

Evapotranspiration from a Saltcedar-Dominated Desert Floodplain: a Scaling Approach

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Abstract—The purpose of this study was to investigate evapotranspiration (ET) from a variety of scales (leaf to landscape) in saltcedar-dominated floodplain vegetation along the lower Virgin River of southern Nevada. Leaf-level gas exchange indicated that saltcedar exhibits similar stomatal conductance as the sympatric phreatophytes arrowweed, mesquite, and willow. However, sap flow in saltcedar was higher per unit sapwood area than the other species, suggesting that it maintains higher leaf area per unit sapwood area. At the stand level, saltcedar ET was found to exceed potential ET early in the summer when soils were moist and the water table was near the surface, but by late summer, after floodplain soils had dried and the water table had dropped, saltcedar ET was well below potential rates. Summer irrigation did not result in increased conductance of saltcedar for at least four weeks, suggesting that saltcedar does not utilize summer rainfall under normal conditions in the arid Mojave Desert.

The importance of riparian zones in the arid Southwest as wildlife habitat and as recreational resources has recently led to a considerable amount of research and management efforts that seek to determine the instream flow requirements of riparian vegetation (Stromberg and Patten 1990). There have been numerous ecological studies of the floodplain vegetation of many riverine systems in the West. Much of the literature consists of little more than inventories of dominant plant and wildlife communities, although recent studies have linked ecological processes with various hydrogeological variables. For example, studies of the relationships between the population biology of riparian plants and stream discharge dynamics (Everitt 1968; Stromberg and others 1991) have helped to clarify the essential role of flooding in the recruitment of trees in riparian forest communities. Studies of diverted streams in the western U.S. have shown that curtailment of annual flooding may result in a long-term senescence of riparian vegetation (Smith and others 1991; Stromberg and Patten 1990).

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The riparian communities of the arid Southwest are dominated by saltcedar (*Tamarix ramosissima*), a naturalized thicket-forming shrub that is reputed to be capable of losing vast quantities of water through evapotranspiration (ET). From a very localized distribution in the 1920's, saltcedar has spread across the floodplains of rivers in the West, and is continuing to expand its dominance of floodplains and of isolated springs and wetlands today. Most of the large river systems of the Southwest were historically dominated by gallery cottonwood-willow (*Populus-Salix*) forests, only a small percentage of which are left today. In a study of the distribution of saltcedar, Everitt (1980) concluded that the invasion of saltcedar along southwestern watercourses was related to seed becoming increasingly available as changing physical and hydrological factors associated with development (dam-building, levee construction, etc.) was changing the flow regimes that native forests were historically adapted to. At the same time, the lack of annual flooding was resulting in the senescence of the former cottonwood-willow dominants due to increased water and salinity stresses along aridland floodplains (Busch and Smith 1995).

A number of studies have attempted to quantify "consumptive use" (i.e., ET) from southwestern riparian zones. Researchers have tended to conduct these studies in floodplains that have been invaded by saltcedar due to the widespread belief that it is a "water spender" relative to native phreatophytes such as cottonwood, willow, and mesquite. Most of these studies have used lysimeters or vertical micrometeorological masts (e.g., Bowen ratio) to estimate ET from individual plants or whole stands. Estimates on the order of 150-210 cm (ca. 60-80 inches) annually, based largely on lysimeter studies in Arizona and New Mexico (van Hylckama 1970; Horton 1972) have been reported and used in management programs throughout the Southwest. Robinson (1965) used such data to estimate that over $1.2 \times 10^9 \text{ m}^3$ of water are consumed in the Southwest by saltcedar each year. Unfortunately, some of the early water consumptive studies were conducted in open areas, rather than in characteristic dense vegetation, leading to potentially large overestimates of ET due to advective water loss (Anderson and Idso 1987). Potential extrapolation problems from lysimeter studies led to attempts to predict the ET of saltcedar communities from meteorological data and vegetation structural characteristics (Gay and Fritschen 1979). However, such estimates were often obtained without accurate knowledge of the effects of environmental factors on stomatal resistance of the plant surfaces in question.

