RELATIONSHIP OF SALINITY AND DEPTH TO THE WATER TABLE ON

Tamarix spp. (SALTCEDAR) GROWTH AND WATER USE

A Thesis

by

KURTISS MICHAEL SCHMIDT

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2003

Major Subject: Rangeland Ecology and Management

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Approved as to style and content by:

Larry D. White (Chair of Committee)	James R. Kiniry (Member)
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ABSTRACT

Relationship of Salinity and Depth to the Water Table on *Tamarix spp.* (saltcedar) Growth and Water Use

(December 2003)

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Saltcedar is an invasive shrub that has moved into western United States riparian areas and is continuing to spread. Saltcedar is a phreatophyte that can utilize a saturated water table for moisture once established and is also highly tolerant of saline soil and water conditions. Literature has indicated that depth to the water table and salinity has a significant effect on growth and water use by saltcedar. Several studies were initiated to help develop a simulation model of saltcedar growth and water use based on the EPIC9200 simulation model. A study was initiated at the USDA-ARS Blackland Research Center Temple, Texas in the summer of 2002 to better understand the effects of water table depth and salinity on (1) saltcedar above and below ground biomass, root distribution, leaf area and (2) water use. Five different salinity levels (ranging from 0 ppm to 7500 ppm) and three different water table depths (0.5m, 1.0m, and 1.75m) were studied.

Results indicated that increasing depth to the water table decreased saltcedar water use and growth. For the 0.5m water table depth, saltcedar water use during the 2002 growing season averaged 92.7 ml d^{-1} while the 1.75m depth averaged 56.6 ml d^{-1}. Both root and shoot growth were depressed by increasing water table depth. Salinity had no effect on saltcedar growth or water use except, at the 1250 ppm level, which used 110 ml of H_2O d^{-1}. This salinity had the highest water use indicating that this may be near the ecological optimum level of salinity for saltcedar. A predictive equation was developed for saltcedar water use using climatic data for that day, the previous days climatic data, water table depth and salinity that included: previous day total amount of solar radiation, water table depth, previous day average wind speed, salinity, previous day total precipitation, previous day average vapor pressure, minimum relative humidity, previous day average wind direction, and maximum air temperature. Data from the field study and a potential growth study were integrated into the model. The model was parameterized for the Pecos River near Mentone, Texas. Predicted saltcedar water use was slightly lower than results reported by White et al. 2003.

DEDICATION

This thesis is dedicated to all my friends and family. Without their love, patience, and help, I would not have ever completed this research.

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First, I would like to thank Dr. Larry D. White for his help and guidance with this project. Without his advice, ideas, encouragement, and help I would have not completed this project.

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A special thanks to Tracy Gwaltney for reminding me about the details since I rarely worried about them and to Theresa Swihart for listening to my complaints and letting me vent.

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INTRODUCTION

Saltcedar (*Tamarix spp.*) was introduced to the United States from Asia and southeastern Europe. It was first introduced into the US around the 1870's as an ornamental (Tesky 1992). Later widespread planting to control stream bank erosion accelerated its establishment throughout the United States. There are thought to be approximately 54 species of *Tamarix spp.* in the world (DeLoach and Lewis 2000). Of these, ten have been introduced into the U.S. Out of these ten, three are widespread with *T. ramosissima* and *T. parviflora* being major problem species while *T. aphyllla* is not considered a problem species.

Saltcedar is an aggressive and invasive phreatophyte that can tolerate a wide range of environmental conditions, producing large amounts of seed, propagating vegetatively and withstanding high salinity. Saltcedar has been blamed for displacement of native plant species, decreased wildlife habitat values, increased salinity of surface soil, and excessive groundwater consumption (Carpenter 2000). Saltcedar has some positive benefits such as habitat for nesting birds, ornamental and shade trees, windbreaks, erosion stabilization, and for production of honey.

Saltcedar has a competitive advantage over many native plant species through several mechanisms. DeLoach et al. (1997) identified nine factors that gives saltcedar its competitive advantage: 1. Altered hydrologic cycle and flood levels: Shifting from natural hydrologic cycles to ones induced by man through the building of dams and reservoirs has shifted the competitive advantage from native species such as cottonwood and willow to saltcedar. 2. Salinity: In areas with low rainfall or where

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This thesis is written to conform to the style of the Journal of Range Management.

annual floods have been eliminated, saltcedar can raise the levels of salt in and on the soil due to the exudates and high concentrations of salt in the leaves that fall to the soil surface following leaf drop. This gives it a competitive advantage since the salt is not leached and saltcedar can withstand higher levels of soil salinity than many native species. 3. Fire: saltcedar is not killed by fire and quickly re-sprouts, unlike native species such as cottonwood. 4. Drought and low water tables: Saltcedar plants are thought to be more tolerant of low moisture levels and declining water table rates than many native species. This gives saltcedar an advantage during drought and falling water tables. 5. Palatability to grazers: Saltcedar is not very palatable, unlike saplings of native cottonwood and willow. This decreases native plant recruitment and puts natives at a disadvantage. 6. Inundation: Saltcedar survives inundation longer during flooding than most native species. 7. Transpiration:

> Saltcedar has a specialized physiology that causes stomatal closure and results in transpiration rates considerably below potential during the hottest part of the day. This enables saltcedar to minimize transpirational losses relative to carbon gains by being more metabolically active in late morning rather than during the hottest part of the afternoon, as do most other plant species

8. Conventional controls: Most conventional control methods kill native vegetation easier than saltcedar. After controls are applied, saltcedar resprouts while many native species are killed. 9. Lack of natural controls: In its native range in Europe and Asia, saltcedar has over 300 natural enemies. As an exotic plant in North America, it lacks significant natural enemies while native species such as cottonwood and willow have over 100 species of insects preying on them. Lack of natural insects gives saltcedar a competitive advantage. These factors are especially important to saltcedar competing along rivers where the hydrology has been changed.

OBJECTIVES

Several studies were initiated to develop and evaluate a growth and water use model of saltcedar. The specific objectives of each study are listed below:

Characterization of Naturally Established Stands

1. Determine if there are significant correlations between age of plant, leaf area index, and light extinction coefficient.
2. Determine if there are significant differences between collection sites.

Characterization of Artificially Established Stands

1. Determine potential leaf area index and light extinction coefficients for *Tamarix ramosissima* from CA, *Tamarix spp.* from Seymour, Texas, *Salix nigra*, and *Populus deltoids* from Temple, TX.
2. Determine if there are significant differences in leaf area index and light extinction coefficients between species of trees.

Model Development and Testing

1. Advise on the development of a water use and growth model for saltcedar.
2. Evaluate the model using data from literature, depth and salinity study, and ongoing water use studies on the Pecos, Colorado and Canadian rivers in Texas.

Depth and Salinity

1. Determine effects of salinity and water table depth on saltcedar water use and growth.
2. Develop a multiple linear regression predictive equation for water use.

LITERATURE REVIEW

Saltcedar (*Tamarix spp.*)

Saltcedar (*Tamarix spp.*) was introduced into the United States from Asia and southeastern Europe. It was first introduced around the 1870's as an ornamental, but since then was used for stream bank stabilization and has established itself throughout the southwestern United States and Mexico (Tesky 1992). Approximately 54 species of saltcedar are believed to exist in the world (DeLoach and Lewis 2000). Of these, ten have been introduced into the U.S. Out of these ten, three are widespread with *T. ramosissima* and *T. parviflora* being major problem species while *T. aphyllla* is not considered a problem.

Salinity Effects on *Tamarix spp.*

As a soil becomes progressively more saline it becomes more difficult for a plant to extract water from the soil/water profile. This is caused by lower osmotic potential that increases the solution entropy and forms associations between water molecules and the solute. This creates water stress in plants as solute content of the soil/groundwater increases and the ability of the roots to take up water decreases (Lambers et al. 1998). In order to survive in high saline environments, tolerant plants have several mechanisms including exclusion, storage and excretion.

Plants can exclude salt from uptake through passive and active mechanisms. Passive exclusion occurs through having high amounts of phospholipids in their membranes, which restricts movement of chloride to the shoot while allowing uptake of other ions (Lambers et al. 1998). A benefit of active uptake of salts would be lowering the water potential of a plant. This would give the plant the ability to take up more water as the water potential of the soil/groundwater decreases.

Salt tolerance and effects of increasing salinity are difficult to quantify because they vary considerably with both environmental and plant factors (Kozlowski 1997). Environmental factors could include soil fertility, soil physical conditions, distribution of the salt in the soil profile, and climate. Plant factors that could influence a plant's reaction to salinity include stage of growth, variety, and individual plant genetics.

Saltcedar excretes salt by use of salt hairs (trichomes) or through the use of salt glands (Lambers et al. 1998). Plants may employ this strategy when compartmentalization of salt no longer becomes possible. This may occur when the plant can no longer adequately store salts because of simple lack of space. Use of salt hairs and glands are active processes and require energy, which reduces growth. Saltcedar can exhibit both of these mechanisms and excrete salt so effectively that they can acquire masses of salt on their leaves that are easily observed by the naked eye. Excretion rates of NaCl are positively correlated with increasing concentrations of NaCl (Hagemeyer and Waisel 1988). Excretion rates of Ca^{2+} are negatively correlated with increasing levels of NaCl while excretion rates of K and Mg are not significantly affected.

Around Utah Lake in Utah, saltcedar occurs on sites with soil salinities ranging from 700 to 15,000 ppm (Carman and Brotherson 1982). Russian olive (*Elaeagnus angustifolia*), another invasive phreatophyte, occurs on sites with lower salinities ranging from 700 to 3,500 ppm. There is some evidence that significant decreases in growth of saltcedar does not occur until salinity levels reach 36,000 ppm while native

Populus fremontii and *Salix gooddingii* cannot tolerate levels over 1,500 ppm (Jackson et al. 1990). Saltcedar is so tolerant of salinity that Tomar et al. (2003) ranked it as the number one genus when evaluated on the basis of survival, growth, and biomass yield in order of performance and persistence under saline conditions when compared to 31 other tree species under irrigation. Foliar elemental analysis gives support for classification of saltcedar as a halophyte when concentrations of elemental concentrations were compared to native *Populus spp.* and *Salix spp.* on the Bill Williams and Colorado rivers in Nevada (Busch et al. 1995).

Increasing levels of salinity decrease seedling germination, shoot growth, and below ground growth of saltcedar (Tomanek and Ziegler 1962). Growth rates decrease with increasing salinity levels (Kleinkopf and Wallace 1974, Jackson et al. 1990, Glen et al. 1998). This decreased growth is due to energy cost associated with salt pumping, increased respiration (Kleinkopf and Wallace 1974) and decreased photosynthetic rates (Jackson et al. 1990). *Tamarix jordansis* has been reported to contain proline analogues that can ameliorate the effects of increased NaCl levels on rubisco activity (Solomon et al. 1994).

A couple of studies reported different findings. Stevens (1989) found a significant increase in relative growth rates when seedlings of saltcedar where watered daily in pots with a NaCl solution ranging in strength from 0 to 5,844 ppm. He found no shift in root to total biomass ratios across salinities. Shafroth et al. (1995) found no significant effects of increasing salinity on aboveground or belowground growth of saltcedar in salinities up to five times the concentrations of major ions in the Rio Grande at San Marcial, NM.

It has been reported in numerous studies that saltcedar water use is affected by increasing salinity levels. As salinity levels increase transpiration decreases (Van Hylckama 1963, Hagemeyer and Waisel 1987, Hagemeyer and Waisel 1989, and Vandersale 2001).

Water Table Depth Effects on Saltcedar

Since saltcedar is considered a phreatophyte, under natural conditions it gets most of its water from the water table. However, it has been shown that saltcedar is able to utilize shallow soil moisture (Mounsif et al. 2002) when present. Robinson (1958) described how water table depth affected growth and decreased evapotranspiration (ET) of saltcedar. As water table depth increases saltcedar must send its roots down farther to reach the capillary fringe where its fine root mass normally resides. Thus, water use decreases with increasing water table depth.

Water tables can fluctuate considerably due to seasonal and annual changes in inflows as well as fluvial processes (Shafroth et. al. 2000) and transpiration by riparian vegetation. Plant roots tend to accumulate near the surface of the water table and can be flooded or stranded by rapid fluctuations. A water table decline of 1.1 m from the previous year level of 0.9 m resulted in 92-100% mortality of *Populus* and *Salix* saplings, whereas, only 0-13% of saltcedar stems died. According to Shafroth et al. (2000) riparian plant survival depends on the:

> magnitude of groundwater decline relative to the pre-decline distribution of roots, rate of decline, duration of decline, ability of the plant to grow new roots to adjust water demand (e.g., via physiological and morphological adaptations), plant age and size, transpirational demand, and importance of other sources of

> water (e.g., precipitation) to the overall plant water supply…………Plant response is likely mediated by other factors such as soil texture and stratigraphy, availability of precipitation-derived soil moisture, physiological and morphological adaptations to water stress, and tree age.

Gary (1963) found that saltcedar roots adapt to favorable soil moisture conditions. In areas were the water table was deep, saltcedar produced long taproots and the branch roots were vertical in nature. The branch roots occupied the areas immediately above the groundwater table and were in the capillary fringe. He also found that when the water table was high, saltcedar developed a taproot and secondary roots that occupied all zones of the soil profile above the water table. Saltcedar roots have been observed at depths as great as 30m (Robinson 1958).

Stromberg (1998) reported a positive linear correlation between stand age and depth to the groundwater. This indicates groundwater decline may have been caused by the saltcedar and that it is capable of following the declining water table. Busch et al. (1992) found that saltcedar not only gets water from the water table, but also is capable of getting it from unsaturated alluvial soils. This evidently gives saltcedar a competitive advantage over native phreatophytes that are not able to survive when water levels are low or non-existent. Horton and Clark (2001) conducted a greenhouse experiment on seedlings in which water table decline altered growth and survival of saltcedar and *Salix* seedlings. *Salix* seedling survival and growth was greatest with no decline and survival and growth decreased as decline rates increased to 4.0 cm d^{-1}. Saltcedar seedling survival and growth was greatest with no decline and 1.0 cm^{-1} day decline levels and had consistently higher survival and growth when compared to *Salix spp.*

across all treatment levels. Root elongation rates were greatest for saltcedar at the water table decline rate of 1 cm/day. Busch et al. (1992) used isotopes to investigate the source of water for woody phreatophytes on the Bill Williams and lower Colorado Rivers in Arizona. Saltcedar used groundwater and non-saturated alluvial soils. This suggests that saltcedar is a facultative phreatophyte that uses water when it is freely available but "can do just fine" when a constant water supply is not available.

The distance from the water source and depth to the water table directly affects water use. Devitt et al. (1997a,b) found that sap flow decreased in saltcedar as the water table and soil water declined (lysimeters placed at desert edge, river edge and open stand). They found that "daily sap flow totals on a leaf area basis were higher for the plants growing along the river's edge, with midday hourly values significantly higher when a water table was present." This study also had a dry down phase that showed sap flow decreased in the river's edge and open stand lysimeters as the water table dropped. In large stands there can be considerable differences in water use by individual plants across the riparian zone due to water availability and competition. Horton et al (2001b,c) found there was a negative relationship between water table depth and shoot water potential, stomatal conductance, and photosynthetic rate.

Saltcedar uses less water as water table depth increases (Gatewood et al 1950, Van Hylckama 1970, Dahm et al 2002). Saltcedar grown in evapotranspirometers, in a dense thicket in Arizona, used 2.26 m yr^{-1} with a depth to the water table of 1.5 m and 0.87 m yr^{-1} with a depth to the water table of 2.70 m (van Hylckama 1970) (Table 1). He concluded that given a lower water table, saltcedar may thrive but uses considerably less water.

Table 1. Water use by saltcedar decreased as depth to the water table increased. Modified from van Hylckama (1970).

Depth to Groundwater	Water Use $m\ yr^{-1}$ 1961	Water Use $m\ yr^{-1}$ 1962	Water Use $m\ yr^{-1}$ 1963	Average $m\ yr^{-1}$ (STD)
1.50 m	1.99	2.18	2.26	2.14(0.139)
2.10 m	1.41	1.37	1.59	1.46(0.117)
2.70 m	1.05	0.94	0.87	0.95(0.091)

Though several studies have indicated that water table has an effect on water use, several studies showed no significant effect: Wilkinson (1972) found no significant differences in relative water contents of one tree with a water table 0.9 m deep versus trees with a water table of 3.1 m or more in lysimeters. He concluded that water table depth was not a major contributive factor in the water supplies of these trees. Weeks et al. (1987) found no correlation between water use and depth to the water table when they used eddy covariance and energy budget methods. Plant densities and ages varied substantially at all their sites and could have masked any effect water table depth might have. Horton et al. (2001a) reported that shoot water potentials, leaf gas exchange rates, and canopy dieback were significantly related to water table depth for native species, but not *Tamarix chinensis.* This indicated that saltcedar is much more drought tolerant than native species.

Transpiration and Evapotranspiration

Most estimates of saltcedar water use are estimates of evapotranspiration and not transpiration. Estimates of evapotranspiration from saltcedar stands range from as high as 421 cm yr^{-1} on the Canadian river in Texas to as little as 32 cm yr^{-1} on the Colorado River (White et al 2003). This illustrates that ET is very site specific due to differences in water table depth, salinity, and hydraulic conductivity of the water table, soil and solution. Transpiration by saltcedar has been estimated as low as 40 cm yr^{-1} to as high as 285 cm yr^{-1} at Benardo, NM (Davenport et al 1982). See appendix B for summary of reported ET and transpiration values for saltcedar. Variation in estimates of ET can be due to not only the previously mentioned factors of water table depth and salinity, but also due to vegetation/stand characteristics, atmospheric conditions and method used to calculate water use (White et al 2003).

Saltcedar transpires in a diurnal rhythm usually peaking around noon (Gay and Sammis 1977). Hagemeyer and Waisel (1987) found under continuous light in laboratory conditions saltcedar exhibits an endogenous circadian rhythm (24 hour cycle). This indicates that while environmental factors may influence transpiration, saltcedar does have an internal "clock" regulating transpiration. Williams and Anderson (1977) showed saltcedar to transpire at high rates until noon and then began a gradual decrease that continued through out the afternoon. It was also shown that, the relative water content (RWC) and water potential decreased sharply from sunup to 09:00 and then remained constant or increased throughout the afternoon. When twigs were held at constant temperature and relative humidity, a depression in transpiration occurred in the afternoon, suggesting that saltcedar is controlled by a diurnal rhythm. Smith (1989) found maximum water potential occurred at dawn for saltcedar and the minimum water potential at noon. Peak stomatal conductance occurred around 10:00 and decreased throughout the day when relative humidity was 22% and maximum air temperature was 26 C in April. By May peak stomatal conductance occurred at dawn and continued to decrease throughout the day with a relative humidity of 8% and maximum air temperature of 32 C. Transpiration in April peaked around noon and taper off as the day progressed while in May transpiration peaked at 10:00. Mounsif et al. (2002) found peak stomatal conductance of saltcedar to occur around 10:00 and peak photosynthesis to occur between 10:00 and 12:00.

Using carbon isotope ratios to determine water use efficiency of several native species and saltcedar on the Bill Williams and Colorado rivers in Arizona, Busch et al (1995) found that saltcedar had a higher WUE than native phreatophytes, which gave it a competitive advantage over native species when under water stress. Gay and Sammis (1977) found saltcedar to transpire at rates ranging from 0.5 to 2.78 $\mu g\ cm^{-2}\ s^{-1}$ (LAI 8.1) while mesquite, with a leaf area index (LAI) less than 3.0, was found to transpire at 1.2 to 11.2 $\mu g\ cm^{-2}\ s^{-1}$. If projected onto a stand level, the much higher LAI of saltcedar would compensate for the lower rate per unit of leaf area. Anderson (1977,1982) found saltcedar to transpire at a rate of 1.2 $g\ g^{-1}\ h^{-1}$ (mass of water per unit of leaf fresh mass per hour) or 1.5 $g\ dm^{-2}\ h^{-1}$ (mass of water per unit leaf area per hour) and 3.11 $g\ g^{-1}\ h^{-1}$ (mass of water per unit of dry fresh mass per hour) at 30 C and 45% RH.

Stand density and LAI are important factors for saltcedar transpiration on an area basis. Davenport et al. (1982) reported saltcedar water use in stands and drums. In California during July for stands of saltcedar grown in drums, ET varied from 2.0 mm day^{-1}in a sparse stand up to 16.0 mm day^{-1}in a dense stand. While greater stand density had more total water transpired, the amount transpired per plant was greatest on the sparse stand. Cleverly et al. (2002) measured ET using the 3-dimensional eddy covariance method for a growing season at two sites on the Middle Rio Grande in New Mexico, one site being flooded and the other nom-flooded. The unflooded site had a low LAI of 2.5 and a mixture of plants including *Tamarix* ramosissima, *Distichlis* *spicata*, *Atriplex spp*., *Salix exigua*, and *Prosopis pubescens*. The flooded site had a higher LAI but, a monospecific stand of *T. ramosissima*. Total ET was 122 cm yr^{-1} for the flooded site and 74 cm yr^{-1} for the non-flooded site. Smith et al (1995) found that daily sap flow increased linearly with increasing leaf area. Dahm et al (2002) calculated ET using the eddy covariance method on the Middle Rio Grande at several different sites. LAI measurements were positively correlated with daily ET rates in this study.

Methods used to calculate water use can also show mixed results. Gay and Fritchen (1979) estimated ET using the Bowen ratio and constant level lysimeters at Benardo, NM for a 5-day period during hot and dry weather in June. The lysimeters maintained a constant water depth of 1.5m. The Bowen ratio calculated mean ET was 8.2 mm day^{-1} while the lysimeters reported an average use of 7.99mm day^{-1}. Weeks et al. (1987) reported that over a range of sites with saltcedar, ET from the eddy covariance method was consistently lower than the energy budget method. Gatewood et al. (1950) used six different methods to calculate water use by bottomland vegetation including the tank and transpiration well methods. The tank method was found to be 19% above the average of all 6 methods while the transpiration well method was 6% below the average of all 6 methods. This indicates that there is a considerable degree of disagreement between these two methods.

