Density and biomass of salt cedar (*Tamarix* spp.) along a northwest to southeast transect in Oklahoma

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Tamarisk (*Tamarix* spp.) is an invasive, riparian shrub found in much of the southwestern United States. The density and standing biomass of tamarisk were estimated along waterways in a northwest to southeast transect in Oklahoma to test the hypothesis that environmental conditions in northwest Oklahoma would make successful invasion by tamarisk more likely. Fourteen sites were sampled during spring and summer 2009. At each site a quadrat was marked and all tamarisk within were counted. The height and canopy area of each plant or clump of plants were measured to estimate standing biomass. Soil samples were collected and conductivity measurements were made to determine salinity of soils from each site. Climatological and streamflow data from monitoring stations closest to each sampling site were collected. Spearman rank analysis showed that density and biomass of tamarisk were significantly related to location, climatic variables, and streamflow but not to soil salinity. Principal components analysis showed that 69% of the variance in the data could be accounted for in one axis that included gradients of temperature and stream flow. These data suggest that the invasive potential of tamarisk in Oklahoma is likely limited by streamflow and climate but not by soil salinity.

INTRODUCTION

Tamarix species, collectively known as tamarisk or salt cedar, is a genus of invasive, riparian shrubs found in most of the continental United States. Many of the 12 putative species within the *Tamarix* genus found in the U.S. are morphologically and genetically indistinguishable, probably because of hybridization, but all are considered to be potentially invasive (Gaskin and Schaal 2003). Tamarisk was originally introduced in the U.S. to aid in the control of flooding and as an ornamental plant; however, it has naturalized in many areas and threatens native riparian plant species, particularly in the western U.S. (Brock 1994, Di Tomaso 1998).

The competitive success of tamarisk is thought to be related to several factors. It has a high tolerance for the alkaline and saline soils characteristic of the southwest U.S. and can actually increase local soil salinity via root uptake and concentration of salts in leaves, which are shed annually; this increase in soil salinity may inhibit growth of native species that are less tolerant of saline soils (Decker 1961, Glenn et al. 1998). In addition, tamarisk may be very deep rooted and can access soil water resources unavailable to other riparian plants (Brock 1994, Sala et al. 1996, Smith et al. 1998). The invasive potential of tamarisk is not as great in the eastern U.S. as it is in the west, presumably due to higher precipitation rates in the east (Zavaleta 2000), however, no comprehensive research has been conducted to determine why tamarisk has not been as invasive in the eastern United States.

Tamarisk's invasive success in the western U.S. is thought to be related to modification of riparian areas associated with disruption of flow regimes via damming and with agricultural practices (Sala and Smith 1996, Stromberg 2001, Shafroth et al. 2002). Initially it was believed that intolerance for low temperature was also an important factor affecting distribution of tamarisk (Brock 1994), but subsequent research has shown that these species also have invasive potential in cold regions of the country (Lesica and Miles 2001, Kerns et al. 2009, Landenburger et al. 2006).

Because of its central location in North America, Oklahoma provides an interesting system in which to study how environmental factors might influence the distribution of tamarisk. Oklahoma has the steepest precipitation gradient in the continental U.S., with mean annual precipitation of 1270 mm in the southeastern corner of the state compared to only 600 mm in the high plains of the Panhandle (Johnson and Duchon 1995). Average winter lows range from -7.3 C in the northwest to 0.5 C in the southeast. Eastern Oklahoma lies within the Interior Highlands of the Ozark and Ouachita uplifts and is dominated by oak-hickory forests. Western Oklahoma is dominated by relatively flat grassland/prairie with sandstone and gypsum hills (Johnson and Duchon 1995).