Other investigators have attempted to predict stand ET based on transpiration measurements of individual leaf surfaces, but these estimates are criticized due to the inherent problem of "scaling up" from individual leaves to the entire canopy (McNaughton and Jarvis 1991). However, these latter studies do not support the characterization of saltcedar as a profligate water spender, relative to other floodplain phreatophytes, at least at the level of the individual leaf (Anderson 1982; Busch and Smith 1995). Therefore, high ET rates of saltcedar stands must be more related to the maintenance of very high leaf area index (LAI; leaf area per unit ground area) during the growing season, although LAI estimates have yet to be made in southwestern riparian vegetation.

In this study, we examined evapotranspiration from saltcedar stands using multiple scales (leaf to watershed) at two study sites along the lower Virgin River floodplain in southern Nevada. We examined water flux estimates of saltcedar and co-occurring native phreatophytes using conventional gas exchange techniques and sap flow analysis, and we also examined stand-level ET in saltcedar-dominated vegetation with sap flow and Bowen ratio techniques. We hypothesized (1) saltcedar would have comparable water loss rates as co-occurring phreatophytes at the leaf/branch levels, (2) stand density would influence stomatal conductance in saltcedar, but (3) saltcedar stands would exhibit very high ET rates due to the maintenance of high LAI.

Study Sites

Two sites were established within the lower Virgin River floodplain in southern Nevada prior to the river entering Lake Mead. These sites were (1) the Halfway Wash site, near the location where Half-Way Wash enters the Virgin River (36° 40' N, 114° 20' W) and (2) the Duck Club site, located along the lower watershed (36° 35' N, 114° 20' W). Both sites occur at an elevation of ca. 380 m. These sites were selected because they are representative of the overall geomorphology and vegetation structure of the Virgin River floodplain. For example, the upstream Halfway Wash site was characterized by a relatively open, recently burned successional floodplain community with a mixture of saltcedar, arrowweed (*Pluchea sericea*), screwbean mesquite (*Prosopis pubescens*), and other shrubs, with a fairly dense groundcover of saltgrass (*Distichlis spicata*) in the open spaces between thickets. In contrast, the downstream Duck Club site was characterized by a dense thicket of tall saltcedar vegetation (up to 7 m tall) with essentially no subordinate woody species or herbaceous groundcover present.

Methods

Stand Structure

At each site, density of rooted woody stems was measured in fifteen 20 m² (2 x 10 m) plots distributed in a systematic random fashion along three parallel transects placed perpendicular to the river channel. In each plot, all rooted woody stems larger than 5 mm diameter were measured just above ground level with calipers. At the Halfway Wash site (floodplain width = 750 m), average stem densities of arrowweed and saltcedar were 23,500 and 23,000 stems ha⁻¹,

respectively, with willow and mesquite each having stem densities below 1,000 stems ha⁻¹. At the Duck Club site (floodplain width = 1,200 m), average rooted stem density of saltcedar plants was ca. 65,000 stems ha⁻¹, or over 6 stems per m² ground surface area.

At each study site, four 20 m² circular plots were laid out in four cardinal directions from each of three permanent masts used to set up instrumentation. The center of each plot was 10 m from the central mast location. Stem diameter of all woody species present in the plot (with a stem diameter greater than 5 mm) were measured at a height of 0.2 m from the ground surface. Total leaf area of saltcedar in each plot was then estimated from stem diameter-leaf area relationships obtained by destructive sampling of individual stems used to measure sap flow. Leaf-area Index (LAI) was then calculated by dividing total leaf area by the plot area.

Gas Exchange

During several days in the summer of 1994, comparative gas exchange was measured on saltcedar, arrowweed, screwbean mesquite, and coyote willow (*Salix exigua*) on a two-year-old sandbar near the bank of the Virgin River (Halfway Wash site). All plants were young thickets or tree saplings. Commencing near dawn and continuing until early afternoon, photosynthetic gas exchange was measured for terminal shoots using a LI-COR 6200 portable photosynthesis system (Li-Cor, Inc., Lincoln, NE). After obtaining a steady-state measurement of photosynthesis and leaf conductance, the shoot was detached and its water potential was determined immediately using a pressure chamber (Soil Moisture Equip. Corp., Santa Barbara, CA). The shoot was then placed in a sealed bag and stored on ice for transport back to the laboratory where the leaf area of each sample was determined with a leaf area meter (Decagon Devices, Pullman, WA).