Calculated potential evapotranspiration (PET) can be an indicator of how much water saltcedar is going to use but is not an absolute. Several studies have noted that ET from saltcedar stands can exceed PET. Sala et al. (1996) conducted a study on saltcedar, *Pluchea, Prosopsis*, and *Salix* using sap flow measurements to determine estimates of transpiration. It was found that water use increased linearly when weighted by PET with increasing leaf area. It was also found that dense (high leaf area) stands of saltcedar are capable of transpiring 1.6-2.0 times the estimated PET. White et al. (2003) attributed high ET estimates on the Canadian and Pecos Rivers in Texas to advective energy affecting narrow bands of riparian vegetation. Smith et al (1998) conducted a study on the lower Virgin River floodplain in Nevada investigating ET using the Bowen ratio method and the effect of applied irrigation on saltcedar stomatal conductance. ET exceeded PET early in the season when water tables were high and soil was moist because of apparent advection from the surrounding desert. As the summer progressed, ET fell below PET because of lack of soil moisture and water table decline. An irrigation experiment was conducted to determine the effects of summer rain on saltcedar stomatal conductance. Irrigation did not produce any increases of stomatal conductance for at least 4 weeks suggesting that saltcedar does not readily utilize summer rainfall events in the Mojave Desert.

METHODOLOGY

Simulation Model

The simulation model used was a modified version of EPIC 9200.Two studies were conducted to help develop parameters for the growth and water use simulation model for saltcedar. The first (natural stands) was to determine if there were any significant correlations between age of plant, LAI, and light extinction coefficient and determine if there were any significant differences between collection sites. The second (artificially established stand) was to determine potential LAI and light extinction coefficients for *Tamarix ramosissima* from California, *Tamarix spp.* from Seymour, Texas, *Salix nigra*, and *Populus deltoids* from Temple, TX and to determine if there were any significant differences in LAI and light extinction coefficients between these species.

After appropriate parameters were developed, EPIC 9200 was set up by USDA-ARS staff for sites being monitored by the Texas Cooperative Extension on the Pecos River near Mentone, TX and runs made for, sites on the Colorado River near Snyder, TX, and the Canadian River near Canadian, TX. Multiple runs for the Pecos River site were conducted to test sensitivity of the model to changes in soil salinity, plant salt sensitivity, minimum water table depth, maximum water table depth, and potential LAI. The average response of PET, ET, plant transpiration, soil water evaporation, and biomass were evaluated. Model estimates of ET were compared to those reported by White et al. (2003) for the respective sites.

Characterization of Naturally Established Stands

Light interception, leaf area, ring counts, and aboveground biomass to determine leaf area index, radiation use efficiencies, light extinction coefficients and ages were collected in the summers of 2001 and 2002 from the following locations: Lake Proctor, TX; Wichita River near Seymour, TX; Canadian River near Canadian, TX; Colorado River in Borden County, TX; Rio Grande river Las Cruces, NM; and the Pueblo Reservoir near Pueblo, CO. Small isolated trees were targeted for collection for development of the simulation model. Light interception was measured using a Decagon PAR light bar 0.8 m long. First one average reading was taken above the plant then an average of readings was taken below the plant along the length of the shadow then another average above light reading was recorded. Foliage was then stripped and the same series of measurements were taken again. Light interception by leaves could then be calculated. The foliage was saved to determine weight using a scale and leaf area using a LI3100 leaf area meter (LiCor Inc., Nebraska, USA.) The rest of the plant was then harvested to determine aboveground biomass. The trees were aged by counting growth rings at ground level. After leaf area had been measured the foliage was dried at 55° C and periodically weighed until weights stabilized and then recorded as the dry biomass. Leaf area index was calculated by dividing the total leaf area of each sample plant by the area occupied by the shadow of each plant: m^2 of one-sided leaf area/ m^2 of area occupied by the sample plant's shadow.

Light extinction coefficient was calculated by taking the natural log of one minus the fraction of photosythetically active radiation (PAR) intercepted by the plant and dividing by the LAI: (ln(1-Fraction of PAR intercepted))/ LAI.

Characterization of Artificially Established Stands

This study was initiated at the beginning of June 2001 at the Blackland Research Center, Temple, Texas to determine light extinction coefficients and characterize saltcedar, willow and cottonwood plants under constant irrigation during the 2001 growing season.

Water lines were trenched at the beginning of the summer, one-inch lines were laid in the trenches and 11 drip irrigator heads were installed to assure that water was not a limiting factor. Each of the main lines in turn had a cutoff valve. Forty-eight holes 0.3 m in diameter approximately 0.8 m deep were dug with an auger. They were filled with Pedernales fine sandy loam soil. Four species were planted: *Tamarix ramosissima* from California, *Tamarix spp.* from Seymour, Texas on the Wichita River, and local cottonwood and willow from Temple, TX. They were planted in 4 blocks, each block containing all 4 species with each species occupying 3 holes. They were planted using cuttings approx 0.3 m long and 1.3 cm in diameter. Approximately 5 cuttings were placed in each hole to ensure establishment of viable plants. The cuttings were watered continuously 4-5 days each week during the summer. During the fall of 2001, the plants were thinned out in each hole, leaving one plant per hole so that growth could continue without competition.

During the 2002 growing season plants were continuously watered under drip irrigation throughout the growing season. During the fall of 2002, light interception was measured for each plant using the same procedure as for the field samples.

Saltcedar Simulation Model Development

The saltcedar simulation model was developed by USDA-ARS staff, starting with the EPIC 9200 model, and importing subroutines from the ALMANAC model developed by Jim Kiniry (Input was given on model development by using literature and results from studies. Excerpt from Kiniry et al. (2003):

> The EPIC 9200 model simulates the water balance (including the water table depth), salinity, the nutrient balance, and the interception of solar radiation. The model simulates plant water use by trees and grasses from the soil and water table, provided the water table is within the rooting depth of the plant species. The model has a daily time step. It simulates plant growth reasonably and is implemented easily. Some important modifications were made to enable more realistic simulation of the hydrology at the three sites. Firstly, plant transpiration was increased by 67% over what the EPIC model normally simulates, in order to account for effects of advected energy from adjacent arid areas, as described in Arizona by Dugas et al. (1991). This response has also been demonstrated in central Texas by Dugas and Bland (1989).
>
> Secondly, while not reported herein, diurnal fluctuations in water table were simulated from the daily value for transpiration from the daily value of water table before recharge, to give a maximum range of fluctuation each day. The value of daily transpiration was divided by 0.41, assuming 41 percent soil porosity, to calculate the daily fluctuation of water table.
>
> Next, maximum ranges of water table depths over the season were set for each site based on results from Hays (2003). Water table fluctuations are calculated based on an assumed value for maximum ground water storage of 100 mm for all three sites. This affects how a water table rises after a rain. The value for the parameter for ground water storage loss was set to 0.2 mm per day for all the sites. We also allowed river flow rates or lake levels to affect ground water using river flow values from adjacent bodies of water.
>
> Light Interception
>
> EPIC simulates light interception by the leaf canopy with Beer's law (Monsi and Saeki, 1953) and the LAI. The greater the value of the extinction coefficient k, the more light will be intercepted at a given LAI. The trees were allowed to intercept the light first, with the grasses having the remaining light available to them.
>
> The fraction of incoming solar radiation intercepted by the leaf canopy is
>
> Fraction = 1.0 - exp (-k * LAI)
>
> Light extinction coefficient of saltcedar was determined by the potential growth study.
>
> Leaf Area Development
>
> Accurate prediction of light interception depends on realistic description of leaf area. Values for saltcedar LAI are being developed from ongoing work by Schmidt Likewise, simulation of light

interception also requires accurate description of leaf area production and decline. The model estimates leaf area production up to the point of maximum leaf area for the growing season using Eq (2). The model generates a curve that is forced through the origin and through two points, asymptotically approaching y=1.0. The s-curve function takes the form:

$$F = X / (X + \exp(Y1 - Y2 * X)) \qquad (2)$$

where F is the factor for relative LAI, X is the fraction of heat units from planting to maturity, and Y1 and Y2 are the s-curve coefficients generated by EPIC. For each day, the fraction of total heat units that have accumulated is determined, denoted as SYP. The sum of heat units is zero at planting in the establishment year and at tiller emergence in subsequent years, and is maximum at maturity. The s-curve describes how LAI can increase, under nonstress conditions, as a function of SYP.

Biomass Production and Partitioning

Biomass growth is simulated with a RUE approach (Kiniry et al., 1989). Values for RUE have been previously derived for many crops (Kiniry et al., 1989; Manrique et al., 1991; and Kiniry et al., 1992). For grasses, we have used RUE values ranging from 1.8 to 5.0 g per MJ of intercepted photosynthetically active radiation (Kiniry et al., 1999).

The maximum rooting depth defines the potential depth in the absence of a root-restricting soil layer. Soil cores from plots at Temple in 1994 indicate that grass roots varied in depth among the species, with switchgrass roots extending to 2.2 m (Kiniry et al., 1999). For saltcedar, we assumed a deep maximum rooting depth 30 m to assure that plants could extract water from the water table. For the Pecos River site, we only simulated saltcedar. We assumed grass roots could extended to 2.0 m at the other two sites.

Model Testing

In order to test the simulation model a total of 156 model runs were completed (see appendix A). The model was set up for the east side of the Pecos River in Loving County, TX just west of Mentone adjacent to the river channel. This site has been described by White et al. (2003). The soil was predominately sand. Flow of the Pecos River is regulated by water releases (for irrigation) from Red Bluff Lake. Since there were 18 years of available river flow data the simulation run was set up for 18 years. Factors such as potential LAI (runs 107-119), minimum and maximum water table depths (runs 78-106, 120-156), and soil salinity and plant salt sensitivity factors (runs 1-77) were varied to determine how they affected predicted biomass production, potential evapotranspiration (PET), evapotranspiration, soil water evaporation, and plant transpiration (EP).

Effect of Salinity and Water Table Depth on Saltcedar Growth and Water Use

This study was conducted in the summer of 2002 (June-December) at the Blackland Research Center Temple, Texas. Four replications (randomized block design) of three depths to saturated soil (0.5, 1.0, and 1.75 m) and five salinities (tap water, 1250, 2500, 5000, 7500 ppm) of water solution were used. Saltcedar was established from cuttings in early spring of 2002, raised in a greenhouse and transplanted to containers by June 1.

Cutting Establishment

The cuttings, approximately 0.45 m long and at least 1.6 cm in diameter, were taken from the United States Department of Agriculture, Agricultural Research Service (USDA-ARS) study site near Seymour, Texas. The cuttings were placed in an ice chest, chilled, and stored until potted. The cuttings were potted in a greenhouse as soon as possible in a 1.0 m long by 10 cm diameter PVC sewer pipe filled with course sand. These were irrigated daily (with bottom drainage) from Monday through Friday to allow growth to begin as soon as possible.

Development of Experimental Unit

Plants were arranged in a complete randomized block design with 4 replications (Figure 1). There were 15 possible treatments consisting of 5 different salinity levels (tap-water, 1250, 2500, 5000, 7500 ppm) and 3 depths to saturated soil (approx. 0.5, 1.0, and 1.75 m). There were 4 plants per treatment per replication.

Physical Facilities

Plants were grown in a nursery (outside of the greenhouse) in 2.05 m long tubes that had each respective treatment plumbed to it. Tubes were arranged in a complete randomized block design (Figure 1). They were held up by a rack system constructed of 4"x4" and 2"x6" treated wooden boards. The plants were oriented in rows from north to south to reduce shading. The plant rows were spaced 2.13 m apart so that each row did not cast a shadow on other plants. Plants were placed on the end of each row and given the same treatment, but were not sampled until the end of the study. This was done so that each plant would have a plant next to it and receive equal treatment. The outside plants received the lowest salinity (0 ppm) and middle water table depth (1.0 m).

Salinity Treatment

Different salinities were mixed using Morton Mixing Salt (NaCl) and tap water. The following salinities were used: tap water (0 ppm), 1250 ppm, 2500 ppm, 5000 ppm, 7500 ppm. The salinities were mixed and stored in 5 separate containers. Each salinity level also received Miracle-Gro All Purpose Plant Food, 15-30-15 (191.6 mg l^{-1} H_2O) in order to insure plant growth would not be limited by lack of nutrients in a sand medium.

Depth to Water Table

There were three depths to water tables: 0.5m, 1.0m, and 1.75 m studied. Saturated soil was maintained by using a float bucket to supply each plant. As plants utilized water, the floats in the respective buckets immediately refilled the bucket and maintained a relatively constant water level (Figures 2, 3, and 4). The float valves and buckets were small horse troughs that were sealed with plastic on the top to prevent evaporation and rainfall input.

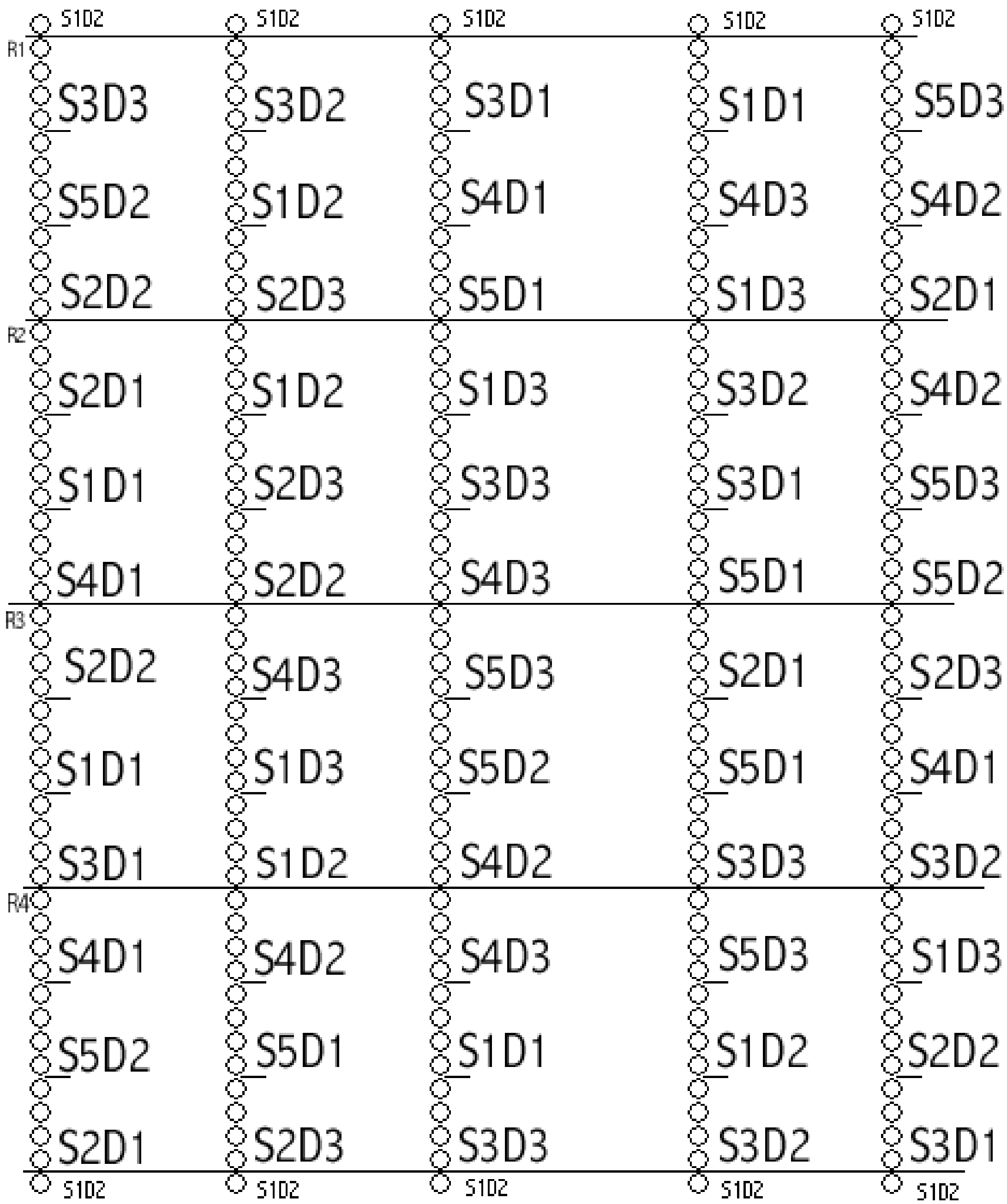


Figure 1. Layout of experimental unit for water table depth and salinity study. Salinities are designated by: S1= Tap water, S2=1250 ppm NaCl, S3=2500 ppm NaCl, S4=5000 ppm NaCl, S5=7500 ppm NaCl.

Sampling Procedure

On May 24, the healthiest 250 plants growing in the greenhouse had another section of pipe filled with coarse sand added to the bottom, resulting a total length of 2.05 m. These were installed in the randomized block design experiment. The plants were then hooked up to the water supply system.

Three harvests took place on the following dates: August 5-8, September 17, and December 18. The first two harvests each contained ¼ of the total plants in the study. Plants were randomly selected for harvest for each date. The last harvest contained the last half of the plants in the study. After each of the first two samplings the remaining plants were moved together so that each plant continued to have the same amount of space and shading between itself and its neighbor.

Data Collection

Aboveground Biomass and Belowground Biomass

The harvested plants were partitioned into aboveground and belowground biomass. The aboveground biomass was separated into leaves and stems, then, weighed after being oven-dried. The belowground portion was divided into 0.25 m sections starting at the top of the plant growth tube and going down. The sand medium on the first two harvests was washed away using a screen. On the last harvest, the sand medium was washed from the roots on a sloped piece of plywood (Figure 5). A screen was not used since it was determined that the fine roots stuck to the screen and could not be easily recovered. Roots per section per plant were oven-dried, weighed and recorded.

Leaf Area

Leaves were hand stripped from each plant and then run thru a LiCor leaf area machine to determine fresh one sided leaf area for the first two harvests. The last harvest did not have this done since it was occurred after leaf drop.

Water Use

Water use was measured by two methods. The first method measured water use by treatment (15 plants per treatment). This was achieved by placing a water level logger in each of the treatment water supplies. Since there were only 5 loggers, data could not be recorded for all the treatments at the same time. Therefore, the 5 water loggers were placed at only one depth to the water table level each week and moved to a new depth every 7 days. The data for days when water loggers were moved and negative values were obtained due to logger malfunction were not used for analysis. Only times that occurred after and before 13:00 were used for calculation of low water use. Only values that occurred after 13:00 were used to determine time of peak average use.

The second method was to turn off the water supply of each plant and record the amount the water dropped in the soil profile using a sight tube. This was done twice during the summer. Each plant's water supply was turned off in the morning and then the depth to the water level in the sight tube was recorded. The next day at the same time, the water level was recorded again. The difference between these two measurements was then calculated giving the amount of drop in the water table. This was then multiplied by the specific yield (18%) of the soil to determine the amount of water used. Specific yield of the coarse sand was determined by saturating a known volume of soil and measuring the volume of water that freely drained over a 24-hour period (expressed as a percent). Statistical analysis was run on the average of the two days of readings. In order for a reading to be included, it had to be positive and not have a leak on that sample unit.

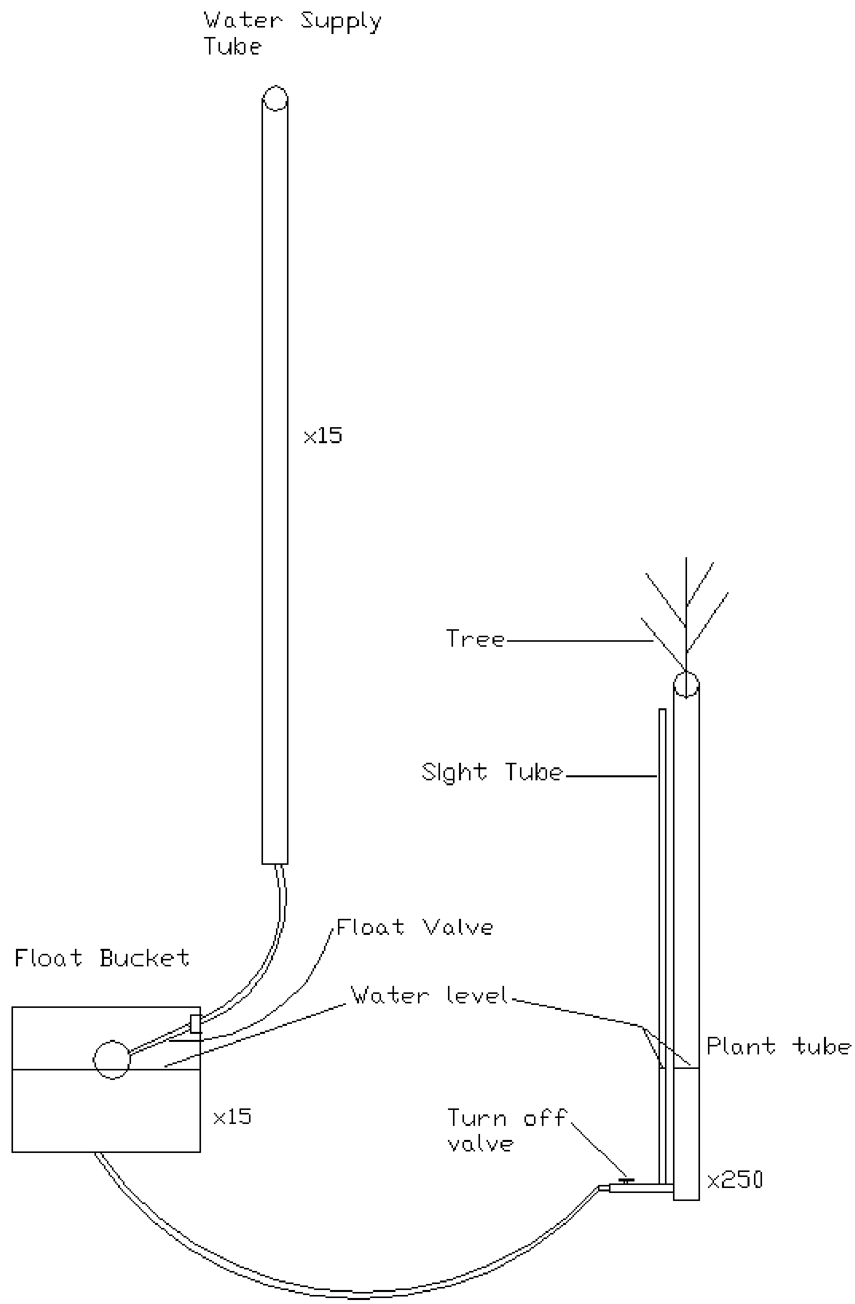


Figure 2. Diagram of depth and salinity study equipment setup.