Herbarium samples collected in Oklahoma indicate that since 1910, tamarisk species have been found throughout the state with the exception of the southeastern corner (Crawford and Hoagland 2009). Morisette et al. (2006) predicted that only 0.07% of land area in Oklahoma is highly suitable for tamarisk invasions, but that 14.8% of land area in the state is moderately suitable. Those predictions were based on regression models that used presence or absence of tamarisk at numerous sites and remotely sensed environmental data. In addition, all of the major waterways in Oklahoma are dammed and irrigation of crops is common in western Oklahoma, which might increase soil salinity there (Ali et al. 2000). Because of the climatic gradients and water management strategies that exist in Oklahoma, investigation of the occurrence and abundance of tamarisk there, as well as elucidating the factors that influence its distribution in Oklahoma, is of interest.

The objective of this study was to evaluate the occurrence, density, and standing biomass of tamarisk along waterways in a northwest to southeast transect in Oklahoma. Our hypothesis was that the density and standing biomass of tamarisk would be greater in the northwest than in the southeast, primarily due to the precipitation gradient that exists in Oklahoma. Data were collected for climatic conditions, stream flow of waterways, and soil salinity along a northwest to southeast transect in Oklahoma to see if those factors were related to presence and abundance of tamarisk.

METHODS

Fourteen sites were sampled 14 sites along the North and South Canadian Rivers, the Cimarron River, and their tributaries during spring and summer 2009. Sites were chosen along a NW (36.711 N, -99.233 W) to SE (35.389 N, -96.862 W) transect in Oklahoma based primarily on accessibility. Initial efforts to visit sites where tamarisk had previously been documented in the Oklahoma Vascular Plants Database were unsuccessful because of land use change and private property issues. Sites used by the Oklahoma Water Resources Board for surface water sampling and of broad enough geographic range to reflect the temperature and precipitation gradients that exist between western and central Oklahoma where tamarisk had previously been reported were selected. All sampled sites were accessible from roads that crossed waterways. Coordinates of sampled sites were recorded using an e-trex Vista® Cx GPS unit (Garmin Ltd., Olathe, Kansas). At each site, we measured a quadrat adjacent and parallel to the waterway and marked its limits using small flags. Quadrat size at most sites was limited by fences demarcating private property lines, but no quadrat was smaller than 150 m^2 and most were larger than 400 m^2. The southeastern limit of our sampling transect was based on absence of tamarisk at three consecutive sites.

The number of tamarisk present in each quadrat was counted. The height of every tamarisk less than 2 m tall within each quadrat was measured using a tape measure. Height of tamarisk over 2 m tall was measured using a clinometer. Canopy area of each plant was calculated assuming a circular canopy using the formula: $A = \pi r^2$, where A was the canopy area and r was half the average of the north-south and east-west canopy diameters measured using a measuring tape. For clumped plants, canopy area was estimated as percent cover of a measured rectangle encompassing all of the plants. Aboveground biomass of tamarisks at each site was estimated using an allometric relationship developed by Evangelista et al. (2007). We used the formula:

$$\mathrm{Log}_{10}(\mathrm{TAGB}) = c + \alpha \log_{10}(\mathrm{CA}) + \beta \mathrm{Ht} + \gamma \mathrm{Ht}^2$$

where TAGB is total above ground biomass, CA is canopy area, and Ht is plant height. Coefficient values (c, α, β, and γ) were obtained from the model developed by Evangelista et al. (2007) which produced the highest adjusted r^2 value (0.966). Biomass of individual plants was calculated and summed biomass of all plants for each quadrat was determined. Biomass of clumps of plants was estimated using the same allometric formula with average plant height and total clump canopy area (Evangelista et al. 2007). Density of tamarisk was calculated as number of plants in a plot x 10,000 m^2 (1 ha) divided by the plot area in m^2. Biomass of tamarisk per ha was calculated as total biomass of all plants in a plot x 10,000 m^2 divided by the plot area in m^2.