Sap Flow

Sap flow (transpirational flux) was estimated in the four study species, and in different densities of saltcedar stands, in both 1993 and 1994 using the stem heat balance method (Baker and van Bavel 1987). Devitt and others (1993) successfully applied the sap flow method in woody ornamental trees under a similar climate. The sap flow system consisted of a DNX10 data logger (Dynamax Inc., Houston, TX) attached to three 8-channel multiplexers, which were mounted on three permanent posts set up at 50 m intervals from the river channel edge into the floodplain. Groups of eight sap flow gauges (Dynamax, Dynamax Inc.) were connected at each multiplexer and operated at constant power.

Global shortwave radiation, air temperature, relative humidity, wind velocity and rainfall were measured simultaneously with sap flow during each measurement period with a Campbell Scientific Weather Station (Campbell Scientific, Logan, UT). At each study site, weather sensors were mounted on a 5 m mast located in an open area. Weather and gauge outputs were measured every minute and stored every 30 minutes in a Campbell SM716 storage module. Potential evapotranspiration was estimated from standard hourly weather data using the Penman-Monteith equation, as modified by van Bavel (1966).

Sap flow was calculated according to gauge output signals, gauge characteristics, and stem diameter. Stem diameters ranged from 10 to 40 mm to accommodate intra- and inter-specific variability. Whenever possible gauges were installed on main stems at a distance greater than 0.3 m from the ground. Gauges were covered with insulating foam and several layers of aluminum foil to avoid direct insolation and naturally induced temperature gradients (Gutierrez and others 1995; Shackel and others 1992). The sheath thermal conductance (K_{sh} ; see Baker and van Bavel 1987) was determined from the average minimum apparent values calculated at night when transpiration was assumed to be near zero (this was later confirmed by severing the branch above the stemflow gauge at the end of the run, thus forcing flow to zero).

Bowen Ratio

Evapotranspiration can be estimated via an energy balance which takes into account the vapor pressure and temperature gradient above a soil-plant system. However, in the field, it is often difficult to measure the transfer coefficient, h , which is a function of wind velocity, surface roughness, and height. Furthermore, this coefficient cannot be directly measured but must be inferred from a transfer model. One alternative method to get around the difficulty of measuring this coefficient is called the Bowen Ratio. The Bowen Ratio makes the assumption that the ratio of H (sensible heat flux away from the surface) to LE (latent heat flux away from the surface) is the same at a height above the surface as it is at the surface. This ratio can be expressed by the equation:

$$B = V * (T_2 - T_1) / (e_2 - e_1)$$

where T (temperature) and e (vapor pressure) are measured at two heights above the vegetated surface and V is the psychrometric constant. ET then becomes:

$$LE = (R_n - G) / (1 + B)$$

where R_n is the net radiation at the surface and G is the conductive soil heat flux away from the surface. When carefully measured and properly averaged, this method has been shown to yield good estimates of ET under a variety of circumstances (Tanner 1968).

A ca. 13 m (40') Bowen Ratio mast was placed near the center of the floodplain at the Duck Club site, assuring that there was at least 100 m of "fetch" in uniform vegetation (i.e., dense saltcedar vegetation) in all directions. Mast arms were placed at 1 m and 3 m above the canopy to measure temperature and vapor pressure at two heights above the canopy.

Potential evapotranspiration (ET_0) was estimated with the Penman combination equation:

$$ET_0 = W * R_n + (1 - W) * f(u) * (e_a - e_d)$$

where W is a temperature related weighting factor, $f(u)$ is a wind related function, and $(e_a - e_d)$ is the difference between saturation vapor pressure at air temperature and the mean actual vapor pressure of the air. Meteorological data (solar radiation, wind run, maximum and minimum temperature, maximum and minimum relative humidity, and rainfall) were collected with an automated weather station (Campbell Scientific) at a central location on the site. ET_0 estimates

were then used to assess environmental demand and to determine the extent to which plant water status was directly coupled to changes in environmental demand.

The response of saltcedar thickets to summer rainfall was assessed by irrigating six thickets at 100% of ET_0 and six at 50% of ET_0 . Plants were watered weekly from during June and July. The amount of water applied to each group of plants (water was applied by hand with buckets in bermed depressions around each thicket) was based on the ET_0 predicted from the previous weeks weather data (see previous equation). Plants were instrumented with sap flow gauges and were monitored one day per week for stomatal conductance and plant water potential, as described previously.