Figure 3. Photograph of lysimeter study, angle view showing rows of trees before initiation of study.

Figure 4. Photograph of lysimeter study, side view, showing different water levels.

Figure 5. Demonstration of root washing technique using a slanted board.

Climatic Data

Daily maximum and minimum air temperature, maximum and minimum relative humidity, average vapor pressure, total solar radiation received, average wind speed, average wind direction, and total precipitation was obtained from an on-site weather station maintained by the United States Department of Agriculture, Agriculture Research Service (USDA-ARS) staff at Temple, Texas. These data were available directly from the web located at: http://arsserv0.tamu.edu/hydata.htm.

Statistical Analysis

Descriptive statistics such as mean, standard deviation, standard error of the mean, and confidence intervals were calculated for the field data study, potential growth study, and salinity/water table depth study. One-way ANOVA's were then performed for each of these studies. If significance was indicated a multiple comparison was performed using Tukey's HSD method to discern if there were any significant differences between means. Differences were considered significant at the $p<0.05$ level. For water use data, linear regression equations were developed using the stepwise method. All analyses were performed using the Statistical Package for the Social Sciences (SPSS) for Windows v. 11.01.

RESULTS

Characterization of Naturally Established Stands

The average LAI of the trees sampled across all sites was 0.31 with no significant differences between sites (Table 2). The Seymour site had the highest average LAI of 0.53, while the Las Cruces site had the lowest average LAI of 0.13. The average light extinction coefficient (k) was -0.54 with no significant differences between sites. The Seymour site had the highest average k, -0.58, while the site at Lake Proctor had the lowest average k, -0.47. Average age of trees sampled, assuming one growth ring equaled one year of growth, was 3.6 years. The Seymour site had the oldest trees averaging 5.4 years while the youngest trees where sampled at the Pueblo site, 1.75 years (Table 2). There was a significant correlation at the $p<0.05$ level of $r=0.524$ between LAI and k across all sites.

Table 2. Average leaf area index, light extinction coefficient, and age of small saltcedar trees from sites in Texas, New Mexico and Colorado.

Location	N	LAI	K	Age (years)
Seymour, TX	5	0.53±0.66 a	-.058±0.53 a	5.4±1.1 a
Lake Proctor, TX	3	0.29±0.27 a	-0.47±0.40 a	2.0±0.0 b
Las Cruces, NM	4	0.13±0.06 a	-0.55±0.31 a	3.0±0.0 b
Pueblo, CO	4	0.29±0.20 a	-0.52±0.13 a	1.8±1.0 b
Canadian river, TX	2	0.18±0.13 a	-0.57±0.14 a	6.0±0.0 a
Overall	18	0.31±0.38	-0.54±0.33	3.6±1.9

Values are means ± SD. Means with same letter are significantly different ($p<0.05$) within columns.

The ratio of leaf area to fresh weight averaged 16.8 $cm^2\ g^{-1}$ across all sites and samples (Table 3). The samples from Las Cruces had a significantly higher ratio than samples from the other sites. The ratio from Lake Proctor was significantly lower than the average ratios from the Canadian River and Las Cruces.

Table 3. Means of the ratio of saltcedar leaf area to fresh weight ($cm^2 g^{-1}$) from five sites.

Location	N	Mean
Wichita river Seymour, TX	17	16.1±2.1 a,b
Lake Proctor, TX	3	13.9±0.6 a
Las Cruces, NM	4	21.8±1.6 c
Pueblo, CO	5	15.7±1.5 a,b
Canadian river, TX	10	17.6±0.7 b
Overall	39	16.8±2.5

Values are means ± SD. Means with same letter are significantly different ($p<0.05$) within columns.

Characterization of Artificially Established Stands

Saltcedar had lower LAI values than cottonwood or willow, but the highest light extinction coefficient (Table 4). Cottonwood had the highest LAI but the lowest light extinction coefficient. If *Tamarix spp.* are separated into the two types used in this study, the saltcedar cuttings from Seymour, TX had the lowest LAI across among all plants and had a lower light extinction coefficient than *Tamarix ramosissima* from California. There were statistically significant differences between species for LAI whether both types of saltcedar where lumped together or analyzed separately, though no significant difference between saltcedar types. There were significant differences between saltcedar and *Salix nigra* for light extinction coefficient. There was no significant difference between *Populus deltoides* and any of the species with regards to radiation use efficiency, whether both types of saltcedar were lumped together or not.

Table 4. Average leaf area index (LAI) and light extinction coefficients (k) of *Tamarix spp.* from Seymour, Texas, *Tamarix ramosissima*, *Salix spp.*, and *Populus spp.*

Tree Species	N	LAI	K
Tamarix spp. (Seymour, TX)	12	0.09±0.05 a	-0.74±0.48 a
Tamarix ramosissima (CA)	12	0.11±0.08 a	-0.78±0.32 a
Salix nigra (Temple, TX)	12	0.50±0.35 b	-0.36±0.12 b
Populus deltoids (Temple, TX)	3	0.57±0.17 b	-0.33±0.14 a,b
Overall	39	0.26±0.29	-0.60±0.38

Values are means ± SD. Means with same letter are significantly different (p<0.05) within columns.

Effect of Salinity and Water Table Depth on Saltcedar Growth and Water Use

Water Use

Minimum and Maximum Rate of Recharge

The amount of recharge to the saturated soil profile in each plant container is a direct measure of the water use by the plant but recharge occurs after transpiration and root water uptake. The average minimum recharge rate per hour was 0.70 ml hr^{-1} per tree and occurred at 06:15 while the average maximum rate was 15.84 ml hr^{-1} per tree and occurred at 19:20 (Table 5). When ANOVA was calculated there was no indication of linearity between the maximum time and salinity. There was a significant difference between the 1.00 m and the 1.75 m water table depth and time of peak occurrence of water use, the 1.00 m water table occurred at 19:55 while the 1.75 m water table depth occurred at 18:19 (Table 6).

Table 5. Average minimum and maximum hourly rates of recharge of the soil profile (water use) per day and time of occurrence with filtered observations across salinities.

Salinity ppt	N	MIN TIME	MAX TIME	Minimum ml/hr/plant	Maximum ml/hr/plant
.00	16	6:41±3:25 a	18:24±2:11:45 a	1.09±1.75 a	17.24±13.14 a
1.25	31	5:39±4:04 a	19:39±1:51 a	0.69±0.79 a	17.20±9.61 a
2.50	18	7:27±2:60 a	19:41±1:49 a	0.57±1.23 a	14.44±6.80 a
5.00	10	5:30±3:50 a	19:45±1:13 a	0.32±0.79 a	14.67±9.70 a
7.50	16	6:04±4:45 a	18:60±3:01 a	0.72±1.30 a	14.12±7.69 a
Mean	91	6:15±3:52	19:20±2:07	0.70±1.18	15.84±9.46

Values are means ± SD. Means with same letter are significantly different ($p<0.05$) within columns.

Table 6. Time of peak and minimum recharge (water use), and average minimum and maximum recharge (water use) rates.

Water table depth m	N	MIN TIME	MAX TIME	Minimum ml/hr/plant	Maximum ml/hr/plant
0.50	21	5:11±3:39 a	19:40±2:03 a,b	0.92±1.18 a	15.17±5.87 a
1.00	40	6:27±4:06 a	19:55±2:07 a	0.88±1.32 a	16.26±7.64 a
1.75	30	6:42±3:40 a	18:19±1:51 b	0.31±0.89 a	15.74±13.23 a
Mean	91	6:15±3:52	19:20±2:07	0.70±1.18	15.84±9.46

Values are means ± SD. Means with same letter significantly different ($p<0.05$) within columns.

Daily Recharge

Using logger data the average amount of recharge (water use) per plant per day was 80 ml (Table 7). Plants in the 1.25 ppt salinity level used significantly more water (109 ml per day per plant) than plants in other salinity levels. Plants utilizing a 1.75 m water table used significantly less water (57 ml per day per plant) than plants with other water table levels.

Table 7. Average daily recharge (water use by saltcedar) for each salinity and water table level.

Salinity ppt	N	ml of H_2O day^{-1}
0.00	63	67.8±72.4 a
1.25	107	109.4±81.3
2.50	108	76.5±65.2 a
5.00	63	71.3±62.2 a
7.50	103	67.3±61.0 a
Water Table Depth m		
0.50	120	92.7±76.1 a
1.00	206	86.5±72.8 a
1.75	118	56.6±55.0 b
Overall	444	80.3±70.8

Values are means ± SD. Means with same letter are significantly different ($p<0.05$) within columns.

When a predictive equation was developed for daily recharge (ml day^{-1}) using salinity and water table depth as the independent variables, the r^2 was extremely low (0.050) (Table 8). Including climatic data for the site resulted in a multiple regression equation (stepwise method) with an r^2 of 0.568 (Table 9). The variables in this predictive equation are as follows:

Previous[1] Total Solar Radiation (kJ m^{-2}), Water Table depth (m), Average Wind Speed (m s^{-1}), Salinity (ppt), Previous Total Precipitation (mm), Previous Average Wind Speed (m s^{-1}), Previous Average Vapor Pressure (kPA), Minimum Relative Humidity (%), Previous Average Wind Direction (Degrees), and Maximum Air Temperature (C).

The coefficients for each variable within each equation showed all variables, except the previous days average vapor pressure, had a negative influence on water use,

[1] Previous= average for the day before.

Table 8. Regression equation for recharge (water use by saltcedar) (ml d^{-1}) using the enter method with salinity and depth to the water table as the independent variables.

	Unstandardized Coefficients	
	B	Std. Error
(Constant)	124.016	9.293
Salinity (ppt)	-3.278	1.221
Water table depth (m)	-30.727	7.104
r^2	Adjusted r^2	Standard Error of the Estimate
0.054	0.050	69.050

Table 9. Regression equation for recharge (water use by saltcedar) (ml d^{-1}) using the stepwise method with salinity, depth to the water table and climatic data as the independent variables.

	Unstandardized Coefficients	Standard error	R^2
(Constant)	93.856	16.703	
Prev Total Solar Rad. (kJ/m2)	4.734E-03	0.001	0.398
Water table depth m	-21.102	5.107	0.440
Avg Wind Speed (m/s)	-4.609	2.292	0.494
Salinity ppt	-3.726	0.835	0.515
Prev Total Precip (mm)	-0.801	0.380	0.520
Prev Avg Wind Speed (m/s)	-8.773	2.378	0.527
Prev Avg Vapor Pres. (kPA)	41.765	6.055	0.532
Min RH(%)	-0.753	0.161	0.544
Prev Avg Wind Dir. (deg)	-9.170E-02	0.028	0.561
Max Air Temp (C)	-2.422	0.846	0.568
r^2	Adjusted r^2	Standard Error of the Estimate	
0.568	0.558	47.106	

Sight Tube Data

Only two days of data were obtained from sight tube measurements. Average water use on 7/18/02 was 94 ml, average water use on 7/25/02 was 155 ml. The average was 125 ml of water per plant per day. While there were trends of decreasing water use with increasing salinity there were no statistically significant differences between salinities (Table 10). There were significant differences between water table depths (Table 11). On 7/18/02 plants with a 1.00m water table used 67 ml, which was significantly lower than plants using water from the 0.5m level (120 ml). On 7/25/02 saltcedar used significantly less water (87.55 ml) with a 1.75 m water table compared to plants with a water table depth of 0.50 m (170 ml) or 1.00m (168 ml). When the two days were averaged, 96 ml was used by plants in the 1.75 m water table treatment, which was significantly lower than the 145 ml of water use by plants with a 0.50 m water level.

Table 10. Average recharge (water use by saltcedar) (ml/plant) across salinities for the sight tubes.

Salinity ppt	N	Use (ml) on 7/18	Use (ml) on 7/25	Average of 7/18 and 7/25 (ml)
0.00	37	103±77 a	180±105 a	141±80 a
1.25	30	130±235 a	144±87 a	137±119 a
2.50	28	89±66 a	166±69 a	127±61 a
5.00	25	85±56 a	147±39 a	116±42 a
7.50	29	58±39 a	133±47 a	95±41 a
Overall	149	94±120	155±77	125±77

Values are means ± SD. Means with same letter are significantly different ($p<0.05$) within columns.

Table 11. Average recharge (water use by saltcedar) (ml/plant) with increasing water table depths for the sight tubes.

Water table depth m	N	Use (ml) on 7/18	Use (ml) on 7/25	Average of 7/18 and 7/25 (ml)
0.00	37	120±63 a	170±74 a	145±61 a
1.00	30	67±49 b	168±78 a	118±58 a,b
1.75	28	105±263 a,b	88±41 b	96±129 b
Overall	149	94±120	155±77	125±77

Values are means ± SD. Means with same letter are significantly different ($p<0.05$) within columns.

Biomass

There where some statistical differences in biomass variables between harvest dates (time from establishment). Cutting size of the original stem material, total stem weight, and length of the longest stem increased with each harvest (Table 12, 13, 14, 15). Roots at the 0.75-1.0 m and the 1.0-1.25 m soil depth and total stem counts decreased with successive .

Root biomass distributions differed among water table depth treatments. Root biomass was greatest in the 0.50-0.75 m zone for plants with a 0.50 m water table, in the 0.75-1.0 m with a 1.00 m water table, and in the 0.25-0.50 m and 1.50-1.75 m soil profile for the 1.75 m water table (Figure 6). Root distributions did not differ between salinity levels, except for the 1.25 ppt level, which had a significant peak in the 0.50-.75 m zone (Figure 7). The second harvest date had a higher peak biomass of roots than the other harvest dates (Figure 8).

There where no significant differences in root biomass variables between salinity treatments, harvest dates or within harvest dates (Table 16, 17). There where significant differences in root biomass between depths to the water table among harvest dates and within each harvest. Root to shoot ratios were not statistically different between salinity levels or water table depths.

There were significant correlations between average water use from the sight tube data and salinity (-0.218), water table depth (-0.228), cutting weight (0.208), roots in the 0.25-0.75 m zone (0.257), total amount of roots (0.262), stem weight (0.328), leaf weight (0.311), leaf area (0.283), and length of longest stem (0.241). There were significant correlations between salinity and cutting weight, root biomass in soil profile section B (0.194), root biomass in section C (0.166), and root biomass in section E (-.185). There were also significant correlations between water table depth and cutting biomass, root biomass in section B (-0.267), root biomass in section B (-0.424), root biomass in section C (-0.346), root biomass in section F (0.213), root biomass in section G (0.401), root biomass in section H (0.384), total root biomass (-0.197), total stem biomass (-0.415), total leaf area (-0.302), and length of longest stem (-0.236).

Table 12. Average cutting sizes for each harvest date following establishment of saltcedar in June 2002.

Harvest	N	Cutting section 0-.25m (g)	Cutting Section 0.25-.50 (g)	Total Cutting (g)
August 5	59	66.80±28.81 a	29.06±16.88 a	96.50±33.88 a
September 17	51	74.61±32.14 a,b	31.59±21.60 a,b	107.36±40.30 a
December 18	130	87.18±47.35 b	38.34±22.66 b	125.97±55.16 b
Overall	240	79.50±41.28	34.63±21.47	114.86±49.29

Values are means ± SD. Means with same letter are significantly different ($p<0.05$) within columns.

Table 13. Average amount of saltcedar roots in sections D and E for each harvest.

Harvest Date 2002	N	Roots Section D 0.75-1.0m (g)	Roots Section E 1.25-1.50m (g)
August 5	59	4.97±4.97 b	0.91±1.49 a
September 17	51	2.98±3.18 a	0.31±0.55 b
December 18	130	3.35±2.93 a	0.67±1.14 a,b
Overall	240	3.67±3.65	0.65±1.16

Values are means ± SD. Means with same letter are significantly different ($p<0.05$) within columns.

Table 14. Average saltcedar stem weight, number and length for each harvest date.

Harvest Date 2002	N	Total Stems (g)	Number of Main Stems	Length of Longest stem (m)
August 5	59	11.17±7.00 b	5.6±2.2 a,b	0.37±0.12 b
September 17	51	16.47±9.74 a	6.4±2.6 b	1.03±0.33 a
December 18	130	16.84±9.92 a	5.1±2.0 a	0.98±0.33 a
Overall	240	15.39±9.53	5.5±2.3	0.84±0.40

Values are means ± SD. Means with same letter are significantly different ($p<0.05$) within columns.

Table 15. Average saltcedar biomass (g) for all harvest dates, salinities, and water table depths.

	N	Mean	Std. Deviation
Cutting Section A(0-.25m) in g	240	79.50	41.29
Cutting Section B(.25-.50m) in g	240	34.63	21.47
Cutting Section C(.50-1.0m) in g	240	1.09	4.85
Total Cutting Weight in g	242	114.86	49.29
Roots Section A (0-.25m) in g	240	.78	1.31
Roots Section B (.25m-.50m) in g	240	4.00	3.56
Roots Section C (.50-.75m) in g	240	4.62	5.41
Roots Section D (.75m-1.0m) in g	240	3.67	3.65
Roots Section E (1.0-1.25m) in g	240	2.74	3.54
Roots Section F (1.25-1.5m) in g	240	.65	1.16
Roots Section G (1.5-1.75m) in g	240	.63	1.48
Roots Section H (>1.75m) in g	240	.32	.95
Total Dry roots in g	242	17.42	12.10
Total Stems in g	245	15.39	9.53
Total dry leaves in g	115	8.84	7.69
leaf area in cm^2	115	200.08	170.33
Number of Main stems	239	5.51	2.25
Length of Longest stem in m	244	.84	.40
Root to shoot ratio	112	.90	.76
Valid N (listwise)	105		

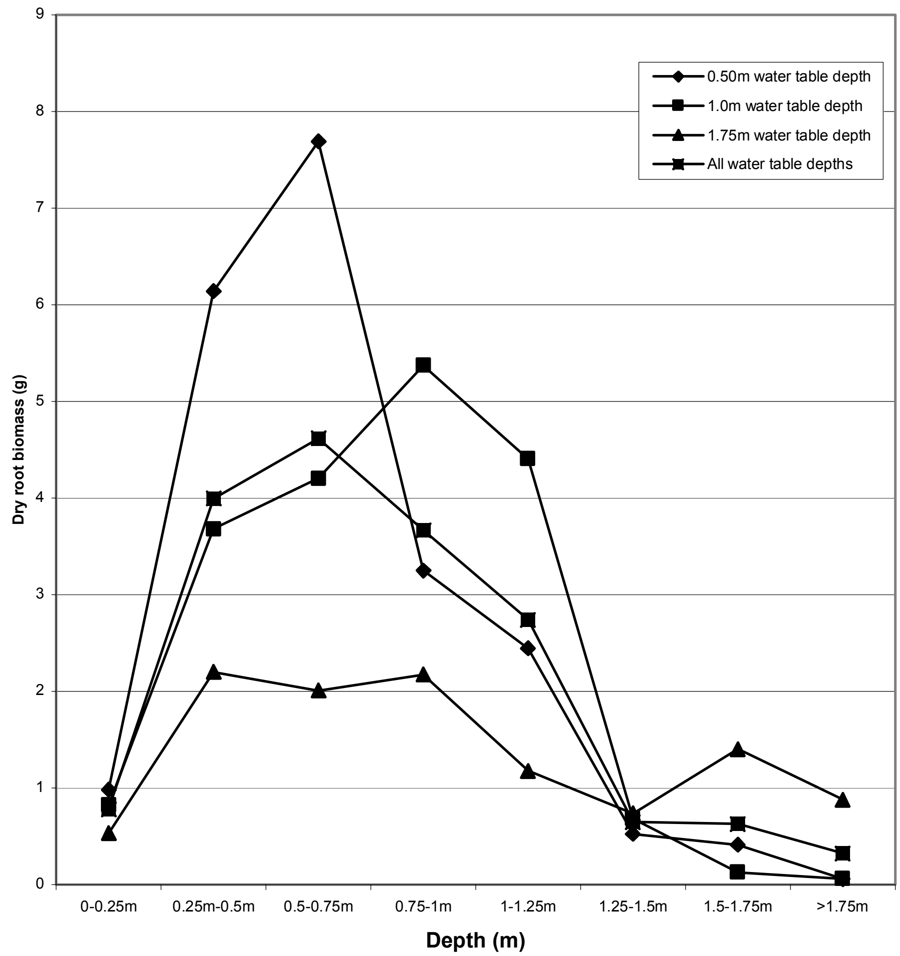


Figure 6. Average saltcedar root biomass distribution (g) for water table depths across all harvest dates and salinities.