At each site where tamarisk was present, three soil samples were collected to a depth of approximately 10 cm using a soil corer. For sites with tamarisk present, one sample was collected at the base of the largest tamarisk present, one at the base of another large woody plant species, and one in an area at least 2 m from any woody plants. If no tamarisk was present, only two soil samples were collected as described above. Soil samples were analyzed to determine salinity by measuring electrical conductivity of solutions extracted from the soil samples (Rowell 1994). To prepare extracts, soils were air dried and passed through a 2 mm sieve to remove gravel and large particles of organic matter. A suspension (1:5, soil:water, mass: mass) was prepared and 1 drop of tetrasodium pyrophosphate was added as a dispersing agent. The suspensions were passed through coarse and then fine filter paper until a clear solution was obtained for measurement of conductivity. Electrical conductivity of solutions was measured using an HI 9033 multi-range conductivity meter (Hanna Instruments, Woonsocket, Rhode Island).

Climate data for each sampling site were obtained from the closest Oklahoma Mesonet sampling station. Data obtained included average winter low temperature during January, average summer high temperature during July, and average annual precipitation. Annual streamflow data were obtained from the closest USGS monitoring station upstream of each site and average annual stream flow was calculated based on the past 10 years worth of streamflow data.

To obtain a single value for each site location, UTM data were transformed in the following manner: for northings, the minimum value minus one was subtracted from all values; for eastings, the minimum value minus one was subtracted from all values and then the inverse was taken to reflect the relative location west. Finally, transformed northings and eastings were multiplied to obtain a single value such that the northwestern-most site had the highest value and the southeastern-most site had the lowest value.

Data for calculated standing biomass per ha, density per ha, and location were log transformed to better fit the assumptions of correlation models (Gotelli and Ellison 2004). An analysis of variance using type IV sums of squares to was performed determine if soil salinity varied between samples collected at the base of tamarisk relative to those collected from other locations. Spearman rank correlation analyses were used to determine which factors, including location, average low and high temperatures, precipitation, average annual streamflow, and mean soil salinity were most closely correlated to density and estimated standing biomass of tamarisk per ha. A principal components analysis was also performed to determine to what degree climate characteristics, streamflow, and soil characteristics might be correlated to location and to each other.

RESULTS

Density and estimated standing biomass of tamarisk were highest in the northwestern part of the state and lowest at the southeastern sites (Fig. 1). The site with the highest density had 510 plants/ha and also had the largest plants and highest estimated standing biomass of 20,305 kg/ha (Fig. 2). The southeastern-most sites had no tamarisk present. Density of tamarisk was positively correlated to location and to average summer high temperature and negatively correlated to average annual streamflow, average annual precipitation, and average winter low temperature (Table 1). Estimated standing biomass of tamarisk was positively correlated to location and average summer high temperature and negatively correlated to average annual streamflow and average winter low temperature (Table 1). The relationship between estimated standing

