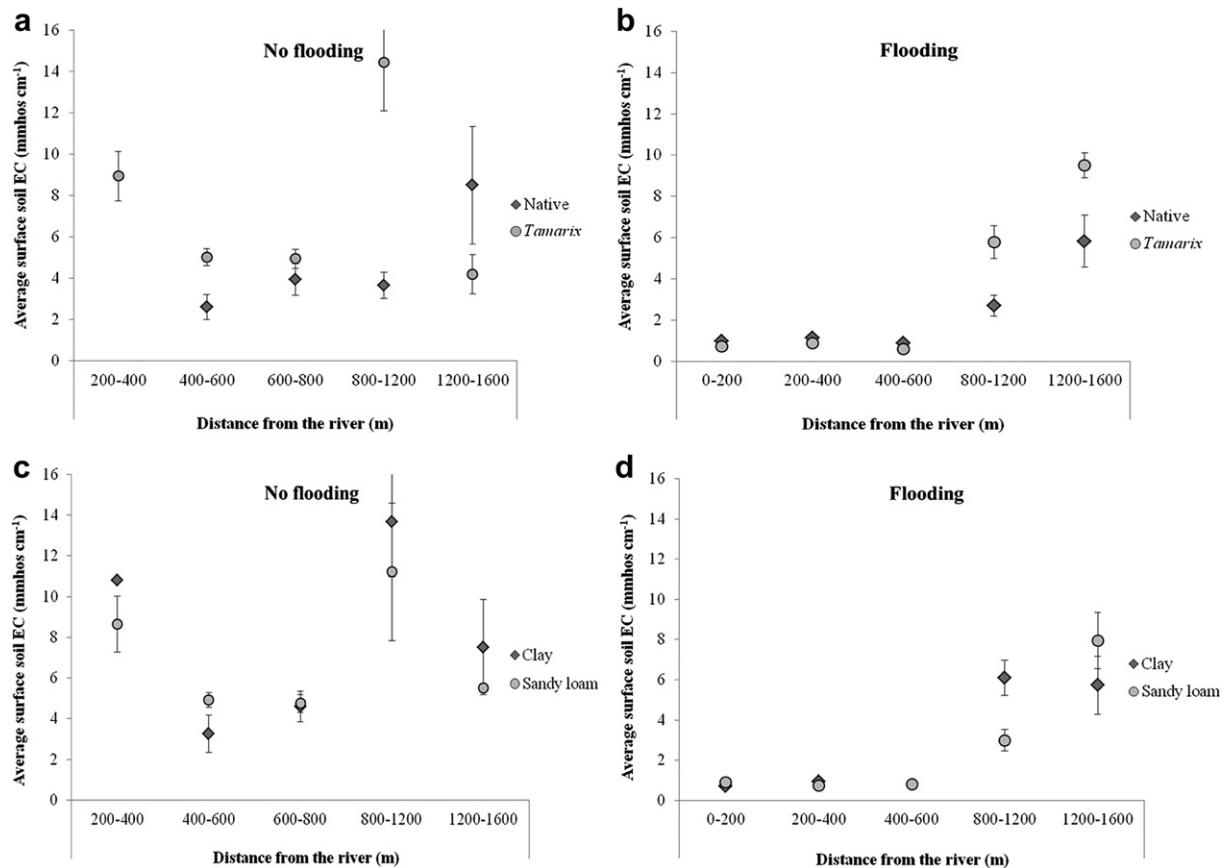


Fig. 4. Average surface soil (0–15 cm) EC with increasing distance from the Middle Rio Grande river channel for non-flooded and flooded soils collected under woody species (a and b; ANOVA, $N = 271$, F -ratio = 8.13, $P = 0.005$, mean ± 1 SE) and by soil texture (c and d; ANOVA, $N = 271$, F -ratio = 5.90, $P = 0.02$, mean ± 1 SE).

saline for native trees than *Tamarix*. These results shed light on previous discrepancies in the literature about the causal relationship of *Tamarix* and environmental salinity, and may indicate an effect of this invasive species on its abiotic environment.