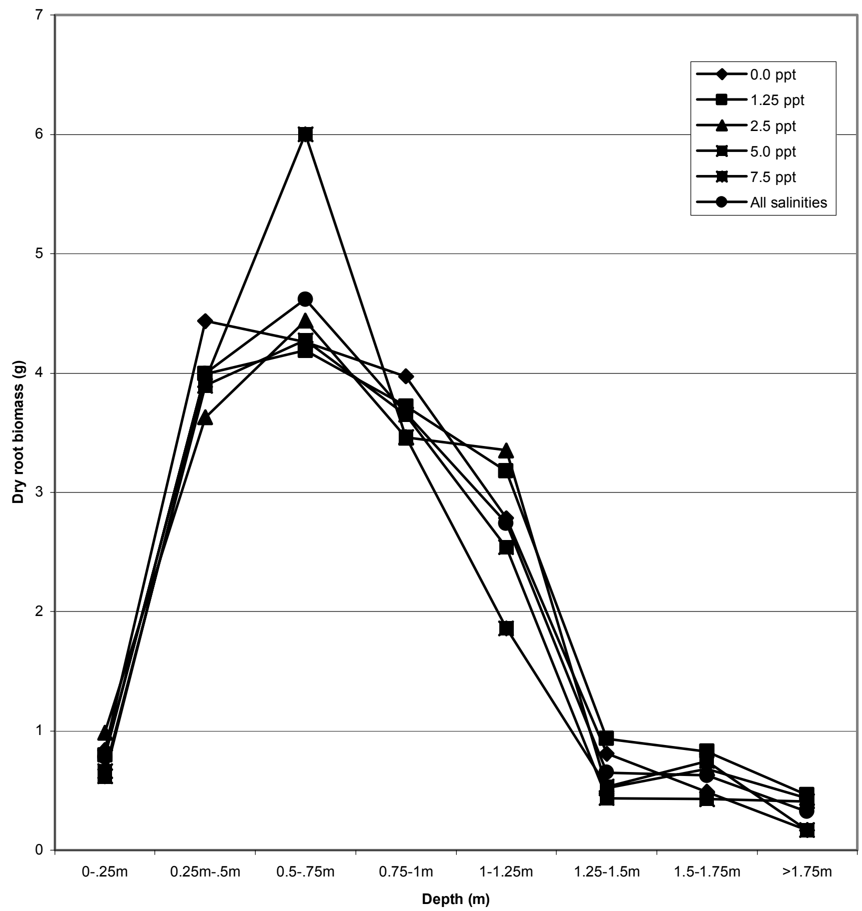


Figure 7. Average saltcedar root biomass distribution (g) for salinities across all harvest dates and water table depths.

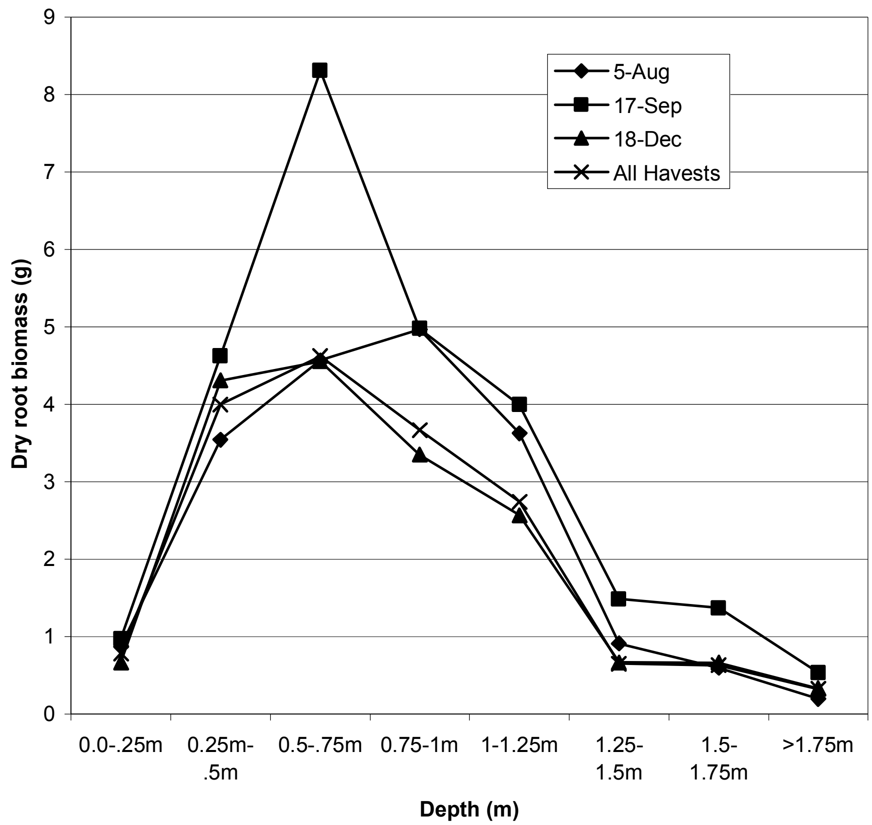


Figure 8. Average saltcedar root biomass distribution (g) by water table depth for each harvest date across all salinities.

Table 16. Average amount of saltcedar root biomass across all harvest dates and salinities for each water table depth.

Water table depth (m)	N	Roots Section 0.25-0.50m (g)	Roots Section 0.50-.75m (g)	Roots Section 0.75-1.0m (g)	Roots Section 1.00-1.25m (g)	Roots Section 1.5-1.75m (g)	Roots Section >1.75m (g)	Total Dry Roots (g)
0.50	77	6.14±4.70 a	7.69±8.24 a	3.25±3.50 a	2.44±3.49 a	0.41±1.61 a	0.06±0.29 a	21.50±14.33 a
1.00	86	3.68±2.53 b	4.21±2.32 b	5.37±4.32 b	4.41±4.09 b	0.13±0.45 a	0.06±0.34 a	19.36±10.937 a
1.75	77	2.20±1.61 c	2.01±1.27 c	2.17±1.75 a	1.18±1.65 c	1.40±1.76 b	0.88±1.46 b	11.12±7.79 b
Overall	240	4.00±3.56	4.62±5.41	3.67±3.65	2.74±3.54	0.63±1.48	0.32±0.95	17.42±12.10

Values are means ± SD. Means with same letter are significantly different ($p<0.05$) within columns.

Table 17. Average saltcedar top growth across all harvest dates and salinities for each water table depth.

Water table depth (m)	N	Cutting Section 0.25-.50m (g)	Total Stems (g)	Total Dry leaves (g)	Leaf area (cm^2)	Length of longest stem (m)
0.50	77	41.82±22.55 a	20.56±10.54 a	11.65±7.57 a	284.24±181.42 a	0.94±0.40 a
1.00	86	34.94±21.99 a	14.88±8.41 b	11.33±7.86 a	239.59±157.24 a	0.83±0.40 a,b
1.75	77	27.08±17.04 b	10.76±6.82 c	3.49±4.14 b	76.54±82.84 b	0.75±0.38 b
Overall	240	34.63±21.48	15.39±9.53	8.84±7.69	200.08±170.31	0.84±0.40

Values are means ± SD. Means with same letter are significantly different ($p<0.05$) within columns.

Saltcedar Simulation Model Testing

Water Use by Saltcedar for the Pecos, Colorado, and Canadian Rivers

(Reported by Kiniry et al. 2003)

At a low LAI for the Pecos River the saltcedar simulation model predicted 377 mm of water use per year with an average daily transpiration of 2.5 mm. As saltcedar LAI was increased, transpiration also increased up to 2260 mm with a LAI of 5 (Table 18). For the Colorado River 1060 mm of transpiration was predicted with a saltcedar LAI of 1 and for the Canadian River 1404 mm with a saltcedar LAI of 0.5.

Table 18. Mean annual and mean daily plant water use (transpiration) (mm) as estimated by the saltcedar simulation EPIC model, for the Pecos River site with different saltcedar cover (LAI) and for the Colorado and Canadian sites with representative plant cover (Kiniry 2003).

		Tree LAI:					
		0.5	1	2	3	4	5
Pecos River	Mean Annual (mm yr^{-1})	377	688	1286	1889	2203	2260
	Mean Daily (mm d^{-1})	2.5	4.7	8.8	13.0	14.8	14.7
Colorado River	Mean Annual (mm yr^{-1}) (LAI=1.0 for trees and 1.0 for grass)		1060				
	Mean Daily (mm d^{-1})		7.1				
Canadian River	Mean Annual (mm yr^{-1}) (LAI=0.5 for trees and 3.0 for grass)	1404					
	Mean Daily (mm d^{-1})	12.2					

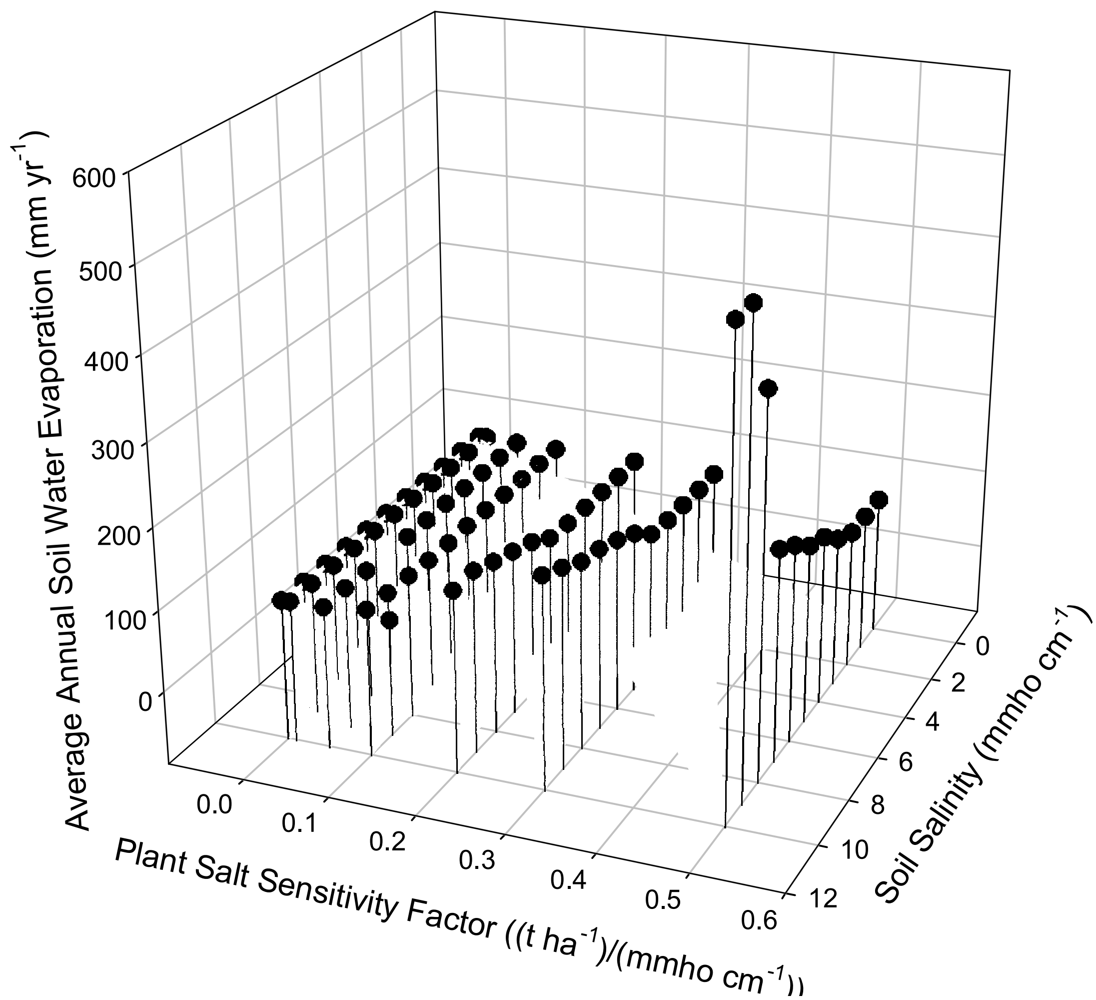
Saltcedar Simulation Model Sensitivity

The saltcedar simulation model developed by Kiniry (2003) was evaluated by varying the plant sensitivity factor, soil salinity, minimum and maximum water table depth, and potential leaf area index. Each time a new factor was adjusted other factors were held constant as per the original model.

Plant Salt Sensitivity Factor and Soil Salinity

As the plant salt sensitivity factor ranged from 0.0 to 0.5 (t ha^{-1})/(mmho cm^{-1}) and initial soil salinity ranged from 0.0 to 10.0 mmho cm$^{-1,}$ soil water evaporation increased by a factor greater than 5 (Figure 9). Plant transpiration showed a decreased 36 fold from 2263 mm yr^{-1} to 62 mm yr^{-1} (Figure 10). Evapotranspiration also decreased from 2347 mm yr^{-1} to 554 mm yr^{-1}, a factor of 4 (Figure 11). Potential evapotranspiration showed an increase as plant salt sensitivity and soil salinity increased. PET ranged from 2321 mm yr^{-1} to 2533 mm yr^{-1} (Figure 12). Biomass production decreased as plant salt sensitivity and soil salinity increased. When plant salt sensitivity and soil salinity were low the model predicted 10.4 t ha^{-1}of biomass production compared to zero production when plant salt sensitivity and soil salinity where both high (Figure 13).

Figure 9. Effect of plant salt sensitivity factor and soil salinity on the saltcedar simulation model's predicted soil water evaporation.



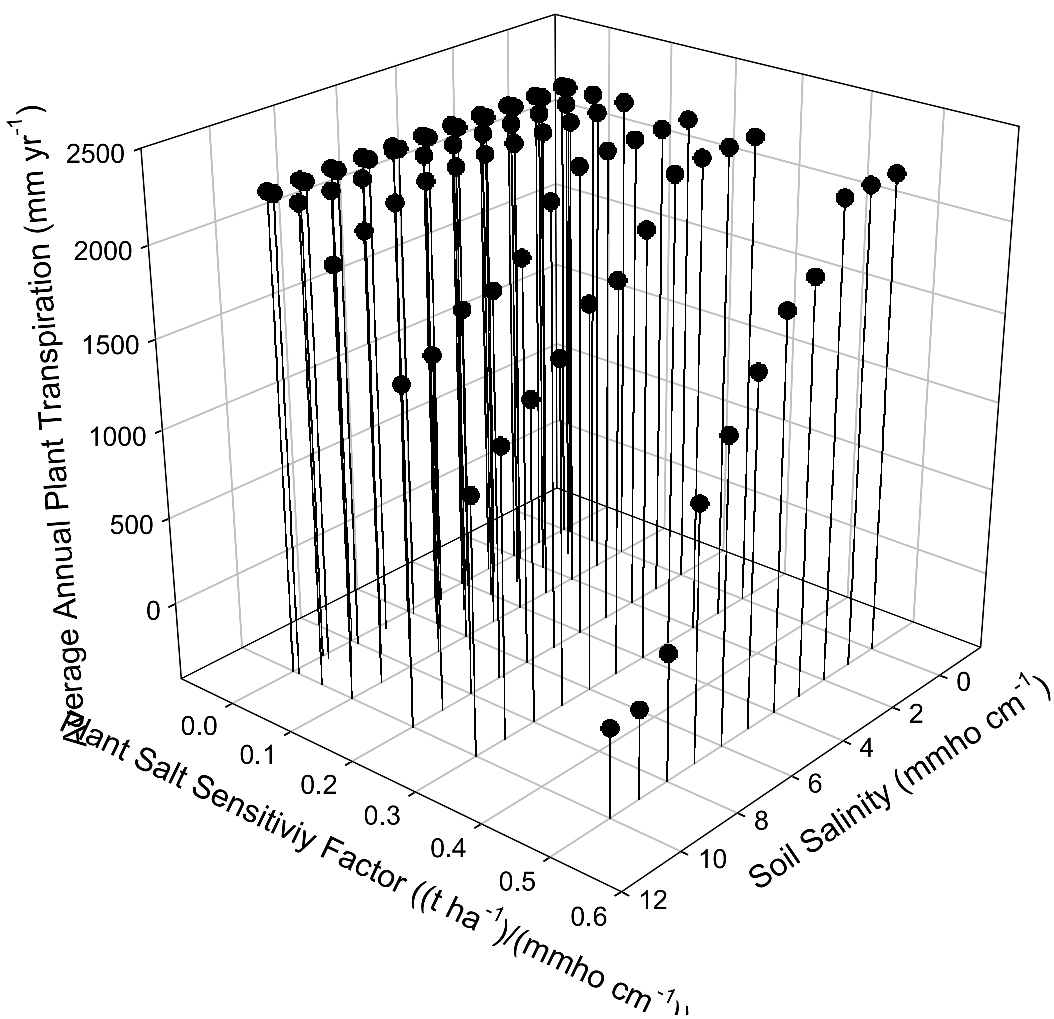


Figure 10. Effect of plant salt sensitivity factor and soil salinity on saltcedar simulation model's predicted plant transpiration.

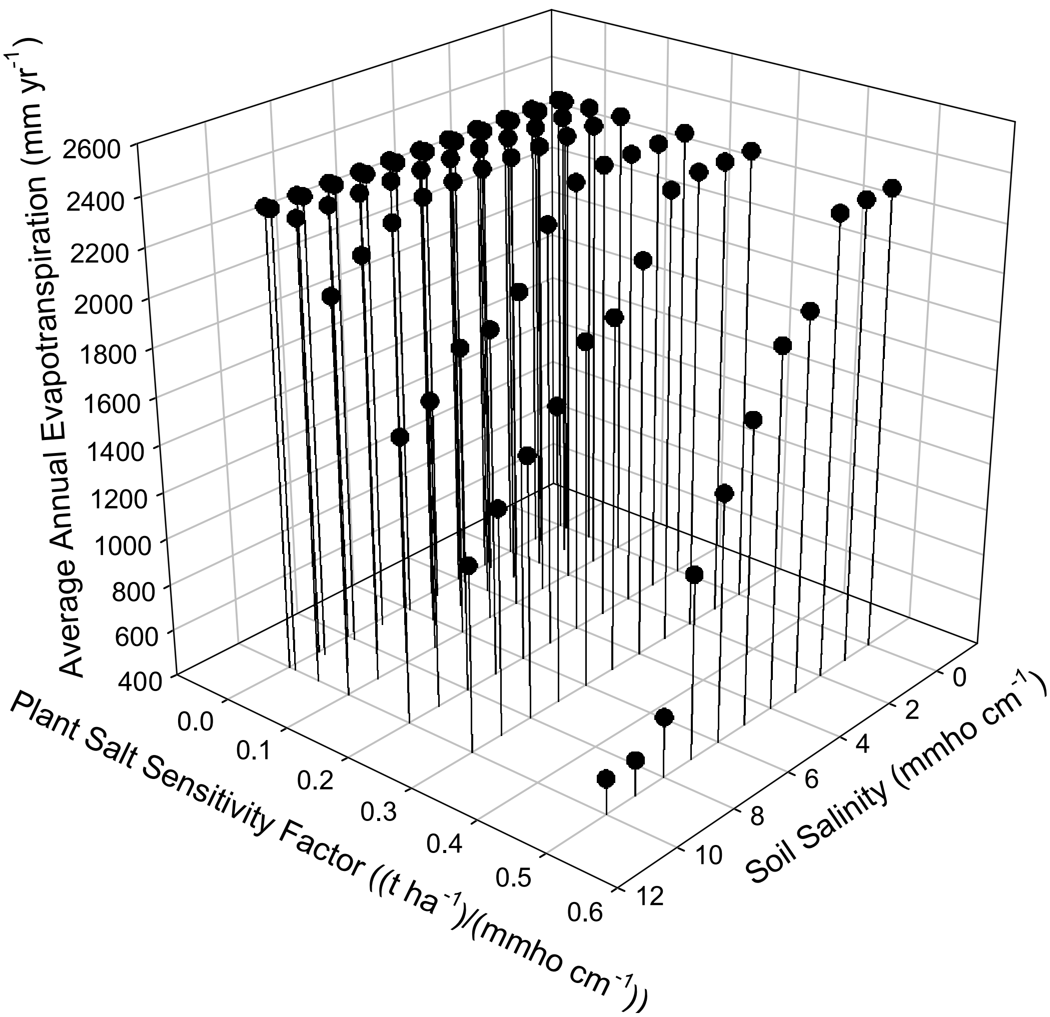


Figure 11. Effect of plant salt sensitivity factor and soil salinity on saltcedar simulation model's predicted evapotranspiration.

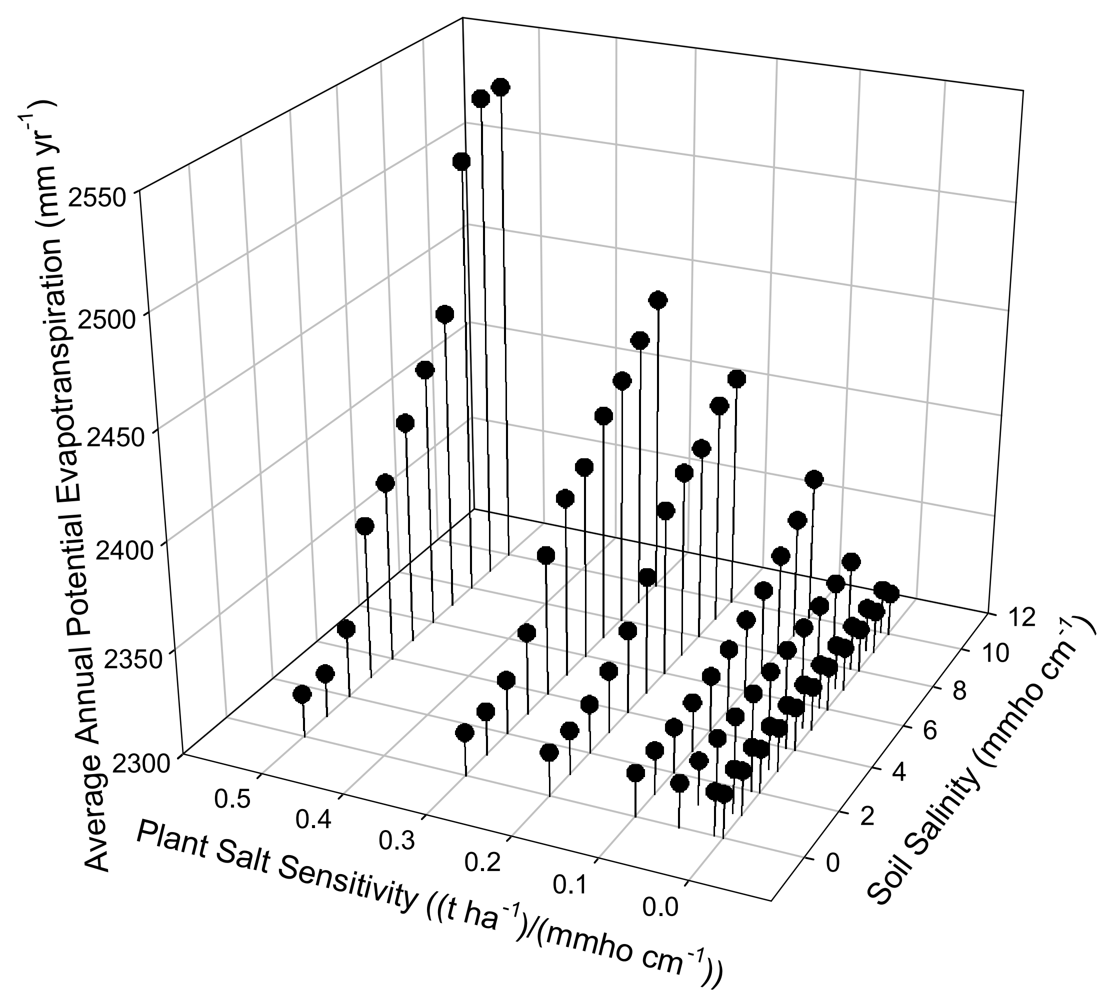


Figure 12. Effect of plant salt sensitivity factor and soil salinity on saltcedar simulation model's predicted potential evapotranspiration.