Results and Discussion

Gas exchange of saltcedar, arrowweed, mesquite and willow was investigated on June 9, 1994, at the Halfway Wash site. Environmental conditions during that time were indicative of early in the growing season on the Virgin River floodplain. Due to below average flows in late spring, water tables were starting to seasonally decline (but were still less than 1 m) and soils were dry at the surface but still moist in the subsurface. Air temperatures were very warm ($>42^\circ\text{C}$) and relative humidity was low ($<10\%$) around midday. Comparative results (table 1) showed that saltcedar maintained the lowest daily plant water potentials whereas willow maintained the highest water potentials. Willow had significantly higher stomatal conductance (g_s) than saltcedar or mesquite, and arrowweed had the lowest conductance. CO_2 assimilation rate (A) was highest in mesquite, intermediate in willow and saltcedar, and lowest in arrowweed. Finally, the slope of the $A:g_s$ relationship (A as the dependent variable), which is an indication of intrinsic water use efficiency, was highest in mesquite and saltcedar (table 1). In other words, per unit decrease in conductance as the day progressed, carbon dioxide assimilation decreased more slowly in mesquite and saltcedar than in arrowweed and willow.

Comparative gas exchange of these four species on the same site in August 1994 provided similar results. Some of these gas exchange results obtained from plants in the Virgin River floodplain support previous findings for saltcedar. Anderson (1982) found saltcedar stomata to be extremely sensitive to changes in light intensity, but they were less sensitive to changes in humidity. Busch and Smith (1995) found saltcedar to exhibit midday declines in stomatal conductance during the hot summer months, but these declines were often less pronounced than were midday declines in conductance of sympatric cottonwood and willow trees. Busch and Smith (1995) also found saltcedar to operate at lower plant water potentials and to exhibit higher water use efficiency than did cottonwood and willow along the lower Colorado River, in agreement with our findings from the Virgin River.

Rates of sap flow in the four species during the same time period that gas exchange was measured (June 8-13, 1994) showed that saltcedar maintained significantly higher daily accumulated sap flow per unit sapwood area than did the other three species (fig. 1). Averaged over the six day period, saltcedar exhibited a 1.9-fold higher sapflow rate than did

Table 1—Mean daily values of plant water potential (Plant WP), stomatal conductance (g_s), CO_2 assimilation (A) and the slope of the CO_2 assimilation:conductance relationship (A:g) for four species of floodplain phreatophytes. For the two regression relationships, the slope is based on the latter variable in each case being the independent variable and the first listed variable being the dependent variable. Data were taken from a whole, sunny day (June 9, 1994) at the Halfway Wash site on the lower Virgin River, Nevada. Data points in the same row that are followed by different letters are significantly different at $p = 0.05$ (one-way ANOVA).

Parameter (unit)	Species			
	Saltcedar	Arrowweed	Mesquite	Willow
Plant WP (MPa)	-2.20a	-1.66b	-1.78b	-0.98c
g_s ($mol\ m^{-2}\ s^{-1}$)	0.340a	0.198b	0.354a	0.550c
A ($mmol\ CO_2\ m^{-2}\ s^{-1}$)	8.4a	4.3b	12.1c	14.7c
A:g slope	26.5	18.5	30.6	15.3