It has been proposed that the high salinity tolerance of *Tamarix* may indicate that invasion is the effect of salinization rather than the cause (Stromberg et al., 2009). The differences in soil salinities between stands dominated by natives versus *Tamarix* in this study could certainly be explained in this way; *Tamarix* can grow better than native *Populus* spp. in soils already made saline by salt accumulations resulting from river regulation and surface evaporation. However, if *Tamarix* is merely an opportunistic “passenger” in this system and does not contribute to surface salinity, we would not expect to see any relationship between stand age and soil salinity, except perhaps a negative one that supports previous research showing *Tamarix* grows better with lower salinity (Cui et al., 2010;

He et al., 2011; Li et al., 2010). The observed low salt levels under smaller *Tamarix* trees relative to older individuals suggests that young plants are not inhibited by lower soil salinity and may preferentially establish in such conditions. However, our observation that surface soil salinity was highest underneath *Tamarix* vegetation with stems between 5 and 10 cm diameter (11 and 22 years of age) in the absence of flooding suggests a more causal role of *Tamarix* itself. Because vegetation cover and/or density typically change with age, we would also expect to see relationships between these variables and soil salinity. Perhaps relationships between surface soil salinity and woody cover and density were not observed in this study because other similar measures, e.g. leaf area index and canopy light penetration, may be better salinity predictors within the sampled area.

Prior to this study, it seemed plausible that older *Tamarix* stands would have the highest levels of salinity because the presence of older individuals suggests longer periods of salt redistribution to surface soils. Where flooding is not present to wash away salt deposits, it is expected that accumulation of exudates and senescent leaf fall over time would result in very high salt levels. At the sites studied in this research, the difference in surface EC by stem size was quite dramatic but the oldest trees had remarkably low levels of salts (6.7 vs. 9.2 mmhos cm^{-1} for middle-aged trees), especially considering the greater amount time for salt accumulation. The relatively low soil salinity associated with older *Tamarix* growth suggests that salts are being removed from surface soils by some mechanism and the rate of replenishment is lower than in younger stands. To better understand the relationship between *Tamarix* age and surface soil salinity, future research should examine stand attributes such as canopy structure, leaf area index,

Table 2

ANOVA model to explain variance in upper (0–15 cm; $N = 18$, $R^2 = 0.48$, F -ratio = 6.18, $P = 0.0068$) and lower (15–30 cm; $N = 18$, $R^2 = 0.54$, F -ratio = 7.62, $P = 0.0029$) surface soil EC relationships by groundwater depth sampled along the Middle Rio Grande in January 2008 during the highest recorded water levels. Log₁₀ transformation was used to normalize the distribution of the data.

Parameter	df	0 to 15 cm depth		15 to 30 cm depth	
		Sum of squares	F-ratio	Sum of squares	F-ratio
Groundwater depth	1	0.18	5.07 ^a	0.11	5.39 ^a
Flooding	1	0.14	4.00	0.03	1.30
Groundwater depth* flooding	1	0.08	2.08	0.11	5.31 ^a

Significance levels: ^a < 0.05.