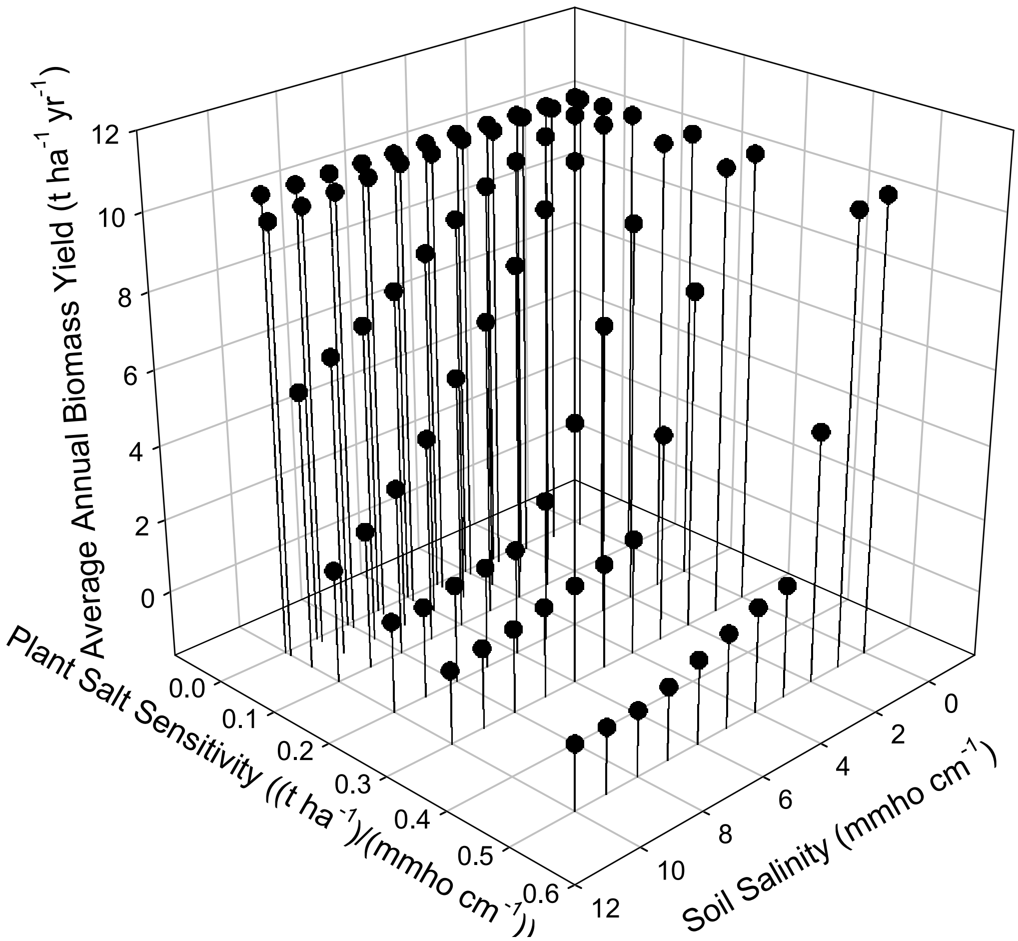


Figure 13. Effect of plant salt sensitivity factor and soil salinity on saltcedar simulation model's predicted biomass production.

Minimum and Maximum Water Table Depth

When minimum water table depth (m) was adjusted from 0.01 m to 3.0 m, saltcedar biomass production, PET, and plant transpiration varied little: 10.3-10.4 t ha^{-1}, 2323-2321 mm yr^{-1}, and 2258-2263 mm yr^{-1} respectively (Figures 14,15,16) Soil water evaporation decreased as minimum water table depth was increased. It ranged from 154 mm yr^{-1} to 59 mm yr^{-1} (Figure 17).

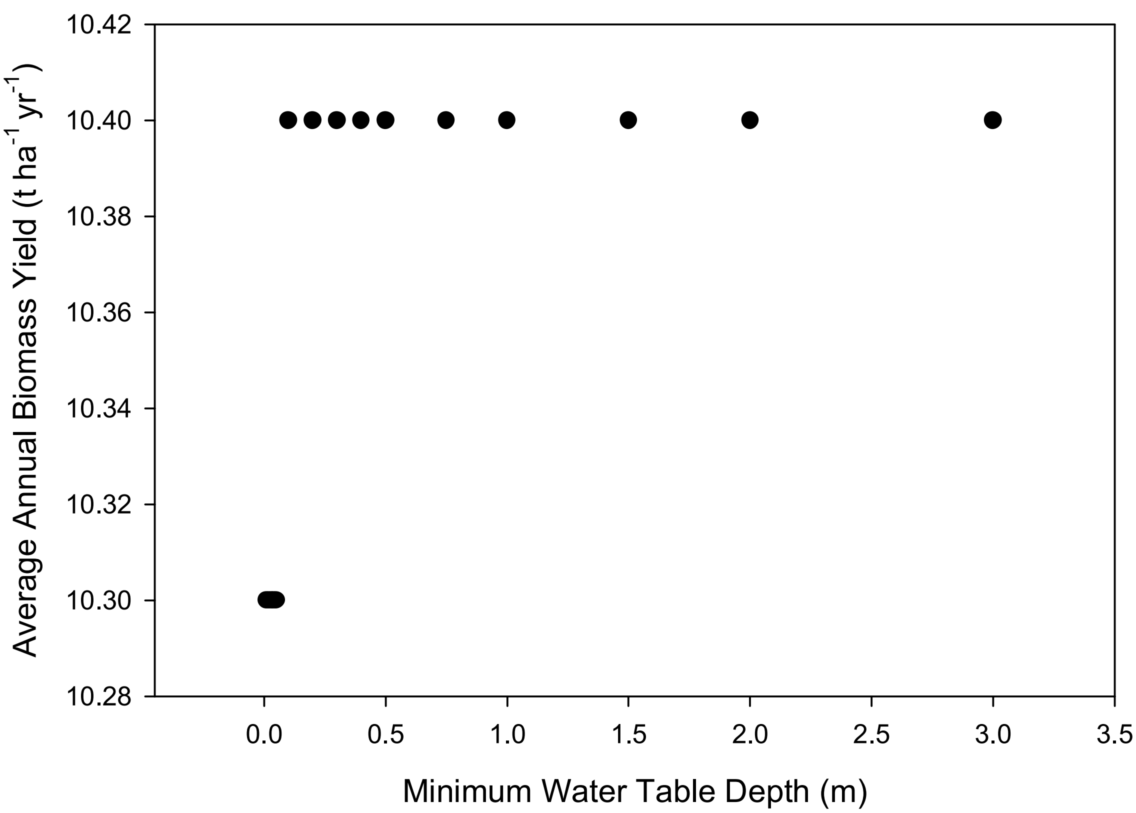


Figure 14. Effect of initial depth to the water table on the saltcedar simulation model predicted biomass production.

Maximum water table depth was varied from 0.0m to 15.0 m. As maximum water table depth increased predicted biomass remained constant at 10.4 t ha^{-1} until the water table was at 3.6 m, where a decline to 4.8 t ha^{-1} occurred. Biomass then exponentially decreased to 0.8 t ha^{-1} for a water table depth of 6.14 m, then remained constant (Figure 18). PET essentially did the opposite by increasing in a stair step fashion until reaching a plateau of 2435 mm yr^{-1} when the water table was at 6.14m (Figure 19).

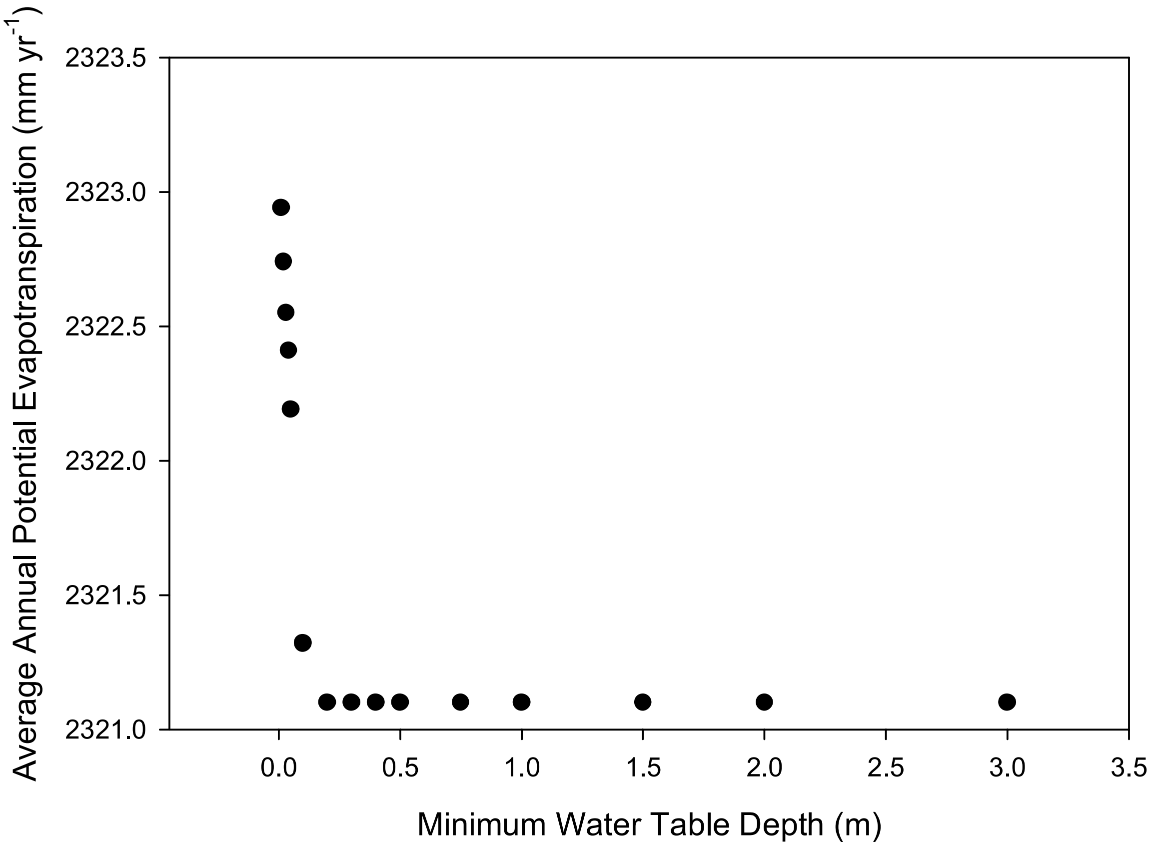


Figure 15. Effect of minimum depth to the water table on potential evapotranspiration using the saltcedar simulation model.

Soil water evaporation started out high (171 mm yr^{-1}) at the shallowest maximum water table depth then decreased to a low when the maximum depth varied between 3 to 6 m (59 mm yr^{-1}). As the maximum water table depth increased from 6 to 15 m soil water evaporation remained constant (84 mm yr^{-1}) (Figure 20).

The effects of the change in maximum water table depth on plant transpiration was similar to the effects on predicted saltcedar biomass. As maximum water table depth increased plant transpiration remained constant (approx. 2263 mm yr^{-1}) until the

3.6 m depth where it stair stepped down to 1354 mm yr^{-1} at the 4 m depth. Plant transpiration then appeared to exponentially decrease to 176 mm yr^{-1} at 6.14m and then remained constant (Figure 21).

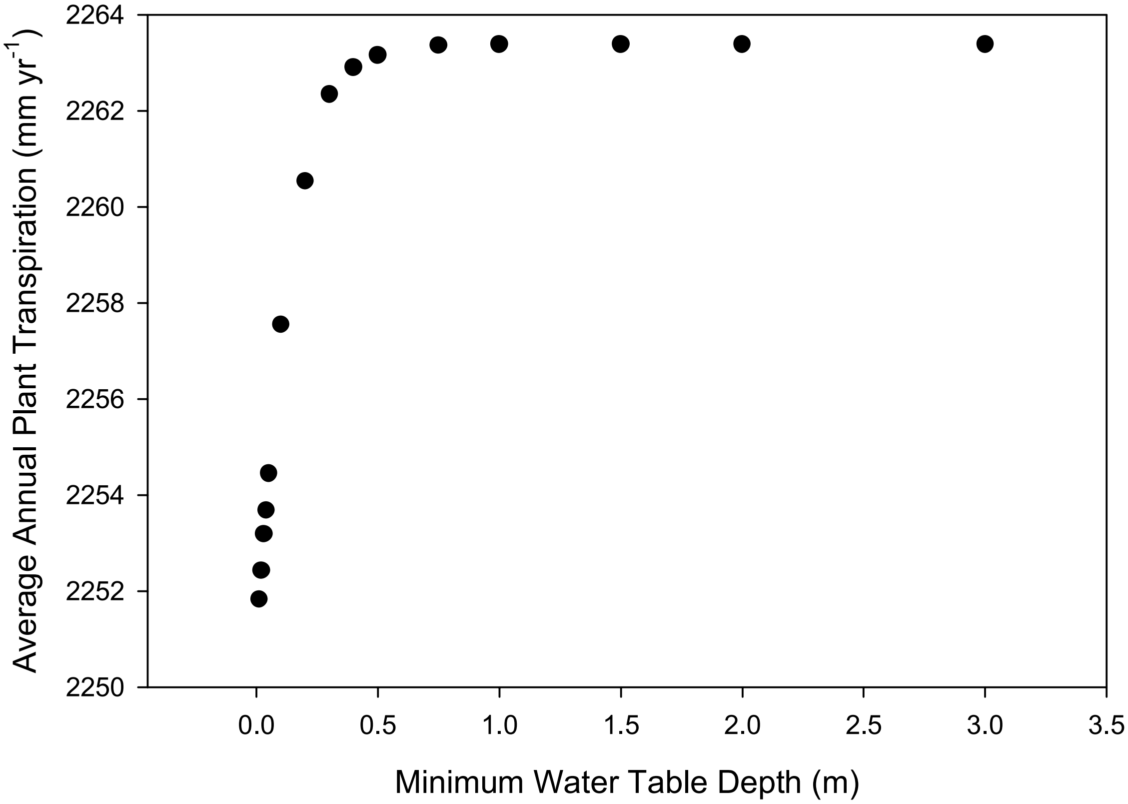


Figure 16. Effect of minimum depth to the water table on plant transpiration using the saltcedar simulation model.

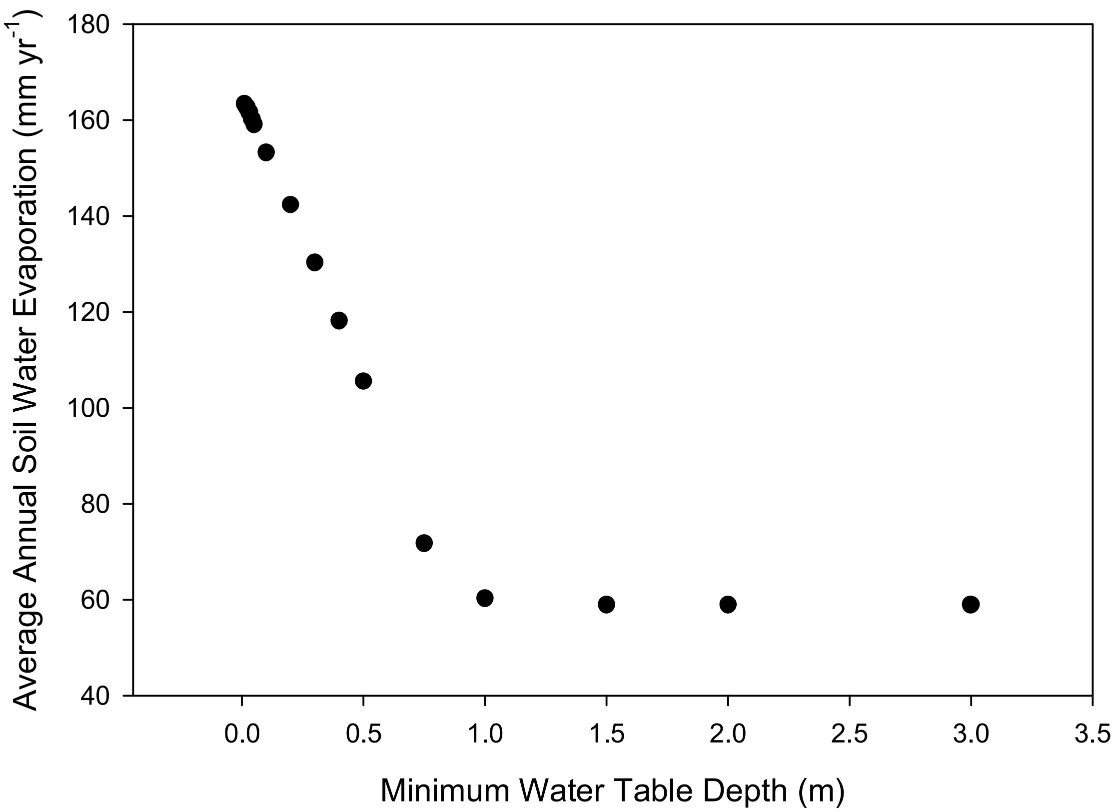


Figure 17. Effect of minimum depth to the water table on soil water evaporation using the saltcedar simulation model.

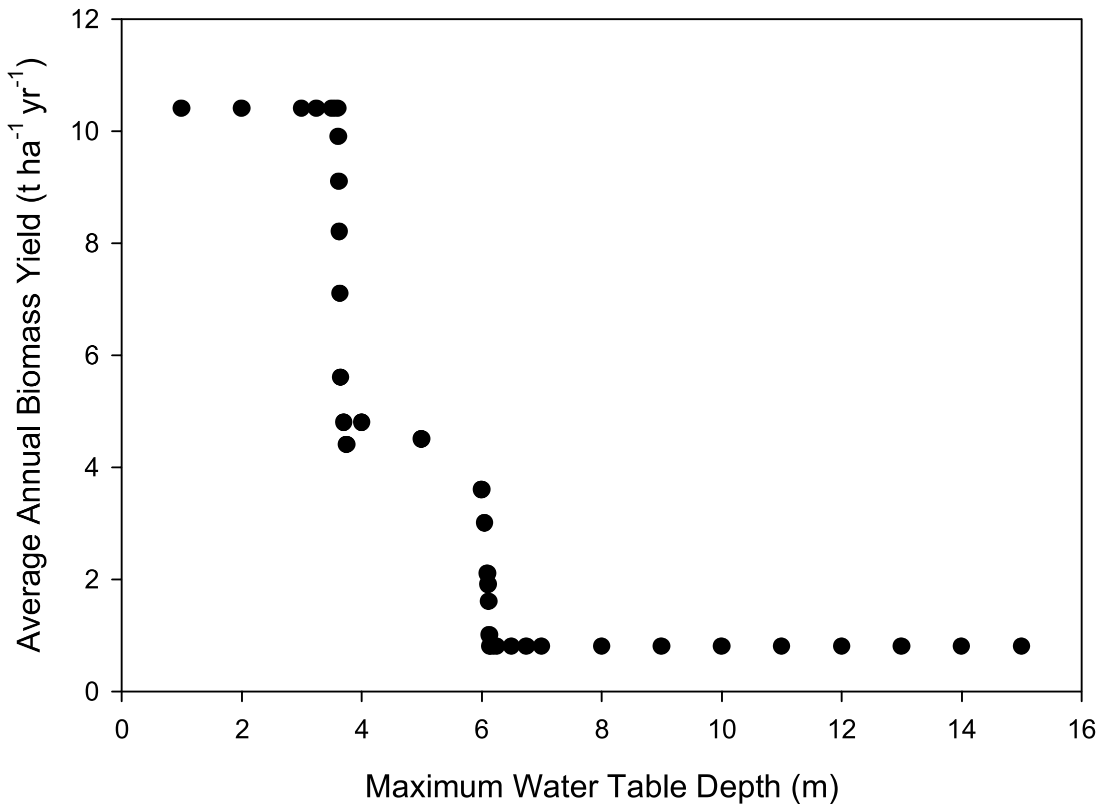


Figure 18. Effect of maximum depth to the water table on biomass production using the saltcedar simulation model.