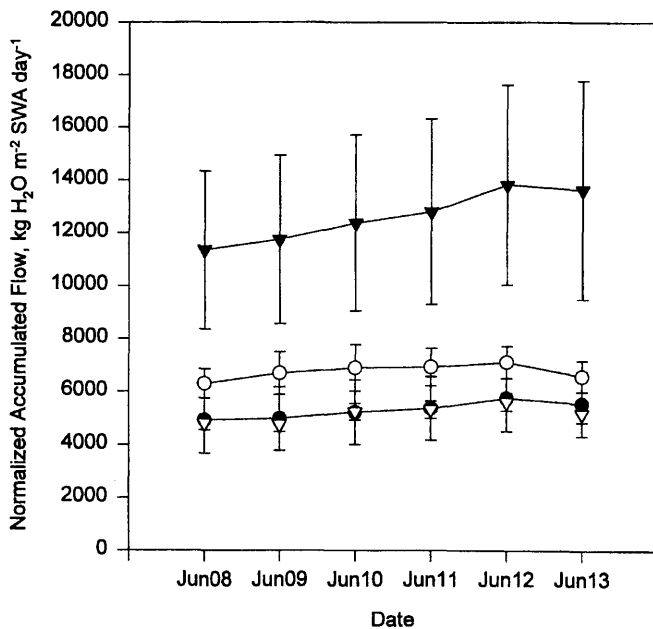


Figure 1—Normalized daily accumulated sap flow in saltcedar from June 8 to June 13, 1994, at the Halfway Wash site, lower Virgin River, Nevada. Symbols represent saltcedar (closed triangles), coyote willow (open circles), screwbean mesquite (closed circles), and arrowweed (closed triangles). Vertical bars represent one standard error.

willow, 2.4-fold higher than mesquite, and 2.5-fold higher than arrowweed. Interestingly, saltcedar does not exhibit higher sap flow per unit leaf area than do arrowweed, mesquite, or willow (Sala and others 1996), which must indicate that saltcedar maintains greater leaf area per unit sapwood area than do the other species.

Observations from the Virgin River suggest that saltcedar exhibits a curvilinear increase in leaf area as stems age (data not shown), and so for mature thickets saltcedar may be able to maintain very high leaf area. Our estimates of LAI (leaf area index) for mature saltcedar on the lower Virgin River is between 3.0 and 4.0 for most mature stands (Sala and others 1996). Under those LAI's, Sala and others (1996) used sap

flow data to calculate that actual evapotranspiration (ET) from mature saltcedar stands can exceed predicted potential evapotranspiration (ET_0), at least when conditions are favorable for high ET rates (i.e., moist soils and/or high water tables).

Given these results, we were interested in determining what may regulate ET under natural conditions. Results from a number of sap flow runs during the 1993 growing season indicated that daily accumulated flow in individual saltcedar plants was linearly related to leaf area of that plant (fig. 2) under conditions when subsurface water was not limiting (1993 was a high flow year). This relationship does not preclude the fact that ET of saltcedar stands may decline as the floodplain environment seasonally desiccates, but does indicate a strong influence of total leaf area on ET rates under mesic conditions. Therefore, environmental

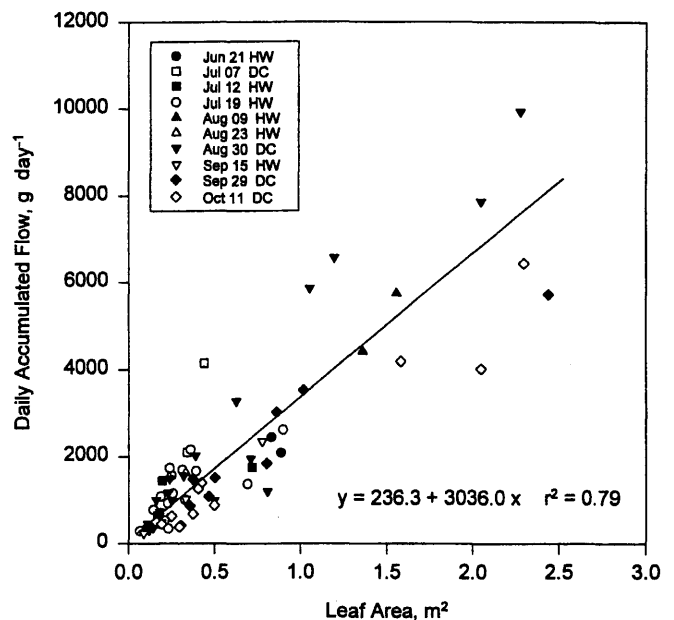


Figure 2—Daily accumulated sap flow as a function of total leaf area in saltcedar at two sites (Duck Club = DW; Halfway Wash = HW) over nine days from June 21 to October 11, 1993.

influences on maintenance of leaf area in saltcedar stands may have far greater influence on seasonal ET rates than do short-term influences on stomata.

