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The Ecology of Saltcedar (Tamarix chinesis)
in Death Valley National Monument and
Lake Mead National Recreation Area:
An Assessment of Techniques and Monitoring
for Saltcedar Control in the Park System

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COOPERATIVE NATIONAL PARK RESOURCES STUDIES UNIT

University of Nevada/Las Vegas - National Park Service

The National Park Service and the University of Nevada signed a Master Agreement on November 4, 1971 that provided for the establishment and operation of this Unit on the Las Vegas Campus. The Unit, although located in the Department of Biological Sciences, is geared to provide a multidisciplinary approach that utilizes all talents on the University Campus to natural resources studies in areas administered by the National Park Service. Primary attention of this Unit is directed to Death Valley National Monument, California/Nevada; Lake Mead National Recreation Area, Nevada/Arizona; and Joshua Tree National Monument, California.

Through the direction and coordination of the Unit Leader, projects are undertaken in these areas that are designed to provide scientific facts upon which the park managers may make appropriate decisions and formulate and implement effective management action plans. Through close association with faculty members and through guidance of graduate students, a greater awareness of problems and needs of the Service are recognized and academic interests are channelized to participate with the National Park Service in studies of mutual interest and concern.

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The Ecology of Saltcedar (*Tamarix chinesis*) in Death Valley National Monument and Lake Mead National Recreation Area: An Assessment of Techniques and Monitoring for Saltcedar Control in the Park System

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ABSTRACT

The community structure of stands subjected to saltcedar (*Tamarix chinensis*) encroachment in Death Valley National Monument and Lake Mead National Recreation Area was quantified with permanently staked hectare plots and line intercepts for the purpose of potentially documenting long term vegetation response to saltcedar control efforts. Additionally, studies were conducted on the population structure and comparative water relations of *Tamarix* in the region. *Tamarix* was found to occur in and potentially dominate a variety of habitats. It occurs in association with obligate riparian trees, obligate halophytic shrubs and grasses, and desert shrubs. *Tamarix* exhibited an absolute cover ranging from 5% to 27% at the primary study sites, with relative cover ranging from 24% to 86% of the plant community. Quantitative analysis of the age/size structure of populations from the Sand Dunes and Amargosa River sites in Death Valley showed that the populations are in a growth phase, although some plots at the Sand Dunes do not show new recruitment. *Tamarix* shows similar stomatal conductances and transpiration rates as co-occurring phreatophytes such as *Populus* and *Prosopis*, but tends to operate at significantly lower water potentials. It shows moderate stomatal control of water loss, contrary to the common perception of it being a "water spender".

An analysis of control methods in the various park units indicates that the most suitable method of saltcedar eradication, at least for small stands, is to use the cut stump/herbicide application technique. The herbicide of choice is Garlon 3A or 4, and should be

applied to cut stumps no more than 5 minutes after cutting. Other control techniques and retreatment strategies are discussed. Methods of monitoring the response of native plant populations to saltcedar control are also outlined. Priority data would seem to be in the areas of: (1) changes in species composition; (2) changes in cover of native species; and (3) evidence for any new recruitment of native species that may occur in the post-saltcedar plant community. Techniques to obtain these types of data are discussed, and the permanent plots established at sites in Death Valley and Lake Mead are described.

INTRODUCTION

Water is the most limiting, and thus perhaps the most important, environmental resource in desert ecosystems (Noy-Meir 1973; Smith and Nobel 1986). Microhabitats within the desert that contain perennial supplies of water such as streams, marshes, springs or seeps tend to have the highest primary productivity and are also the most productive wildlife habitats. Many of the region's animal species of critical environmental concern, such as bighorn sheep, migratory and resident birds, and rare fish depend on the water supplies and associated ecological communities of these microhabitats within the desert for their survival and reproduction. However, aquatic habitats of the Southwest are facing unprecedented habitat alterations due to man's activities, particularly as a result of water diversion and impoundment projects. The primary consequences of these activities are reduced flows, elimination of annual floods, and increased salinization of both surface and groundwater sources. The secondary biotic consequence has been the replacement of native cattail (*Typha*) marshes and riparian woodlands of cottonwood (*Populus* spp.), willow (*Salix* spp.) and mesquite (*Prosopis* spp.) by the exotic saltcedar (Harris 1966; Turner 1974; Turner and Karpiscak 1980; Graf 1982), which in turn can result in lower density and diversity of wildlife species (Johnson and Jones 1977; Hunter et al. 1988).