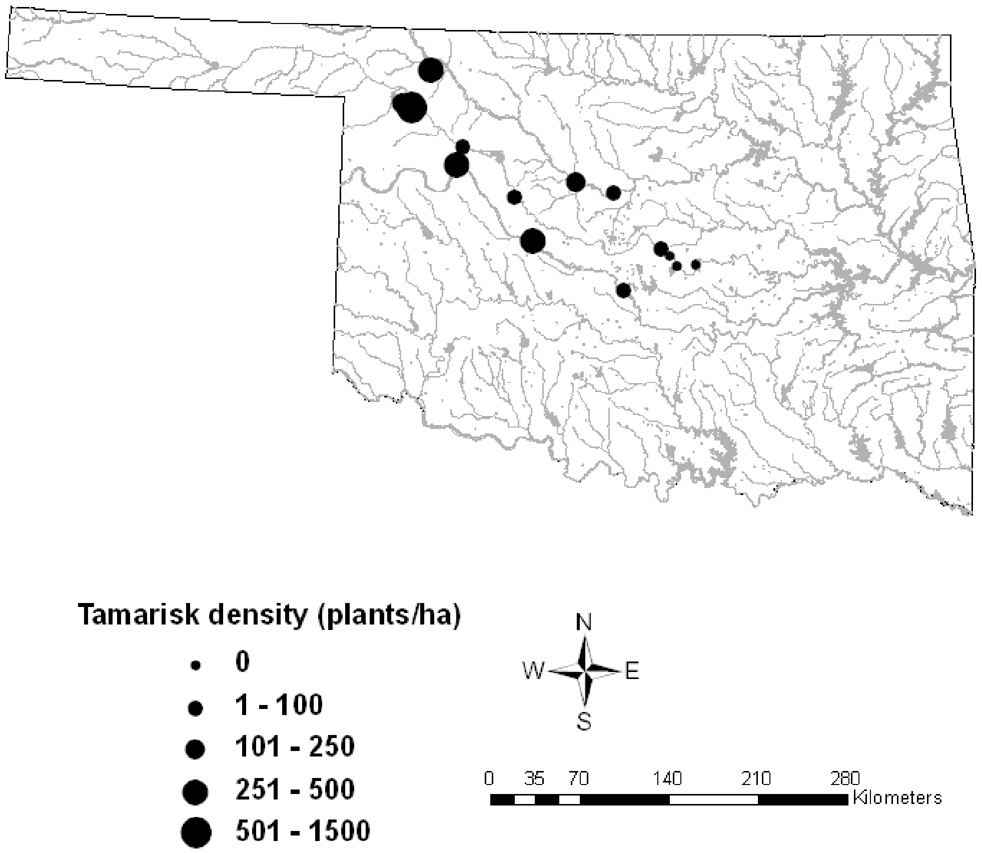

Figure 1. Density of salt cedar (number of plants per hectare) at 14 sites along waterways in Oklahoma. Values are calculated density based on the number of plants present in quadrats ranging in size from 152 m^2 to 416 m^2.