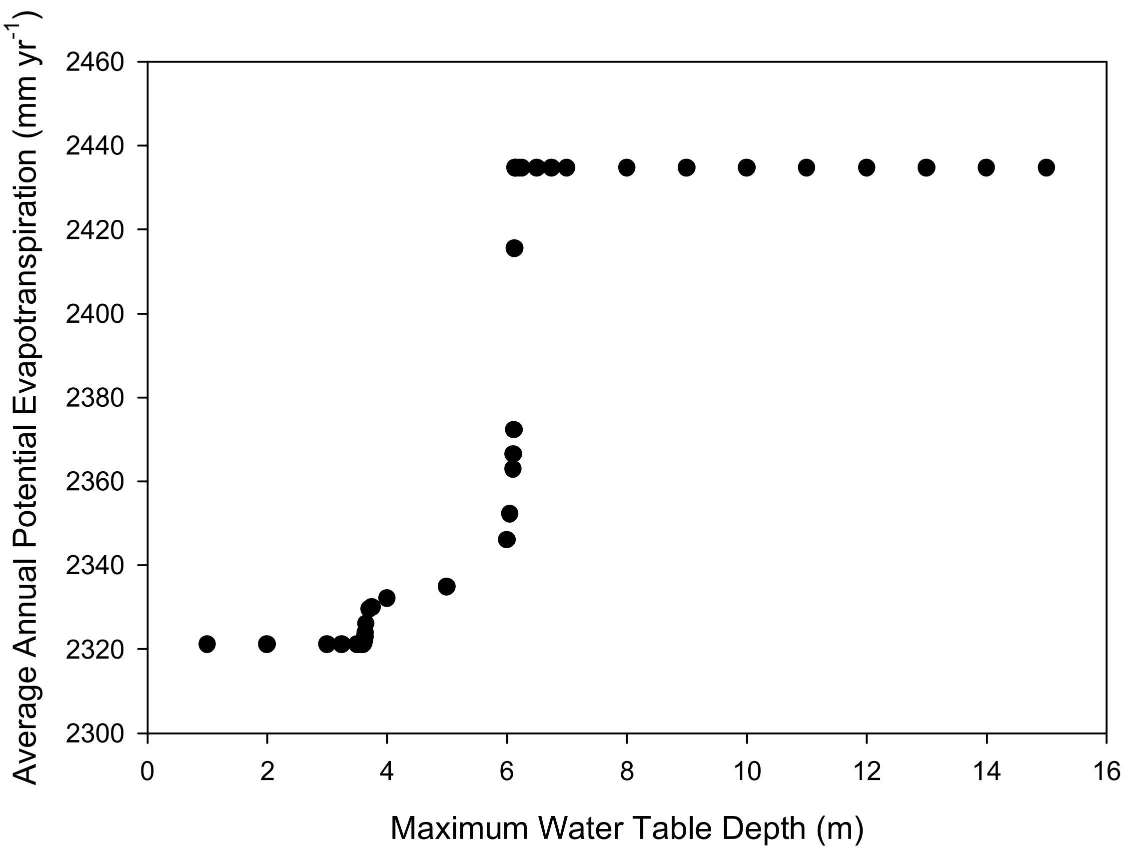


Figure 19. Effect of maximum depth to the water table on potential evapotranspiration using the saltcedar simulation model.

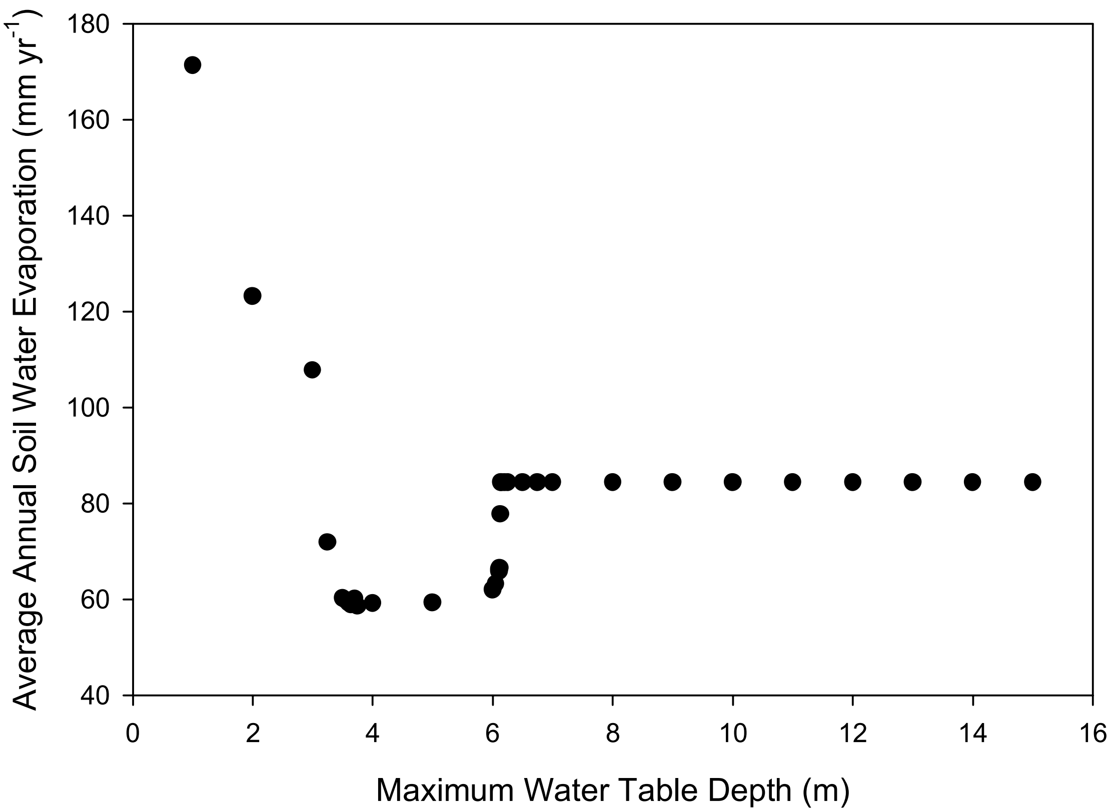


Figure 20. Effect of maximum depth to the water table on soil water evaporation using the saltcedar simulation model.

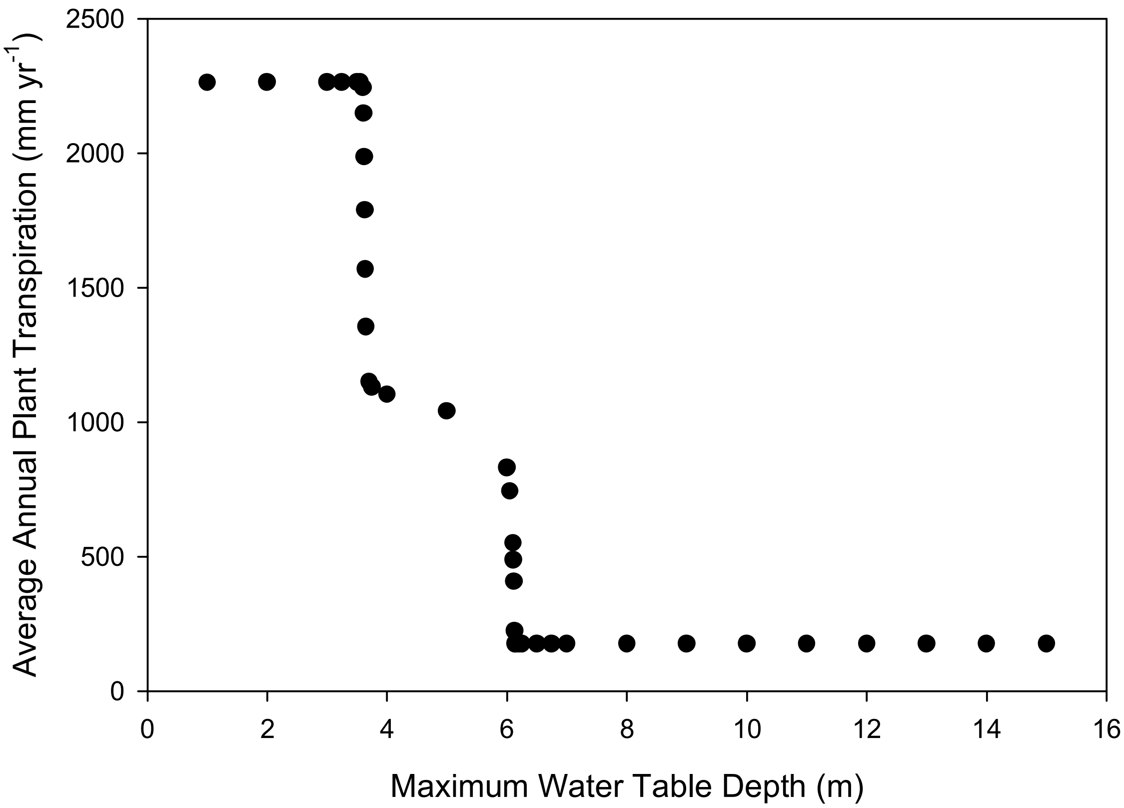


Figure 21. Effect of maximum depth to the water table on plant transpiration using the saltcedar simulation model.

Potential Leaf Area Index

Thirteen runs of the saltcedar simulation model were completed by adjusting the leaf area index from 0.5 to 12.0. As LAI increased, PET and soil water evaporation decreased in an exponential fashion (Figure 22, 23). Predicted ET increased in a linear fashion until the LAI reached 4 when the slope changed and then continued in a linear fashion but with a different slope (Figure 24). Plant transpiration also increased in a

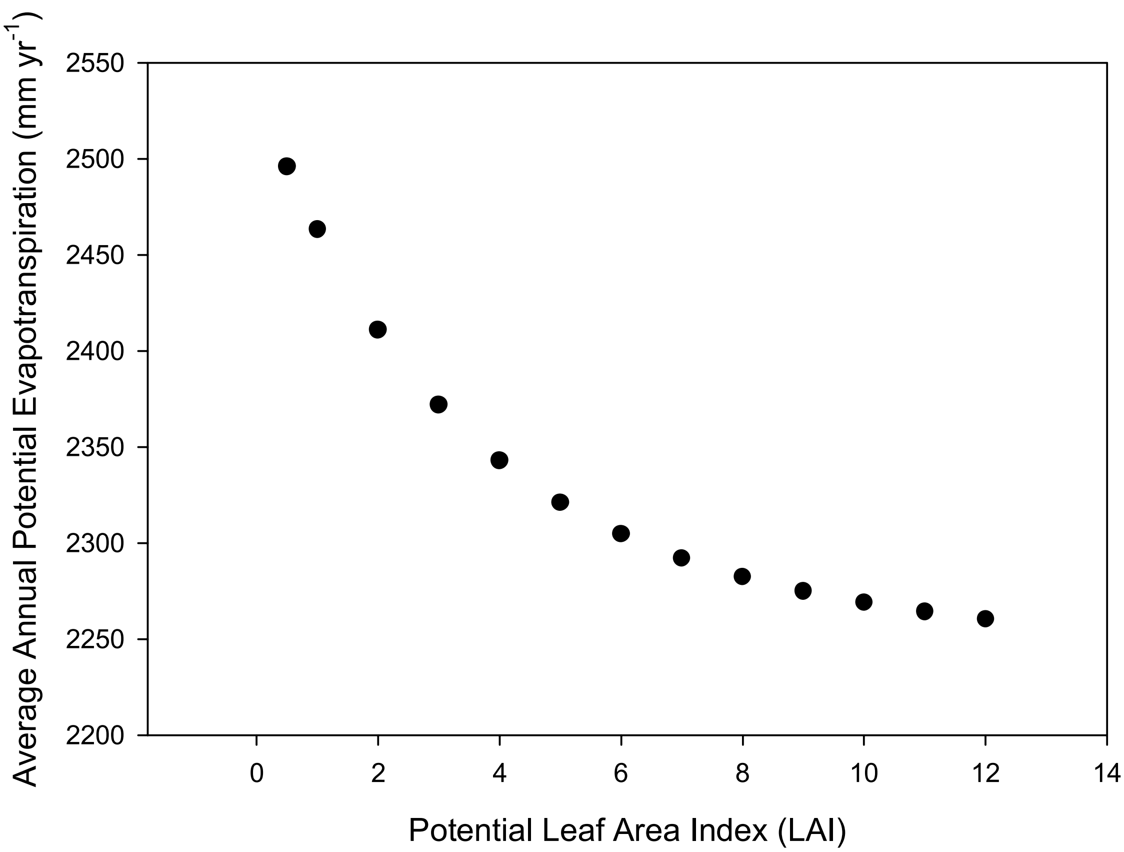


Figure 22. Effect of potential leaf area index on potential evapotranspiration using the saltcedar simulation model.

linear fashion until the LAI reached 4 when the slope changed and then continued in a linear fashion but with a different slope (Figure 25). As leaf area index increased, biomass increased (Figure 26). ET did not exceed PET until the LAI reached 5 (Figure

27).

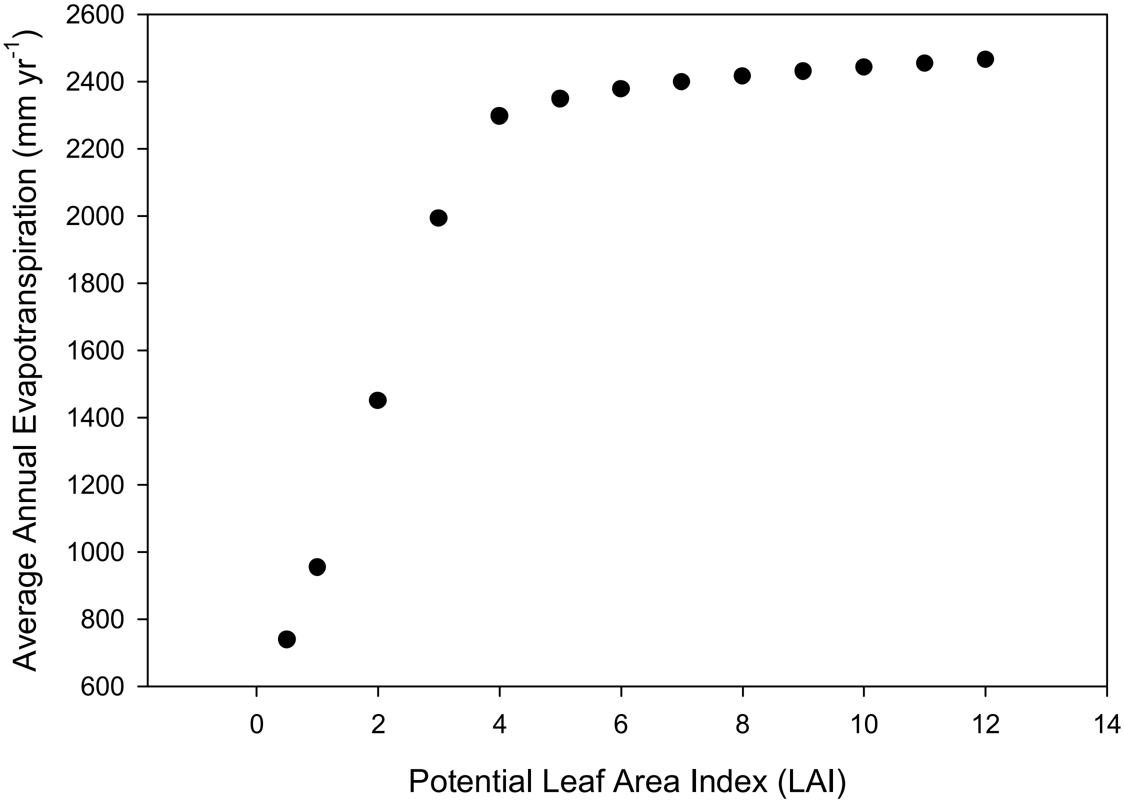


Figure 23. Effect of potential leaf area index on evapotranspiration using the saltcedar simulation model.

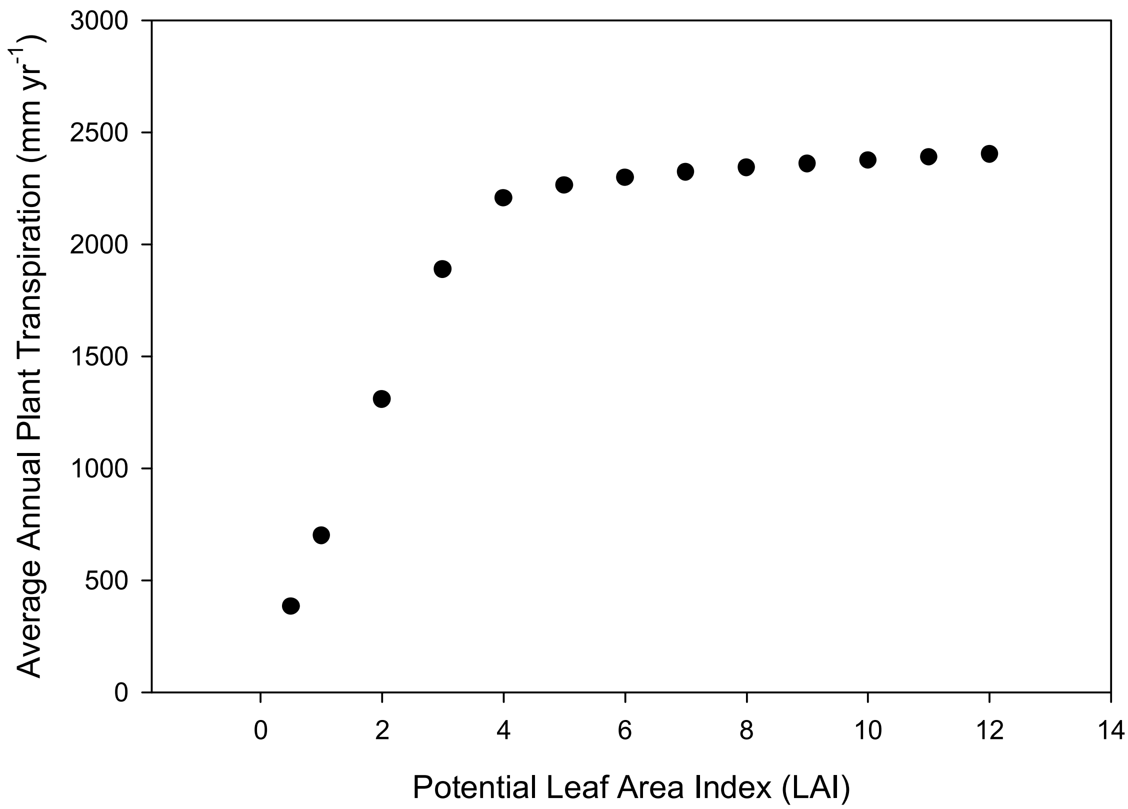


Figure 24. Effect of potential leaf area index on plant transpiration using the saltcedar simulation model.

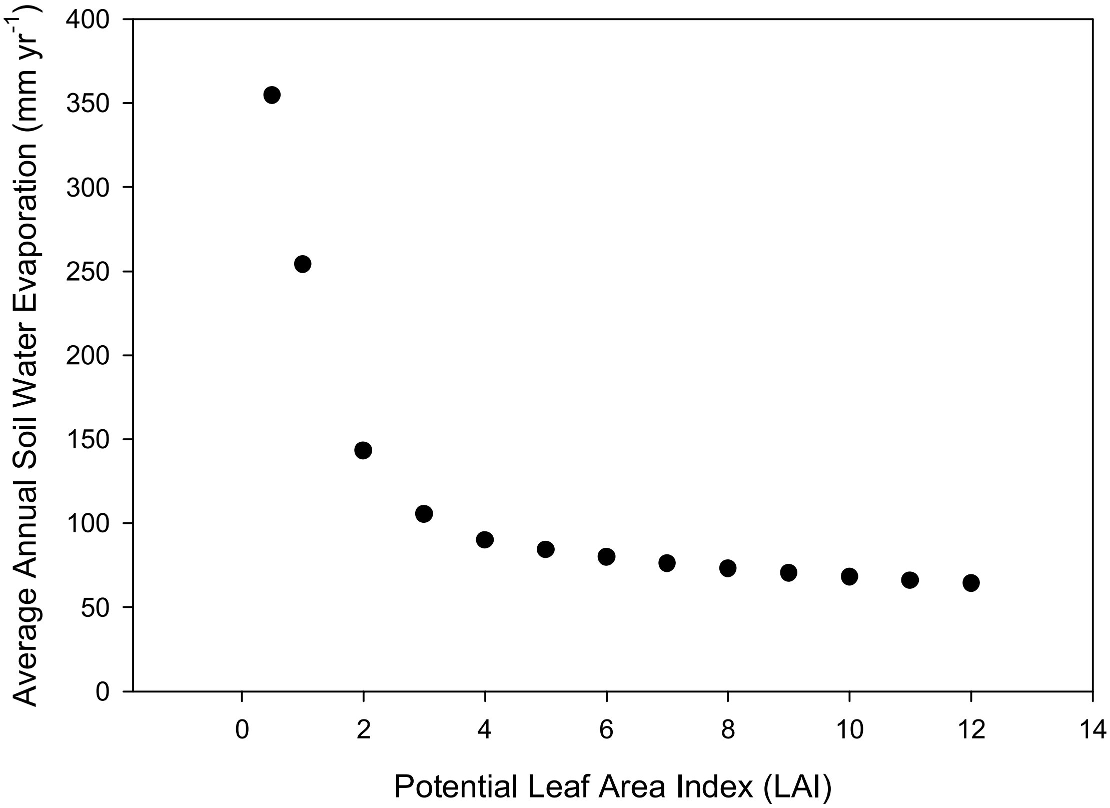


Figure 25. Effect of potential leaf area index on soil water evaporation using the saltcedar simulation model.