One factor that can influence both stomatal conductance and leaf area maintenance is the density of saltcedar canopies. We were particularly interested in understanding how the ET process may change as open, successional saltcedar stands develop into closed, mature stands in which individual saltcedar thickets show considerable overlap of individual canopies. A comparison of mean stomatal conductance at midcanopy level during the summer growing season in 1994 showed that g_s was consistently higher in dense stands than it was in more open stands (fig. 3), which were characterized by individual thickets with non-overlapping canopies and open ground between the thickets. We attributed this difference to a boundary layer effect, in which canopy transpiration in dense stands has a positive feedback effect on stomatal conductance. A large boundary layer would tend to reduce transpiration in comparison to an open thicket exhibiting equal g_s , so that dense stands may be able to operate at higher g_s without exhibiting higher transpiration per unit leaf area. We are continuing experiments to elucidate these types of relationships.

Bowen ratio estimates of ET from mature saltcedar stands from the Duck Club site on the lower Virgin River indicate that latent heat flux (LE) actually exceeded net radiation (R_n) early in the growing season (May and June) when channel flow and the water table were both high (table 2). In fact, on June 17, LE was almost twofold higher than R_n during the middle of the day. Because LE exceeded R_n , the energy to drive such a process must come from other sources besides incoming radiant energy. The source of that energy was apparently the advection (i.e., horizontal transport) of sensible heat from the surrounding dry desert, causing a net influx (-H) of sensible heat into the canopy. By late June, LE was still slightly higher than R_n , but in early July LE began dropping and quickly became lower than R_n , becoming only 35% of R_n on July 21 and 29% of R_n on October 21. On these dates, the dominant flux of sensible heat was upward from the canopy (+H) rather than into the canopy. Therefore, LE

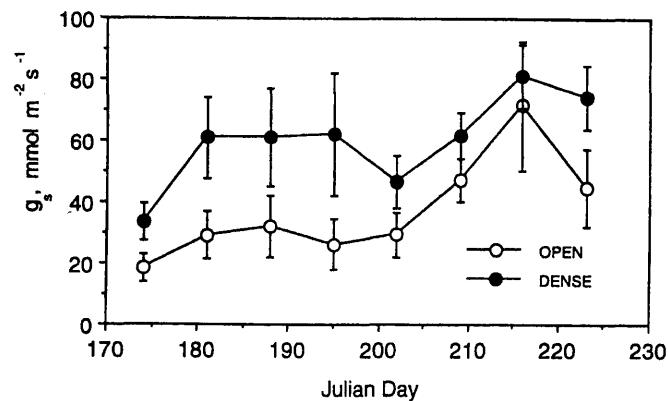


Figure 3—Mean daily stomatal conductance (g_s) of saltcedar in dense stands (closed circles) and open stands (open circles) from mid-June (Day 175) to August (Day 225) at the Duck Club site, lower Virgin River, Nevada. Vertical bars represent one standard error.

Table 2—Bowen ratio analysis of mean daily net radiation (R_n), latent heat flux (LE), sensible heat flux (H) and soil heat flux (G) for a mature saltcedar stand at six times during the growing season in 1994 for the lower Virgin River, Nevada. Means were calculated between 0900 and 1500 h each day. Positive values for net radiation denote net downward flux; positive values for latent heat denote upward flux; for sensible heat, positive values denote upward flux and negative values denote downward flux; and for soil heat flux positive values denote downward flux from the surface into the soil.

Date	Parameter			
	R_n	LE	H	G
	----- $W m^{-2}$ -----			
May 5	509	654	-168	23
June 17	586	1047	-474	13
June 25	616	660	-63	19
July 3	590	431	109	50
July 21	571	204	337	30
October 21	394	114	241	39

appeared to be very high during the first half of the growing season due to sensible heat advection adding considerably more energy to the stand than was provided by net radiation alone. Although we placed the Bowen ratio tower in a location where it had at least 150 m of fetch in each direction, it was apparent that such fetch was not adequate to buffer the tower from horizontal exchange with the surrounding hot, dry desert. That reality, plus the fact that soils were moist and the water table was high, acted to produce extremely high ET rates for these intact saltcedar stands.