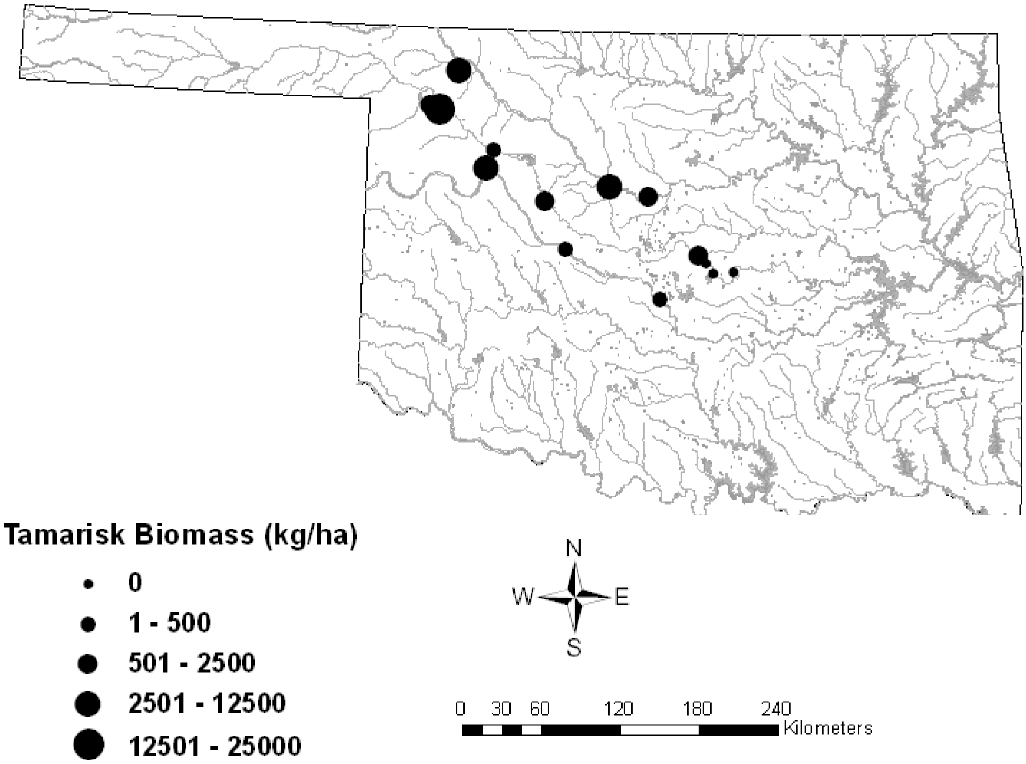

Figure 2. Estimated standing biomass of salt cedar (kilograms per hectare) at 14 sites along waterways in Oklahoma. Standing biomass was calculated using allometric relationships established by Evangelista, et al. (2007) based on canopy area and plant height. Biomass per hectare was calculated based on biomass of plants present in quadrats ranging in size from 152 m^2 to 416 m^2.

biomass and precipitation was not statistically significant (Table 1). Neither density nor estimated standing biomass of tamarisk was significantly correlated to average soil conductivity (Table 1). Streamflow and most climatic variables were correlated to location, but soil conductivity was not (Table 2). Factor analysis conducted on the 5 significant independent variables indicated two significant axes; one included winter low and summer high temperatures and streamflow and accounted for 69% of the variance in the correlation matrix; the other included location and precipitation and accounted for 21% of the variance in the correlation matrix (Table 3). Analysis of variance showed no significant difference in soil conductivity between samples collected at the base of tamarisk and those collected at other locations (p = 0.94, data not shown).

DISCUSSION

As hypothesized, there was more tamarisk present at sites in the northwest part of the state than at sites in the central part of the state. The factor with the highest Spearman rank correlation for both density and estimated standing biomass of tamarisk was location. Location was highly negatively correlated to streamflow and precipitation, and positively correlated to winter low temperature.

Low precipitation might be a very important factor influencing tamarisk's success as an invasive species for several reasons. Low flow regimes in riparian areas have been shown to facilitate establishment of tamarisk (Stromberg 2007), and flow regimes are usually closely related to precipitation in undammed waterways. In

Table 1. Spearman rank correlation coefficients (rho) and p values for the dependence of density and standing biomass of salt cedar (*Tamarix* spp.) on location, average annual streamflow, precipitation, average summer high and average winter low temperatures, and soil conductivity at sites along a northwest to southeast transect in Oklahoma.

Density of Salt Cedar (plants/ha)		
Independent Variable	rho	p value
Location	0.815	0.003
Streamflow	-0.763	0.006
Precipitation	-0.587	0.034
Summer High Temperature	0.649	0.019
Winter Low Temperature	-0.799	0.004
Soil Conductivity	0.385	0.166
Biomass of Salt Cedar (kg/ha)		
Independent Variable	rho	p value
Location	0.802	0.004
Streamflow	-0.769	0.005
Precipitation	-0.529	0.057
Summer High Temperature	0.604	0.029
Winter Low Temperature	-0.697	0.012
Soil Conductivity	0.125	0.452

Table 2. Spearman rank correlation coefficients (rho) and p values for the relationships between average annual streamflow, precipitation, average summer high and average winter low temperatures, and soil conductivity to location for sites along a northwest to southeast transect in Oklahoma.

Location		
Variable	rho	p value
Streamflow	-0.952	0.001
Precipitation	-0.788	0.005
Summer High Temperature	0.662	0.017
Winter Low Temperature	-0.901	0.001
Soil Conductivity	0.516	0.063

addition, regions with higher precipitation tend to have a greater abundance and diversity of vegetation which might be superior competitors for non-water resources under more mesic conditions. Tamarisk has been most successful as an invasive in the desert southwest and in semi-arid regions east of the Rocky Mountains.

Winter low temperatures are not likely a major factor influencing successful invasion by tamarisk because while tamarisk has successfully colonized riparian rivers in cold climates of the northwestern United States, the most suitable habitat for tamarisk invasion is in the southwestern United States (Morisette et al. 2006) where winter low temperatures are not extreme. At the northern margin of tamarisk's naturalized range, the plant is of small stature and is unable to successfully out-compete native vegetation of those regions (Lesica and Miles 2001). Summer highs in Oklahoma also

Table 3. Principal Component Analysis for relatedness of significant factors influencing density and standing biomass of salt cedar in Oklahoma, including location, average annual streamflow, precipitation, average summer high and average winter low temperatures. The eigenvalues and per cent of total variance associated with each component is shown at the top, and the component matrix using a varimax rotation and Kaiser normalization is shown below.