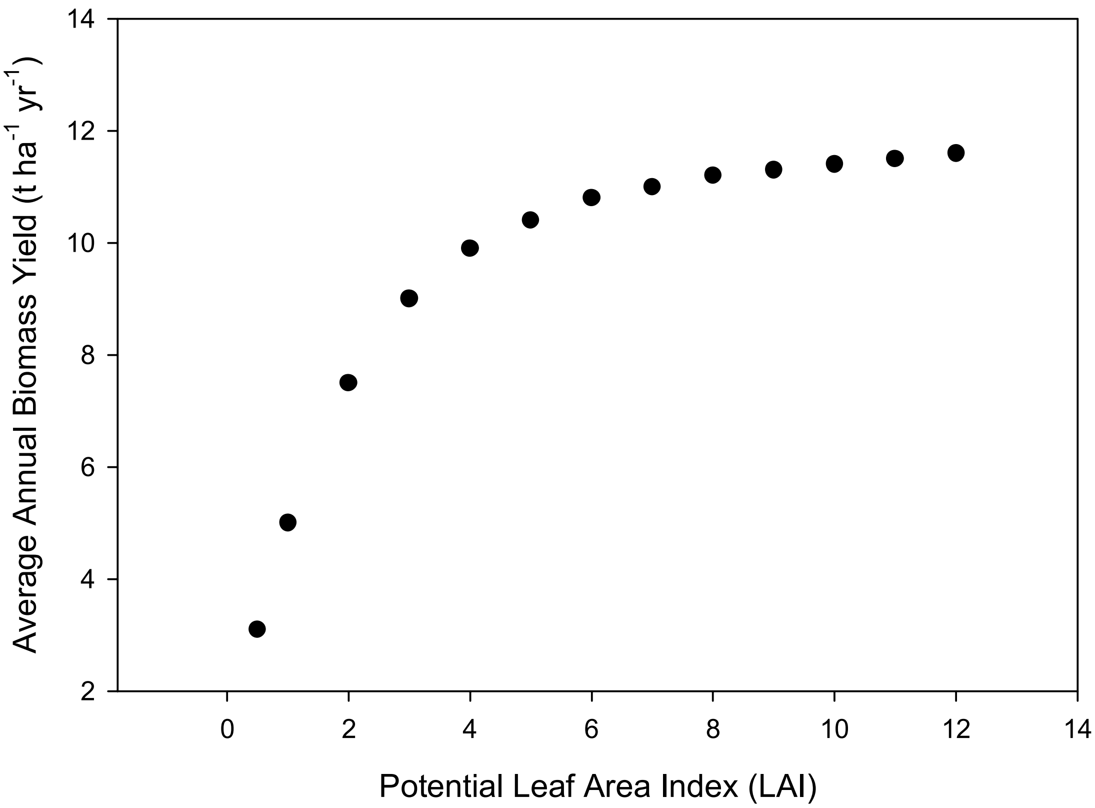


Figure 26. Effect of potential leaf area index on biomass production using the saltcedar simulation model.

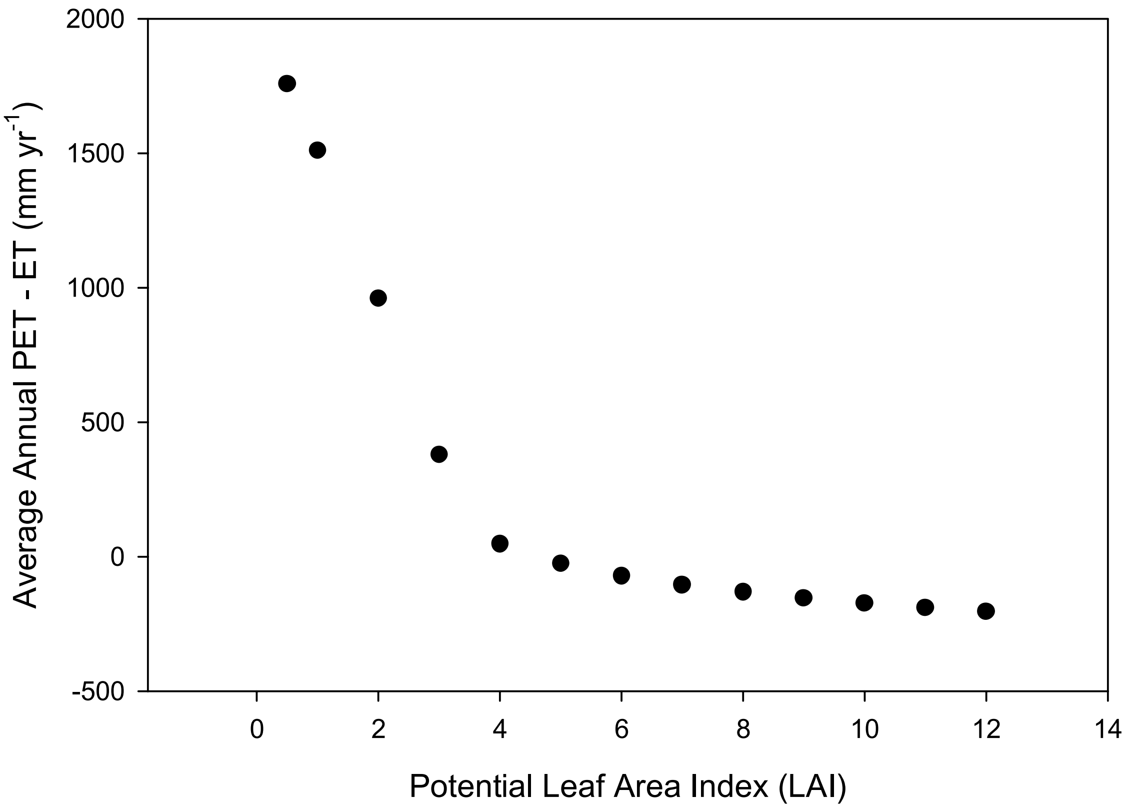


Figure 27. Plot of the difference of PET minus ET (mm) versus potential leaf area index using the saltcedar simulation model.

DISCUSSION and CONCLUSIONS

Characterization of Naturally and Artificially Established Stands

Leaf area indices from all collection sites were low compared to reported values for saltcedar, but this is not unreasonable since small isolated trees were sampled. If larger trees were sampled LAI should have increased. Light extinction coefficients (k) were similar across all sites, with the mean being -0.54. This was lower than the light extinction coefficient of the artificially established trees (-0.76), suggesting that naturally occurring trees were being limited, since the artificially established trees were of similar form and stature as the natural trees sampled. Based on these studies, young isolated saltcedar trees intercept approximately 50% of the incident light that reaches their canopy. LAI and k were correlated which was expected since the LAI increased over a given area the more leaf area there is to intercept light thus increasing the light extinction coefficient. The ratio of leaf area to fresh weight (16.8 cm^2 g^{-1}) can be used to estimate leaf area in the field by weighing the fresh weight of the leaves and then calculating the leaf area. If the area over which the sample was collected was known, then you could easily estimate the LAI for the site by dividing leaf area by the area of the sample.

Since the light extinction coefficient of saltcedar was significantly higher with a lower LAI than *Salix spp.* or *Populus spp.* this apparently gives saltcedar a competitive advantage with greater light interception per unit of leaf area. This could give saltcedar the ability to shift more energy to other areas of growth (i.e. roots) and, thus, not be limited by that factor as much.

Effect of Salinity and Water Table Depth on Saltcedar Growth and Water Use

Saltcedar demonstrated a diurnal pattern in the rate of discharge from the water supply tubes (water use), with discharge occurring in the early morning and the low occurring late afternoon/early evening. This peak discharge time is different from Gay and Sammis (1977) and Smith (1989) which reported that peak transpiration occurred around noon. White et al. (2003) found the diurnal cycle in the shallow groundwater table to occur in late afternoon or evening. The lag time between transpiration and changes in the water table have not been adequately documented. Salinity did not have any significant effect on the timing or the minimum or maximum rate of discharge (water use). Hagemeyer and Waisel (1987) reported that salinity did not affect the timing of saltcedar transpiration but did dampen its transpiration rates.

As salinity increased to 1.25 ppt, water use (with the water logger discharge records) peaked at 109 ml of water per day then decreased to a level nearly equal to the 0.0 ppt level even though salinity was 7.5 ppt. This seems to indicate that salinity may increase water use up to a certain point and then decrease water use once this "optimum" is reached. However, the sight tube results for two days in July did not indicate this (Figure 28). The sight tubes indicated a trend of decreasing water use as salinity increased, with the peak water use at the lowest salinity level.

Water table depth had a significant effect on water use. Both the sight tubes and water loggers indicated that as water table depth increased water used decreased (Figure 30). This research supports the findings of numerous authors that indicated depth to the water table is a major factor affecting saltcedar water use.

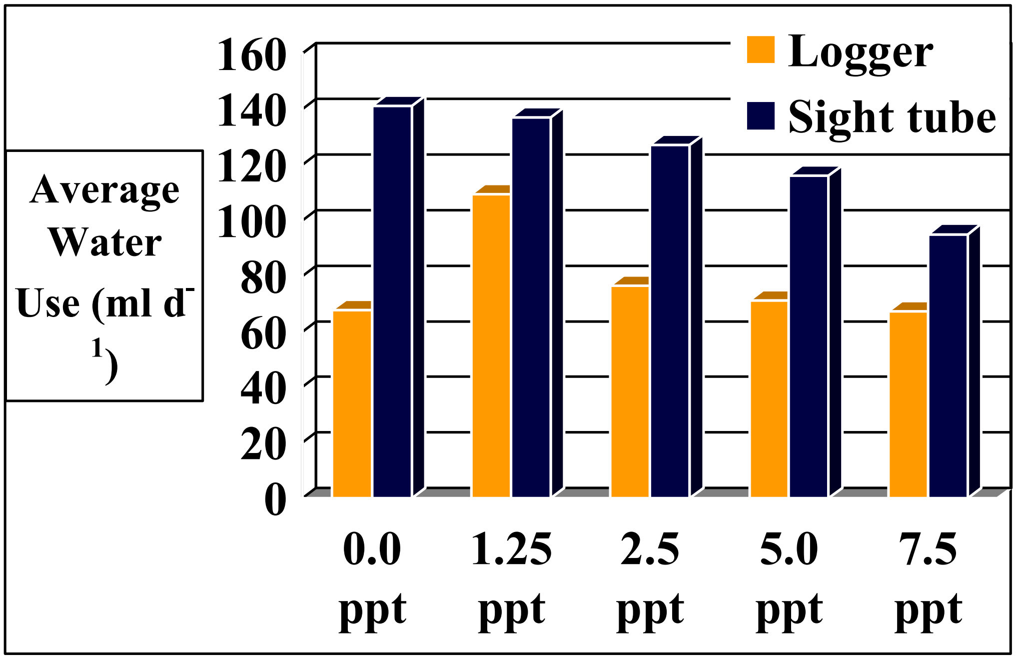


Figure 28. Average water use of saltcedar using water loggers and sight tubes for each salinity level across all water table depths.

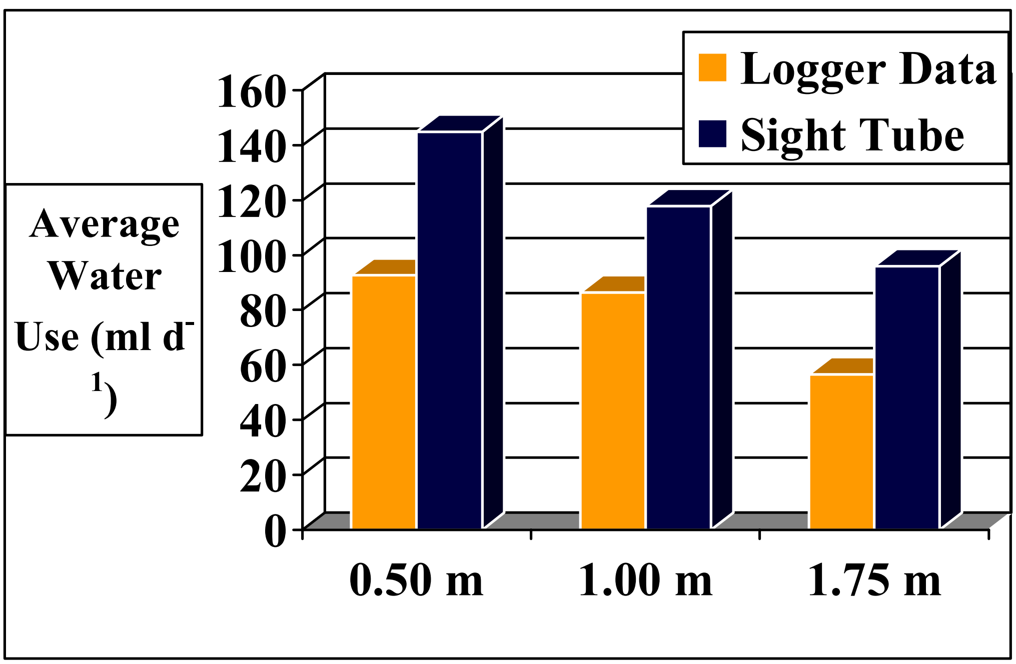


Figure 29. Average water use of saltcedar using water loggers and sight tubes for each water table depths across all salinities.

The average use of 77 ml day^{-1} for the sight tube results is close to the water logger average for the whole season of 71 ml day^{-1}. Thus the two methods appear to validate each other. A comparison of this research with other studies in shown in Figure 30. The regression equations from four of the studies have very similar interception points and slope, indicating that regardless of many other factors depth to the water table may be useful in estimating water use. These regressions should not be extrapolated beyond a 2.5 meter depth to the water table. Numerous studies indicate saltcedar water use still occurs at depths greater than 7 meters. A combined regression equation showed an interception point of 364.2 cm/yr (water table at the soil surface) (for a very shallow water table on the Canadian River in Texas, White et al. (2003) estimated growing season water use by saltcedar and associated vegetation was 350.5 cm/yr to 420.6 cm/yr in 2001). In addition, the saltcedar simulation model predicted water use in relation to changes in depth to the water table. Regression of these results produced the following equation: water use (cm/yr) = 263.5+-47.18*depth_in m with an r-square of 0.86. More research is needed across an array of situations to determine if this single variable can be used in new situations to estimate the impact of saltcedar on groundwater availability. However, White et al. (2003) identified several factors that would need to be measured and comparison between sites based on common standards, i.e., length of growing season.

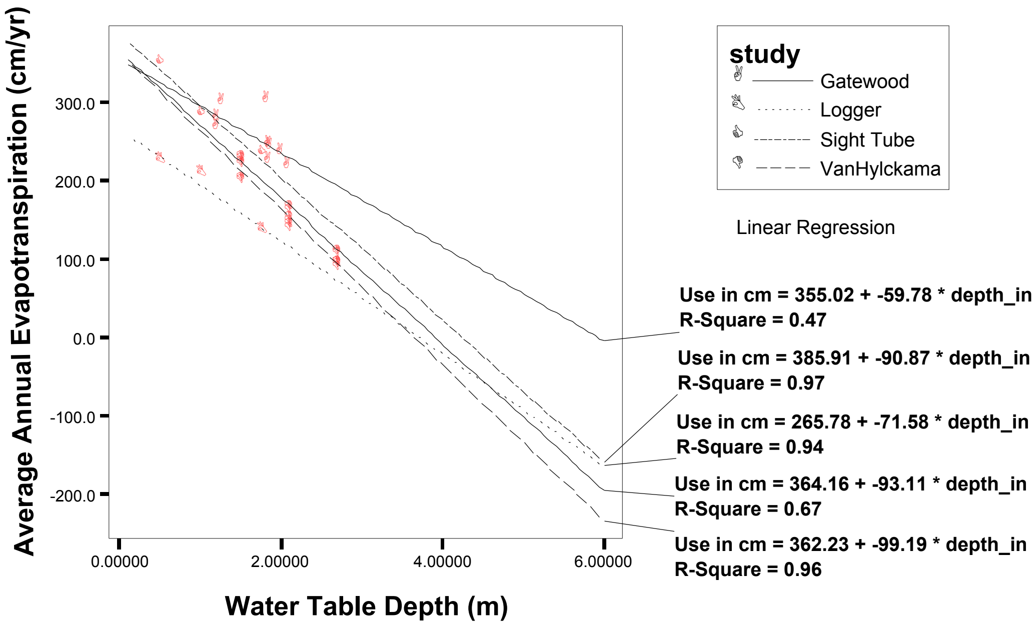


Figure 30 Regression equations for this study and other studies using water table depth to predict average annual saltcedar water use (cm yr^{-1}).

When a predictive equation for saltcedar daily water use was developed using salinity and water table depth as the dependent variables it explained very little of the variation ($r^2 = 0.050$). Other authors have noted daily fluctuations in water use even when the water table was relatively steady. An equation that explains much more of the variability (r^2=0.568) resulted when climatic data from the current day and the previous day are included (in a stepwise procedure). That the later equation included more variables from the previous day than variables from the day of occurrence indicating that the previous days weather may have just as great or maybe greater influence on current day's water use. The previous amount of solar radiation explained the most variability with water table depth, average wind speed, and salinity following.

Original saltcedar transplant material increased in biomass indicating that growth of the original stems continued throughout the study. Total stem weight increased after each harvest even though total number of branches decreased indicating that even though plants were losing total number of stems as the season progressed they were able to compensate for this by increasing growth of the remaining stems.

Root biomass generally peaked at the water table interface. The 1.75 m water table level was an exception although there was a second a peak at the water table interface. This could be an artifact due to greenhouse plants with an accumulated root mass at the bottom of the 1m long tubes that did not disappear after adding the additional meter of soil and moving the water table from a one meter depth to the 1.75 meter depth. It also could be due to the taproots weighing more than fine roots that had to extend into the new soil profile. The dominant amount of fine root biomass was observed at the water table level for all depths (Figure 31). The saltcedar plants also had roots extending into the saturated soil profiles. This could be a survival mechanism to insure that if the water table were to drop the plants would continue to survive and grow.

Salinity levels did not significantly affect biomass for any harvest date or harvest dates combined. This would lend credence to the classification of saltcedar as a halophyte.

Water table depth affected distribution of roots, total amount of roots, stem weights, leaf weight, leaf area, and height of the plant. This indicates that water table depth has a very significant effect on plant growth form. There were positive correlations between sight tube water use and root weight, stem weight, leaf area, and leaf weight indicating that as biomass increased transpiration increased.

Figure 31. Photograph of root distribution of saltcedar grown in an individual lysimeter. Note the fine root biomass at the bottom of the tube; this was at the water table level.

Saltcedar Simulation Model Testing

The saltcedar simulation model prediction of water use for the Pecos River approximated water use reported by White et al. (2003) when a high LAI was used. White et al (2003) reported an average of 2399 mm of water use per growing season compared to the model prediction of 2260 mm per year with a LAI of 5. The model had much higher predicted use (1060 mm) for the Colorado River than White et al (2003) showed (438 mm per growing season). This could be due to the water table being set for 1.0 m compared to the reported depth to the water table of 6.7 m and a LAI for grass was set at 3 when grasses are minimal and only access surface water from precipitation. The model predicted 1404 mm of water use on the Canadian river, which is less than half the estimate of 3043 mm (White et al 2003). This is most likely due to the very low LAI used in the model and the model failing to increase water use when the water table was shallower than 2.0m. The site at the Canadian river probably has one of the highest LAI for sites studied. The Canadian River site has a mix of saltcedar, cottonwood, willow, Russian olive, buttonbush, and grasses. It also has the shallowest water table and lowest salinity.

Generally the model functioned in the manner expected: ET, transpiration, and biomass decreased as soil salinity and the plant's salt sensitivity factor increased. The plant salt sensitivity factor is critical. If the plants salt sensitivity is set too high or too low, the effect of soil salinity and transpiration and biomass could be underestimated. . Increasing soil salinity and plant salt sensitivity unexpectedly increased PET. It is not clear how these are linked and why this happened since PET is calculated from weather variables.

Minimum water table depth when varied over 0.0-3.0 m did not have much effect on biomass unless the water table was extremely high and even then it only caused a decrease in production of 0.10 ton ha^{1}. PET and soil water evaporation behaved in an expected manner. Transpiration increased by 1 cm until the 1.0 m water table depth and then remained stable.

When maximum water table depth was varied over 0-15 m two critical points became apparent: 3.75 m and 6.0 m maximum water depths. At these points biomass would stair step down. At the 6.0 m water level saltcedar was predicted to no longer be able to access the water table and had to subsist on rainfall, which produced a very low biomass. PET increased as water table depth increased possibly due to increased soil water evaporation. Soil water evaporation decreased until around six meters due two lack of plant transpiration, that is water that normally would have been transpired by saltcedar just evaporates from the soil surface. Transpiration by saltcedar decreased in a stair step fashion until water the water table reached approximately 6.0 m at which point the model predicts the plant can no longer access the water table and must subsist on rainfall alone and thus can only transpire as much rainfall it captures.

Leaf area index affected PET, ET, transpiration, soil water evaporation, and biomass in an expected manner. PET and soil water evaporation each decreased as LAI increased. At a LAI of around 5 or so it should be noted that ET, transpiration, and biomass began to level of. It is not clear to me why this is necessarily so except indicating that there is an upper limit to the amount of water that can be transpired from a site and the amount of biomass that can be produced. When ET is subtracted from PET it was found that ET did not exceed PET until a LAI of around 4 was reached.

Overall Conclusions

1. Increasing depth to the water table was the major factor that decreased saltcedar growth and water use.
2. Depth to the water table appears from this study and others to explain most the variation in seasonal estimates of saltcedar water use, while climatic factors appear to explain daily variation in water use.
3. Increasing salinity slight decreased saltcedar water use.
4. Salt cedar's transpiration functioned in a diurnal rhythm though the timing of this rhythm is probably site and season specific.
5. With more energy efficiency saltcedar has a competitive advantage over willow and cottonwood.
6. The saltcedar simulation model reasonably predicted water use when LAI was adjusted to observed field conditions and water tables were greater than 2.0 m. but less than 4 m.

Recommendations

Salinity and Water Table Depth Experiment

1. Use water loggers on all water supplies instead of rotating them across levels to reduce missing data and have concurrent data sets for the same atmospheric conditions.
2. Use a wider range of depths to the water table and salinity.
3. Use cuttings from one parent tree to avoid genetic variability.

4. Establish all cuttings in complete lysimeters to be used through out the study to avoid transplanting stress and artifact root biomass distribution.
5. Prevent rainfall input to the lysimeters.
6. Sort root biomass into fine roots versus tap roots.
7. Grow plants for more than one growing season.

Saltcedar Simulation Model Development

1. Ascertain what the appropriate salt sensitivity factor is for saltcedar, since this greatly affects the results.
2. Water table depth functions need to be improved since experimental and literature results indicate that water table depth is a major factor.
3. Advection energy adjustments to estimate water use need to be refined to allow effects up to two times PET. Research on the advective energy factor for different saltcedar/riparian situations is needed to provide guidance.
4. Soil/water evaporation losses for very shallow water tables that encompasses the stream channel water evaporation and recharge of surrounding soil profiles need to be explored for different situations.

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APENDIX A

Table 19. Summary of evapotranspiration studies on saltcedar.