Saltcedar (*Tamarix chinensis* Lour.) is a non-native, thicket-forming shrub that occurs in dense, often monospecific stands along many of the perennial watercourses of the arid and semiarid Southwest. It presently occurs in 15 of the 17 western states, and was projected to occupy over 500,000 ha by the 1970's (Robinson

1965). The history of the introduction and spread of saltcedar into the Southwest has been well documented (Christensen 1962; Horton 1964; Robinson 1965) and so need not be detailed here. Briefly, saltcedar was introduced into the U.S. as a cultivar and windbreak species well over 100 years ago. From an estimated 4,000 ha in 1920 it spread rapidly to its present extent. It's most rapid increase has occurred in the past 40 years, primarily in response to regulation of water flows due to construction of reservoirs and large diversion projects (Harris 1966; Everitt 1980). Once established along the major drainages in the Southwest, saltcedar has successfully invaded smaller aquatic habitats such as isolated marshes, springs, and ephemeral watercourses, apparently via its windblown seeds and possibly due to occasional plantings. The extent to which saltcedar assumes dominance in these various habitats is apparently a function of initial plant community structure, seasonal water availability, and water table depth (Everitt 1980; Graf 1982).

The taxonomy of naturalized saltcedar (or saltcedar complex) in the Southwest is unresolved. Tamarix is in the family Tamaricaceae, which was entirely of Old World distribution prior to the 1800's. In his monograph of the genus Tamarix, Baum (1978) recognized 54 species worldwide, with a native distribution from China-Mongolia through Asia and the Middle East to the Mediterranean and North Africa. In addition to the arborescent, evergreen athel tree (Tamarix aphylla) that is cultivated in scattered locations throughout the Southwest, Baum (1967) listed three species of deciduous saltcedar as being common or naturalized in the region: T. chinensis, T. parvifolia, and T. ramosissima. Each of these species has a distinct distribution in Eurasia, but they apparently extensively hybridize in the western

U.S. As a result, saltcedar is commonly treated as a single species, Tamarix chinensis, in most ecological studies (Everitt 1980) and will be so treated inthis study. The fact that several species of saltcedar with previously disjunct distributions across the Eurasian continent now freely hybridize into a single naturalized species complex may help explain its apparent extreme adaptability and tolerance to a wide range of environmental conditions (Brotherson and Field 1987).

Baker (1974) listed the following characteristics of the "ideal weed": (1) continuous seed production throughout the growing season; (2) cross-pollination by the wind; (3) self-compatibility when cross-pollination is unavailable; (4) high seed output under favorable conditions; (5) the ability to produce seed under a wide range of environmental conditions; (6) seeds adapted for long or short range dispersal; (7) vigorous capability for vegetative reproduction; (8) brittleness of stems so that the plant is not easily uprooted; and (9) production of allelochemics as a mechanism for competitive exclusion. Brotherson and Field (1987) concluded that saltcedar possesses all of these characteristics and added four additional ones which further enhance saltcedar's capability as a weedy species: (10) tolerance of an extreme range of environmental conditions; (11) capacity to sprout vigorously following fire; (12) tolerant of both inundation and lack of a saturated soil, and thus being a "facultative phreatophyte" in nature; (13) difficult to control with foliar chemicals. Although some of these characteristics, particularly #'s 9, 10 and 12, have not been documented under rigorous experimental conditions, the above suite of adaptations certainly points to saltcedar's ability to invade and eventually dominate both seasonally and perennially moist habitats in the desert Southwest.