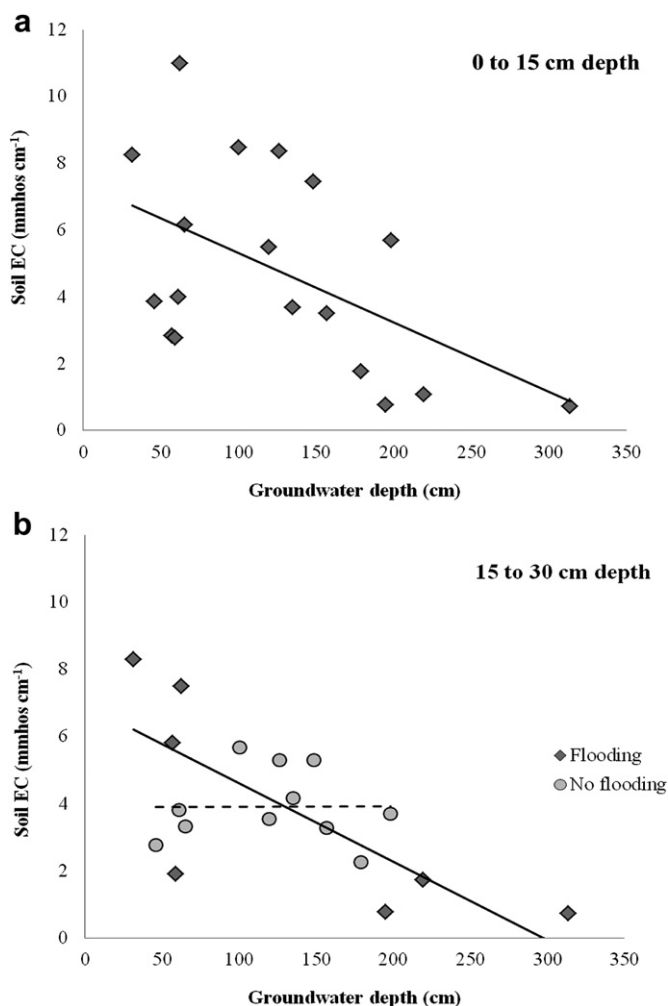


Fig. 5. Soil EC by groundwater depth for a) 0–15 cm soil depth (ANOVA, $N = 18$, F -ratio = 5.07, $P = 0.04$, mean ± 1 SE), and b) 15–30 cm soil depth by flooding status (ANOVA, $N = 18$, F -ratio = 5.31, $P = 0.04$, mean ± 1 SE). Data shows sites along the Middle Rio Grande that received groundwater measurements during the high water period in January 2008. Soil EC represents an average of four composite samples collected in July 2007 along the transect containing the groundwater well.

evapotranspiration, foliage salt concentrations, and microclimate conditions associated with different *Tamarix* ages.

Because both soil texture and *Tamarix* stem age were observed to relate to the level of surface salts, it is important to understand how alluvial textures may vary underneath canopies of different ages for flooded and non-flooded areas. Similar to findings by Stromberg (1998), older *Tamarix* individuals were associated with higher clay content in flooded areas for this study. Clay particles have greater surface areas to adsorb salts, yet more clay did not translate into higher salinity along the Middle Rio Grande; in fact older *Tamarix* vegetation inside the levees had the lowest salt levels. Older trees were often associated with coarser soils in non-flooded areas, which could reduce the salt adsorption capacity of surface soils in older stands.

Attention should also be given to location effects on surface soil salinity such as latitude and distance from the river and other factors that may interact strongly with these variables. Our results suggest that soil salinity increases with greater distance from the river but this relationship varied by species and soil texture and only occurred for sites exposed to flooding. In the active floodplain, soils closer to the river are expected to have lower salinity because they are more frequently flushed by surface water flows. On the

other hand, when flooding is suppressed, soil salinity can be highest for sites nearest (~ 200 m) to the active river channel (Glenn et al., 2012; Nagler et al., 2008). We also observed relatively high levels of soil salts closer to the river for non-flooded sites but the inclusion of artificial sites (e.g. restored native) with managed hydrology (e.g. flooded or non-flooded) makes interpretation of interactions with species and texture difficult.

Higher surface soil salinity in areas with shallow groundwater supports the importance of this variable for understanding surface soil salinity along this arid reach of the Middle Rio Grande. When groundwater is close to the soil surface, dissolved salts are more available for capillary transfer upward to surface soils, especially when evaporative demand is high. The correlation between high salinity and shallow groundwater in flooded sites suggests that this process occurs rapidly following flood flow removal of surface salts. Most of the shallowest groundwater levels (<65 cm depth) in January were observed in native stands containing trees with stems <5 cm diameter and managed with artificial flooding. Shallow groundwater combined with low vegetative cover associated with smaller woody natives could explain the higher soil salinity associated with these individuals relative to other vegetation stem size classes exposed to flooding. However, in addition to other artificial features of these areas, many of these sites were more than 1000 m from the active river channel. Therefore, salinity results for natives exposed to flooding appear to be confounded by groundwater depth and distance from the river; distances that would rarely occur naturally for newly established native cohorts.

This study is the first to perform a quantitative analysis that investigates the potential impact of invasive *Tamarix* on surface soil salinity in the context of environmental factors that can influence salinity. Clearly, soil salinity along the Middle Rio Grande is caused by a complex set of interactions between numerous variables. Results of this study are suggestive of a causal role of *Tamarix* in surface salt-loading because of the relationship between salinity and aboveground age. It appears likely that *Tamarix* stands between 11 and 22 years of aboveground age are contributing to surface salinity in this arid environment, whereas older individuals may actually facilitate lower soil salt levels. For these reasons, from a native plant community restoration standpoint on the Middle Rio Grande system, these lower salinity soils under the most mature stands may be better for establishment of replacement vegetation following *Tamarix* control and removal (particularly mechanically) in light of reduced salinity impacts on the native species palette. Although middle-aged *Tamarix* may significantly elevate surface soil salinity, this cover, from the salinity standpoint, may be better than no cover. Thus, land managers will need to weigh the costs of removing *Tamarix* in areas where flood-deprivation and surface evaporation may elevate surface salinity above the tolerance of any desirable replacement vegetation.

This study also provides a novel comparison of flooded and non-flooded *Tamarix* stands, and found that the presence of flooding can mitigate any observed influences of the exotic tree. However, given the prevalence of river regulation and associated reductions in overbank flooding, the potential role of *Tamarix* for elevating soil salinity cannot be disregarded.

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