A second aspect related to annual ET from saltcedar stands is the effect that the summer dry season has on stomatal conductance and resultant transpiration rates. Although a phreatophyte, saltcedar appears to be a facultative phreatophyte that can take up water from both groundwater and the unsaturated soil profile, whereas cottonwood and willow trees are obligate phreatophytes that only take up water from the water table (Busch and others 1993). Because of their ability to take up water from multiple sources, and because hydraulic resistance to water transport increases as the water table becomes deeper, we tested what the response of saltcedar is to summer rainfall by irrigating saltcedar thickets after the 1994 summer dry season was well under way (1994 was a dry year).

All plants exhibited low stomatal conductance at the start of the experiment in June; plants irrigated at 100% ET_0 took four weeks and plants irrigated at 50% ET_0 took six weeks to exhibit stomatal conductance that was significantly elevated over unwatered controls (fig. 4). Sap flow data showed similar lags before increased sap flows were observed in irrigated plants (data not shown).

This irrigation experiment suggests that saltcedar does not normally respond to summer rainfall in the arid Mojave Desert, unless that rainfall is unusually heavy. This conclusion is based on the observation that plants did not physiologically respond to increased surface water for a full month, and then the response was not dramatic even though the irrigated plants had received the equivalent of potential ET for four to six weeks. Such levels of summer rainfall never occur in the Mojave Desert, although summer flash floods may result in substantial recharge of the soil profile. Even

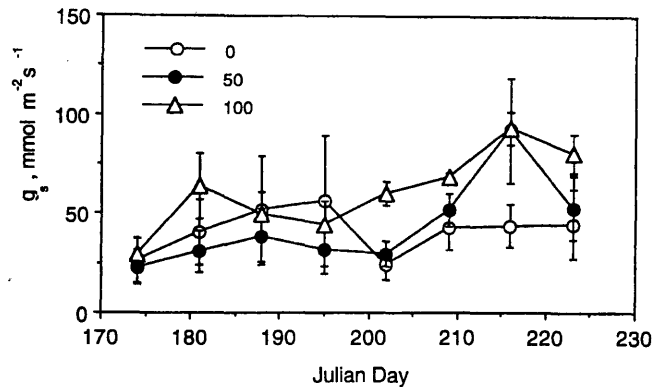


Figure 4—Mean daily stomatal conductance (g_s) of saltcedar plants irrigated weekly at 50 and 100% potential evapotranspiration (closed circles and open triangles, respectively) versus unwatered controls (open circles) at the Duck Club site, lower Virgin River, Nevada. Irrigations commenced in mid-June (Day 175) and continued through August (Day 225). Vertical bars represent one standard error.

so, the potentially rapid response to soil water addition that we thought may occur did not materialize.

We also did not observe a significant increase in root length per unit soil volume, even after four to six weeks of irrigation, leading us to conclude that saltcedar does not normally respond to summer rainfall, except under extremely wet conditions or after repeated flood events.

Conclusions

The results of these experiments, collected at various scales, indicate that saltcedar appears to have similar gas exchange behavior as sympatric woody phreatophytes such as mesquite and willow, but at the whole plant level it exhibits higher sap flow (and therefore transpirational flux) per unit sapwood area. Perhaps due to its ability to support higher ET per unit sapwood area, saltcedar exhibits high ET at the landscape level due to its ability to maintain very high leaf area as stands mature. In such dense stands with high LAI, ET can dramatically exceed net radiation (and thus predicted ET_0) under conditions of moist soils and a high water table, and particularly under advective conditions which result in sensible heat flux into the canopy.

However, even though saltcedar is phreatophytic, it still exhibits reduced ET during the dry summer months when surface soils dry and the water table drops, thus increasing hydraulic resistance for water transport to the leaf canopy. During this time of the year, ET is significantly lower than net radiation. Therefore, the notion that saltcedar stands lose vast quantities of water is only partially true. Under moist, advective conditions we observed extremely high ET from saltcedar stands, but these high ET rates did not continue into the dry summer months. During the dry season, stand-level ET actually dropped to well below predicted ET_0 and stayed at those reduced levels for the rest of the summer and fall.

Therefore, we conclude that dense saltcedar stands can lose large quantities of water during high runoff years or in habitats where the water table is perennially high, but on sites like the Virgin River floodplain where flooding is restricted to late spring snowmelt runoff but then water tables drop as the dry season progresses, saltcedar stands may show dramatic differences in ET between wet and dry times of the year even though it maintains perennial contact with subsurface water.

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