Explanation of Variance

Component	Eigenvalue	% of Variance
1	3.434	68.7
2	1.033	20.7
3	0.328	6.6
4	0.121	2.4
5	0.083	1.6

Component Matrix

	Component 1	Component 2
Location	-0.324	-0.837
Streamflow	0.771	0.563
Precipitation	0.091	0.922
Summer High	-0.978	-0.005
Winter Low	0.845	0.470

do not likely play a big role in tamarisk's success, since it has become established in regions with much hotter summers, such as Phoneix, Arizona (Stromberg 2001) as well as in regions with much cooler summers, such as southeast Montana (Lesica and Miles 2001).

Stromberg et al. (2007) found that human alteration of flow regimes via damming was a key driver which shifts riparian plant communities from native to introduced, invasive species such as tamarisk. Stream flow is tied to precipitation regimes, snow melt, and damming (Poff et al.1997). The Canadian River has its source in the Sangre de Cristo Mountains of northeastern New Mexico; the Cimarron is a tributary of the Canadian and also arises in northeastern New Mexico. Both rivers are dammed at multiple sites in New Mexico and Oklahoma. The site at which we found the highest density and standing biomass of tamarisk was on the North Canadian River approximately 20 km downstream from the Fort Supply dam, the closest of any sampling sites to a major dam. Other sites with high density and standing biomass were either on small tributaries of the major rivers sampled or in areas where tributaries that feed into those rivers, the Canadian and Cimarron, were dammed. Study sites where tamarisk was absent or present in low density and standing biomass were more distant from upstream reservoirs and associated with the highest mean annual streamflow rates. In addition, sites where tamarisk was absent were downstream of the Oklahoma City metropolitan area. Extensive cover by anthropogenic surfaces might be expected to increase runoff into surface waterways and thereby increase streamflow at those sites.

Land use change and management of riparian areas associated with urbanization has likely also influenced the presence of tamarisk near Oklahoma City. A survey of the South Canadian River conducted during the 1930's showed that tamarisk covered up to 57% of the floodplain there (Hefley 1937). While we were unable to survey the sites evaluated during that study due to land use change, no tamarisk were present in nearby sites that we were able to view from roadways.

Another factor associated with site location that might influence the relative abundance of tamarisk is the proximity of the northwestern sites to source populations for tamarisk seeds. Individual tamarisk shrubs may produce up to a million seeds which are readily dispersed by water and wind (Brock 1994). Along the Canadian River in New Mexico, tamarisk has actively invaded the riparian zones in the Cibola National Forest, replacing native plants and wildlife there (Environmental Protection Agency 2005). In southwestern Kansas, tamarisk has been a major invader of riparian corridors along the Cimarron River (VanLooy and Martin 2005).

In addition, tamarisk is a poor competitor in shady microhabitats (Dewine and Cooper 2008, Anderson 1982). Our sites in northwestern Oklahoma were in tallgrass prairie and sandsage grassland type associations; those further southeast were in the crosstimbers region, which is predominantly a post oak and blackjack oak association. Greater canopy cover by native tree species in central and eastern Oklahoma might limit successful colonization by tamarisk in riparian areas there.

Invasion of riparian areas by tamarisk is likely limited to northwestern regions of Oklahoma, probably due to several interacting factors related to location. Our data suggest that diminished flow regimes there relative to central and southeastern Oklahoma are an important determinant. We found no relationship between soil salinity and presence or abundance of tamarisk, suggesting that its invasive potential is not related to its tolerance for saline soils. Further research is needed to determine whether proximity to source populations and light limitation might also limit tamarisk invasion in central and eastern Oklahoma.

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