Study Author	Method	Site description	Depth to water table in m	cm of use[2]
Anderson 1977	Gas exchange chamber	Benardo, New Mexico		1.5 $gH_2O\ dm^{-2}\ h^{-1}$
Cleverly et al 2002	Eddy Covariance	Non-flooding		74
Cleverly et al 2002	Eddy Covariance	Non-flooding		76
Cleverly et al 2002	Eddy Covariance	Unflooded mixture of plants		84.8
Cleverly et al 2002	Eddy Covariance	Flooding		111.0
Cleverly et al 2002	Eddy Covariance	Flooding		122.0
Cleverly et al 2002	Eddy Covariance	Flooded monospecific stand of saltcedar		139.9
Davenport et al 1982	Lysimeter		1.5	72.0
Davenport et al 1982	Drums	3905 plants/ha		39.7
Davenport et al 1982	Drums	15618 plants/ha		116.1
Davenport et al 1982	Drums	27768 plants/ha		173.9
Davenport et al 1982	Drums	62474 plants/ha		284.5
Davenport et al 1982	Drums	Isolated plant		5.8 kg H_2O/day
Davenport et al 1982	Drums	Isolated plant		5.6 kg H_2O/day
Davenport et al 1982	Drums	Isolated plant		5.7 kg H_2O/day
Devitt et al 1998	Bowen Ratio	11% advection		75.0
Devitt et al 1998	Bowen Ratio	25% canopy dieback caused increase in		145.0

[2] When yearly water use was not given water use was assumed to have a 180-day growing season and converted when possible.

		advection to 65%		
Gatewood et al 1950	Well	Baccharis and saltcedar	1.1	125.81467
Gatewood et al 1950	Lysimeter		1.2	266.7
Gatewood et al 1950	Lysimeter		1.2	276.9
Gatewood et al 1950	Lysimeter		1.3	297.2
Gatewood et al 1950	Well		1.4	137.5
Gatewood et al 1950	Lysimeter		1.7	244.0
Gatewood et al 1950	Well		1.8	199.6
Gatewood et al 1950	Well		1.9	156.5
Gatewood et al 1950	Lysimeter		1.8	299.7
Gatewood et al 1950	Lysimeter		1.8	223.5
Gatewood et al 1950	Lysimeter		1.8	243.8
Gatewood et al 1950	Lysimeter		1.9	241.3
Gatewood et al 1950	Well		1.9	109.0
Gatewood et al 1950	Lysimeter		2.0	233.7
Gatewood et al 1950	Lysimeter		2.1	215.9
Gatewood et al 1950	Well		2.17932	274.5
Gatewood et al 1950	Well		2.2	155.4
Gatewood et al 1950	Well		2.4	92.2
Gay and Sammis 1977	Energy balance			0.5-2.8 $\mu g/cm^2$-s
Gay and Sammis 1977	Lysimeter	Lysimeter	1.5	143.8
Gay and Sammis 1977	Bowen Ratio	Bowen ratio		147.6
Glenn et al 1998	Green house			12.86 $g\ g^{-1}\ day^{-1}$
Ingles et al 1996	Well	*Tamarix spp.*	0.8	186.5

		thicket		
Kiniry et al 2003	Model simulation	Pecos River		37.7
Kiniry et al 2003	Model simulation	Pecos River		68.8
Kiniry et al 2003	Model simulation	Colorado River		106.0
Kiniry et al 2003	Model simulation	Pecos River		128.6
Kiniry et al 2003	Model simulation	Canadian River		140.4
Kiniry et al 2003	Model simulation	Pecos River		188.9
Kiniry et al 2003	Model simulation	Pecos River		220.3
Kiniry et al 2003	Model simulation	Pecos River		226.0
Robinson 1958	Tanks	*Tamarix spp.*	1.4	142.6
Robinson 1958	Tanks	*Tamarix spp.*	1.7	167.0
Robinson 1958	Well		1.8	183.8
Robinson 1958	Tanks	*Tamarix spp.*	2.1	213.4
Robinson 1958	Tanks	*Tamarix spp.*	2.2	223.4
Robinson 1958	Tanks	*Tamarix spp.*	2.4	236.2
Robinson 1958	Tanks	*Tamarix spp.*	2.6	256.6
Robinson 1958	Tanks	*Tamarix spp.*	2.8	279.5
Tomanek, G.W., Ziegler, R.L. (1962)	Field box apparatus			0.129 g H_2O dm^{-2} (leaf area) hr^{-1}
Tomanek, G.W., Ziegler, R.L. (1962)	Field box apparatus			0.050 g H_2O dm^{-2} (leaf area) hr^{-1}
Tomanek, G.W., Ziegler, R.L. (1962)	Green house gravimetric			0.16 g H_2O cm^{-2} (leaf area) day^{-1}
Tomanek, G.W., Ziegler, R.L. (1962)	Green house gravimetric			3.8 g H_2O dm^{-2} (leaf area) day^{-1}
Van Hylckama 1970	Evapotranspirometers		1.5	214.7
Van Hylckama 1970	Evapotranspirometers		1.5	216.7
Van Hylckama 1970	Evapotranspirometers		2.1	145.9
Van Hylckama 1970	Evapotranspirometers		2.1	153.0
Van Hylckama 1970	Evapotranspirometers		2.7	95.1
Van Hylckama 1970	Evapotranspirometers		2.7	98.2
Vandersande et al 2001	Green house gravimetric	500 NaCl mg/l		2.86 kg H_2O
Vandersande et al 2001	Green house gravimetric	1000 NaCl mg/l		2.75 kg H_2O
Vandersande et al 2001	Green house gravimetric	2000 NaCl mg/l		2.80 kg H_2O
Vandersande et al 2001	Green house gravimetric	4000 NaCl mg/l		2.75 kg H_2O
Weeks et al 1987	Eddy Covariance	Wet Old Growth	0.8	39.6
Weeks et al 1987	Eddy Covariance	Wet Old Growth	0.8	77.4
Weeks et al	Energy budget	Wet Old	0.8	79.2

1987		Growth		
Weeks et al 1987	Energy budget	Wet Old Growth	0.8	97.2
Weeks et al 1987	Eddy Covariance	Burned	1.8	34.2
Weeks et al 1987	Eddy Covariance	Burned	1.8	50.4
Weeks et al 1987	Energy budget	Burned	1.8	57.6
Weeks et al 1987	Energy budget	Burned	1.8	73.8
Weeks et al 1987	Eddy Covariance	Mowed	3.3	25.2
Weeks et al 1987	Eddy Covariance	Mowed	3.3	32.4
Weeks et al 1987	Eddy Covariance	Mowed	3.3	39.6
Weeks et al 1987	Eddy Covariance	Mowed	3.3	39.6
Weeks et al 1987	Eddy Covariance	Mowed	3.3	46.8
Weeks et al 1987	Eddy Covariance	Mowed	3.3	63
Weeks et al 1987	Energy budget	Mowed	3.3	37.8
Weeks et al 1987	Energy budget	Mowed	3.3	77.4
Weeks et al 1987	Energy budget	Mowed	3.3	79.2
Weeks et al 1987	Energy budget	Mowed	3.3	86.4
Weeks et al 1987	Energy budget	Mowed	3.3	108.0
Weeks et al 1987	Eddy Covariance	Old growth	3.4	12.6
Weeks et al 1987	Eddy Covariance	Old growth	3.4	21.6
Weeks et al 1987	Eddy Covariance	Old growth	3.4	21.6
Weeks et al 1987	Eddy Covariance	Old growth	3.4	23.4
Weeks et al 1987	Eddy Covariance	Old growth	3.4	28.8
Weeks et al 1987	Eddy Covariance	Old growth	3.4	55.8
Weeks et al 1987	Eddy Covariance	Old growth	3.4	73.8
Weeks et al 1987	Energy budget	Old growth	3.4	23.4
Weeks et al 1987	Energy budget	Old growth	3.4	32.4
Weeks et al 1987	Energy budget	Old growth	3.4	34.2
Weeks et al 1987	Energy budget	Old growth	3.4	48.6

Weeks et al 1987	Energy budget	Old growth	3.4	50.4
Weeks et al 1987	Energy budget	Old growth	3.4	84.6
Weeks et al 1987	Energy budget	Old growth	3.4	86.4
White et al 2003	Well	Canadian River mixed growth well 3	0.4572	351.4344
White et al 2003	Well	Canadian River mixed growth well 4	0.4572	421.2336
White et al 2003	Well	Colorado river mono-typic stand of saltcedar	6.096	17.6784
White et al 2003	Well	Colorado river mono-typic stand of saltcedar	6.096	32.004
White et al 2003	Well	Colorado river mono-typic stand of saltcedar	6.096	81.9912
White et al 2003	Well	Colorado river mono-typic stand of saltcedar	6.096	84.4296
White et al 2003	Well	Pecos river mono-typic stand of saltcedar		120.396
White et al 2003	Well	Pecos river mono-typic stand of saltcedar		288.6456
White et al 2003	Well	Pecos river mono-typic stand of saltcedar		310.896

APPENDIX B

Table 20. Summary of all model runs.

Run #	Soil salinity (mmho/cm)	Plant salt sensitivity (t/ha)/(mmho/cm)	Min water table depth (m)	Max water table depth (m)	Potential LAI	PET (mm)	ET (mm)	EP (mm)	Biomass (t/ha)
1	10	0.01	0.61	3.35	5	2322.07	2341.76	2256.19	9.8
2	9	0.01	0.61	3.35	5	2321.9	2343.1	2257.79	9.9
3	8	0.01	0.61	3.35	5	2321.73	2344.11	2259.09	10
4	7	0.01	0.61	3.35	5	2321.63	2344.91	2259.91	10.1
5	6	0.01	0.61	3.35	5	2321.53	2345.63	2260.81	10.2
6	5	0.01	0.61	3.35	5	2321.39	2346.09	2261.32	10.2
7	4	0.01	0.61	3.35	5	2321.27	2346.5	2261.91	10.3
8	3	0.01	0.61	3.35	5	2321.2	2346.85	2262.4	10.3
9	2	0.01	0.61	3.35	5	2321.14	2347.12	2262.78	10.4
10	1	0.01	0.61	3.35	5	2321.1	2347.33	2263.09	10.4
11	0	0.01	0.61	3.35	5	2321.1	2347.49	2263.33	10.4
12	10	0.05	0.61	3.35	5	2333.14	2335.89	2249.26	5.7
13	9	0.05	0.61	3.35	5	2331.11	2339.82	2252.98	6.3
14	8	0.05	0.61	3.35	5	2328.76	2342.96	2256.95	6.8
15	7	0.05	0.61	3.35	5	2326.88	2345.01	2345.01	7.4
16	6	0.05	0.61	3.35	5	2325.31	2345.9	2260.75	8.1
17	5	0.05	0.61	3.35	5	2324.17	2346.91	2261.92	8.7
18	4	0.05	0.61	3.35	5	2323.09	2347.26	2262.67	9.3
19	3	0.05	0.61	3.35	5	2322.08	2347.04	2262.75	9.7
20	2	0.05	0.61	3.35	5	2321.5	2347.29	2263	10.1
21	1	0.05	0.61	3.35	5	2321.1	2347.33	2263.09	10.4
22	0	0.05	0.61	3.35	5	2321.1	2347.49	2263.33	10.4
23	10	0.1	0.61	3.35	5	2370.86	2076.2	1983.58	1.3
24	9	0.1	0.61	3.35	5	2358.54	2186.76	2096.39	2
25	8	0.1	0.61	3.35	5	2349.31	2266.92	2178.17	2.8
26	7	0.1	0.61	3.35	5	2341.23	2320.04	2234.24	3.8
27	6	0.1	0.61	3.35	5	2335.61	2336.61	2250.58	5.1
28	5	0.1	0.61	3.35	5	2330.71	2344.25	2258.32	6.3
29	4	0.1	0.61	3.35	5	2326.91	2346.96	2261.59	7.5
30	3	0.1	0.61	3.35	5	2324.01	2348.03	2263.38	8.7
31	2	0.1	0.61	3.35	5	2322.04	2347.36	2263.2	9.7
32	1	0.1	0.61	3.35	5	2321.11	2347.34	2263.1	10.4
33	0	0.1	0.61	3.35	5	2321.1	2347.49	2263.33	10.4
34	10	0.2	0.61	3.35	5	2412.88	1611.52	1476.19	0.7
35	9	0.2	0.61	3.35	5	2407.4	1697.25	1560.6	0.7
36	8	0.2	0.61	3.35	5	2394.2	1854.56	1729.42	0.9
37	7	0.2	0.61	3.35	5	2390.44	1877.74	1762.13	1
38	6	0.2	0.61	3.35	5	2380.48	1978.36	1872.88	1.1
39	5	0.2	0.61	3.35	5	2357.13	2198.21	2109.44	2.1

40	4	0.2	0.61	3.35	5	2340.23	2321.67	2236.13	3.9
41	3	0.2	0.61	3.35	5	2330.18	2345.43	2259.85	6.2
42	2	0.2	0.61	3.35	5	2323.77	2348.26	2263.79	8.6
43	1	0.2	0.61	3.35	5	2321.13	2347.36	2263.12	10.4
44	0	0.2	0.61	3.35	5	2321.1	2347.49	2263.33	10.4
45	10	0.3	0.61	3.35	5	2444.3	1193.63	1020.88	0.2
46	9	0.3	0.61	3.35	5	2432.06	1362.21	1203.5	0.4
47	8	0.3	0.61	3.35	5	2419.95	1518.85	1375.08	0.5
48	7	0.3	0.61	3.35	5	2410.35	1659.29	1522.28	0.7
49	6	0.3	0.61	3.35	5	2393.86	1864.86	1738.91	0.9
50	5	0.3	0.61	3.35	5	2386.84	1911	1798.42	1.1
51	4	0.3	0.61	3.35	5	2368.09	2090.37	2001.07	1.4
52	3	0.3	0.61	3.35	5	2339.79	2321.46	2235.53	3.9
53	2	0.3	0.61	3.35	5	2326.48	2348.33	2263.32	7.4
54	1	0.3	0.61	3.35	5	2321.14	2347.38	2263.14	10.3
55	0	0.3	0.61	3.35	5	2321.1	2347.49	2263.33	10.4
56	10	0.5	0.61	3.35	5	2533.25	553.71	62.72	0
57	9	0.5	0.61	3.35	5	2533.25	553.7	62.72	0
58	8	0.5	0.61	3.35	5	2510.28	660.86	281.83	0
59	7	0.5	0.61	3.35	5	2445.31	1185.2	1011.38	0.2
60	6	0.5	0.61	3.35	5	2426.01	1451.63	1295.16	0.5
61	5	0.5	0.61	3.35	5	2408.24	1685.57	1552.29	0.8
62	4	0.5	0.61	3.35	5	2387.35	1924.49	1801.94	1.1
63	3	0.5	0.61	3.35	5	2374.99	2009.42	1911.24	1.3
64	2	0.5	0.61	3.35	5	2333.8	2341.96	2257	5
65	1	0.5	0.61	3.35	5	2321.23	2347.53	2263.41	10.3
66	0	0.5	0.61	3.35	5	2321.1	2347.49	2263.33	10.4
67	10	0	0.61	3.35	5	2321.11	2341.52	2255.86	10.4
68	9	0	0.61	3.35	5	2321.1	2342.86	2257.43	10.4
69	8	0	0.61	3.35	5	2321.1	2343.91	2258.7	10.4
70	7	0	0.61	3.35	5	2321.1	2344.8	2259.78	10.4
71	6	0	0.61	3.35	5	2321.1	2345.49	2260.64	10.4
72	5	0	0.61	3.35	5	2321.1	2346.04	2261.35	10.4
73	4	0	0.61	3.35	5	2321.1	2346.49	2261.93	10.4
74	3	0	0.61	3.35	5	2321.1	2346.84	2262.4	10.4
75	2	0	0.61	3.35	5	2321.1	2347.12	2262.79	10.4
76	1	0	0.61	3.35	5	2321.1	2347.33	2263.09	10.4
77	0	0	0.61	3.35	5	2321.1	2347.49	2263.33	10.4
78	0	0	0.01	3.35	5	2322.94	2415.09	2251.83	10.3
79	0	0	0.02	3.35	5	2322.74	2415.06	2252.43	10.3
80	0	0	0.03	3.35	5	2322.55	2414.73	2253.19	10.3
81	0	0	0.04	3.35	5	2322.41	2413.86	2253.68	10.3
82	0	0	0.05	3.35	5	2322.19	2413.48	2254.45	10.3
83	0	0	0.1	3.35	5	2321.32	2410.75	2257.55	10.4
84	0	0	0.2	3.35	5	2321.1	2402.8	2260.54	10.4
85	0	0	0.3	3.35	5	2321.1	2392.56	2262.34	10.4
86	0	0	0.4	3.35	5	2321.1	2380.96	2262.9	10.4
87	0	0	0.5	3.35	5	2321.1	2368.67	2263.16	10.4

88	0	0	0.75	3.35	5	2321.1	2335.02	2263.36	10.4
89	0	0	1	3.35	5	2321.1	2323.56	2263.38	10.4
90	0	0	1.5	3.35	5	2321.1	2322.26	2263.38	10.4
91	0	0	2	3.35	5	2321.1	2322.26	2263.38	10.4
92	0	0	3	3.35	5	2321.1	2322.25	2263.38	10.4
93	0	0	2.5	5	5	2334.82	1099.57	1040.25	4.5
94	0	0	3	5	5	2335.56	1073.54	1014.16	4.4
95	0	0	4	5	5	2434.64	259.93	175.55	0.8
96	0	0	3.5	6	5	2346	892.45	830.51	3.6
97	0	0	4	6	5	2434.64	259.93	175.55	0.8
98	0	0	4.5	6	5	2434.64	259.93	175.55	0.8
99	0	0	5	6	5	2434.64	259.93	175.55	0.8
100	0	0	5.5	6	5	2434.64	259.93	175.55	0.8
101	0	0	3.5	7	5	2349.58	847.21	784.57	3.2
102	0	0	4	7	5	2434.64	259.93	175.55	0.8
103	0	0	4.5	7	5	2434.64	259.93	175.55	0.8
104	0	0	5	7	5	2434.64	259.93	175.55	0.8
105	0	0	5.5	7	5	2434.64	259.93	175.55	0.8
106	0	0	6	7	5	2434.64	259.93	175.55	0.8
107	0	0	0.61	3.35	0.5	2495.82	738	383.58	3.1
108	0	0	0.61	3.35	1	2463.22	953.3	699.38	5
109	0	0	0.61	3.35	2	2410.82	1450.24	1307.19	7.5
110	0	0	0.61	3.35	3	2371.92	1992.77	1887.51	9
111	0	0	0.61	3.35	4	2342.91	2296.19	2206.31	9.9
112	0	0	0.61	3.35	5	2321.1	2347.49	2263.33	10.4
113	0	0	0.61	3.35	6	2304.62	2377.21	2297.42	10.8
114	0	0	0.61	3.35	7	2292	2398.37	2322.29	11
115	0	0	0.61	3.35	8	2282.38	2415.11	2342.17	11.2
116	0	0	0.61	3.35	9	2274.85	2429.47	2359.22	11.3
117	0	0	0.61	3.35	10	2268.92	2442.3	2374.41	11.4
118	0	0	0.61	3.35	11	2264.15	2454.27	2388.36	11.5
119	0	0	0.61	3.35	12	2260.34	2465.05	2400.89	11.6
120	0	0	0.5	1	5	2321.1	2434.07	2262.75	10.4
121	0	0	0.5	2	5	2321.1	2386.05	2262.9	10.4
122	0	0	0.5	3	5	2321.1	2370.94	2263.14	10.4
123	0	0	1.5	4	5	2332.1	1162.66	1103.53	4.8
124	0	0	2.5	5	5	2334.82	1099.57	1040.25	4.5
125	0	0	3.5	6	5	2346	892.45	830.51	3.6
126	0	0	4.5	7	5	2434.64	259.93	175.55	0.8
127	0	0	5.5	8	5	2434.64	259.93	175.55	0.8
128	0	0	6.5	9	5	2434.64	259.93	175.55	0.8
129	0	0	7.5	10	5	2434.64	259.93	175.55	0.8
130	0	0	8.5	11	5	2434.64	259.93	175.55	0.8
131	0	0	9.5	12	5	2434.64	259.93	175.55	0.8
132	0	0	10.5	13	5	2434.64	259.93	175.55	0.8
133	0	0	11.5	14	5	2434.64	259.93	175.55	0.8
134	0	0	12.5	15	5	2434.64	259.93	175.55	0.8
135	0	0	3.75	6.25	5	2434.64	259.93	175.55	0.8

136	0	0	4	6.5	5	2434.64	259.93	175.55	0.8
137	0	0	4.25	6.75	5	2434.64	259.93	175.55	0.8
138	0	0	0.75	3.25	5	2321.1	2335.27	2263.38	10.4
139	0	0	1	3.5	5	2321.1	2323.53	2263.34	10.4
140	0	0	1.25	3.75	5	2329.91	1188.91	1130.35	4.4
141	0	0	1.05	3.55	5	2321.1	2323.08	2263.31	10.4
142	0	0	1.1	3.6	5	2321.14	2302.5	2243.2	10.4
143	0	0	1.15	3.65	5	2326.04	1413.04	1353.76	5.6
144	0	0	1.2	3.7	5	2329.45	1209.26	1149.12	4.8
145	0	0	3.55	6.05	5	2352.23	806.22	743.07	3
146	0	0	3.6	6.1	5	2362.9	615.56	549.3	2.1
147	0	0	3.65	6.15	5	2434.64	259.93	175.55	0.8
148	0	0	3.7	6.2	5	2434.64	259.93	175.55	0.8
149	0	0	1.11	3.61	5	2321.36	2207.51	2148.27	9.9
150	0	0	1.12	3.62	5	2322.01	2045	1985.77	9.1
151	0	0	1.13	3.63	5	2322.82	1847.89	1788.6	8.2
152	0	0	1.14	3.64	5	2323.86	1627.35	1568.57	7.1
153	0	0	3.61	6.11	5	2366.46	553.12	487.35	1.9
154	0	0	3.62	6.12	5	2372.24	473.78	407.27	1.6
155	0	0	3.63	6.13	5	2415.43	300.56	222.77	1
156	0	0	3.64	6.14	5	2434.64	259.93	175.55	0.8

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