Despite the prevalent alarmist literature on the spread of saltcedar, ecologists are not unanimous concerning its invasive capabilities, particularly concerning undisturbed habitats. Everitt (1980) stated that "existing evidence indicates that saltcedar is a slow starter that does not compete well in established communities", and is certainly not the "aggressive colonizer" as has often been claimed (cf. Robinson 1965; Brotherson and Field 1984). Graf (1982) observed substantial areas of riparian habitat in central Arizona that remained free of saltcedar despite seed sources nearby, while other areas that once had dense growth had become clear without any overt clearing projects having been conducted. Because saltcedar has been widespread in the Southwest for no more than 50 years, Everitt (1980) found in a review of the literature that little is known about the stand demographics or habitat requirements of saltcedar. Thus, the natural successional processes of Southwestern riparian communities experiencing potential encroachment by saltcedar can only be speculated upon. Until this type of information is obtained, successful management strategies of saltcedar impacted habitats cannot be confidently implemented.

There is increasing concern over the effects of invasive species on nature reserves of the American Southwest, particularly those within the National Park System. Vascular plant invasions have not been particularly severe within upland areas of the desert Southwest, but introduced phreatophytes have become extensively established along watercourses, outcompeting native vegetation and sometimes lowering water tables (Loope et al. 1988). Tamarix has been the most successful exotic in this invasion, resulting in its designation as a critical pest species relative to management of wetland resources in the park system. Although saltcedar is the dominant phreatophyte along the low elevation drainages of the arid Southwest, its encroachment into more upland aquatic habitats has recently been of greater concern in some quarters because of its potentially deleterious impacts on wildlife and fish populations. The reason for this is the realization that saltcedar also disperses into isolated mesic microhabitats within desert scrub ecosystems and, due to its phreatophytic habit, can alter the ecosystem's water balance by eventually drying up ponds, marshes and springs (Mooney and Drake 1987). The resulting modification of the hydrology and ecology of the area can result in significant successional changes in the landscape and loss of native species.

Given the above concerns, the primary goal of this study was to obtain basic information on the "saltcedar problem" that would be useful to resource managers at various park units in the Southwest. Primary data collection was limited to Death Valley National Monument and Lake Mead National Recreation Area and included obtaining information on the community composition of habitats of critical concern that contain saltcedar stands, population structure of these saltcedar stands, and the water relations of saltcedar in comparison to sympatric native phreatophytes. Additionally, permanent plots were set up at each study site in order to facilitate sampling of each community in the future, after various saltcedar control treatments have been implemented.

OBJECTIVES

The objectives of this study, as proposed in a March 1987 document to the Park Service and slightly amended during the course of the study, were to:

(1) identify the perennial flora and analyze the community structure of representative saltcedar stands in Death Valley National Monument and Lake Mead National Recreation Area;

(2) determine the age and size structure of the above saltcedar stands in order to assess their relative recruitment potential and successional stage in the community;

(3) compare the water relations of saltcedar with sympatric native phreatophytes, specifically cottonwood (*Populus fremontii*) and screwbean mesquite (*Prosopis pubescens*);

(4) characterize potential short-term responses of phreatophyte communities following saltcedar eradication;

(5) establish procedures for long-term vegetation monitoring of habitats from which saltcedar has been or will be eradicated; and

(6) consult with and assist, if necessary, the resource management staff at Petrified Forest National Park with their saltcedar eradication/monitoring program.

MATERIALS AND METHODS

Study Sites

Primary study sites were located in Death Valley National Monument and Lake Mead National Recreation Area, and water relations studies were conducted in the Las Vegas Valley (Figure 1). No actual studies were conducted in Petrified Forest National Park, although observations of the saltcedar problem and consultation with park officials did occur at that park unit.

Within Death Valley, two sites were established that are representative of _Tamarix_-dominated areas in the Monument (Figure 2). One site was just north of the sand dunes, approximately 5 km southeast of Stovepipe Wells (36°37'N, 117°12'W, 10 m elev.), and will henceforth be called the "Sand Dunes site". A second site was located at the southern extremity of the Monument in the floodplain of the ephemeral Amargosa River, just west of Saratoga Springs (35° 41'N, 116°27'W, 50 m elev.), and will henceforth be called the "Amargosa River site". The Death Valley sand dunes and Saratoga Springs are considered valuable resources, both from natural history and recreational perspectives, and so encroachment of saltcedar into the native communities of each area is viewed as highly undesirable.

At the Sand Dunes site, _Tamarix_ occurs as dense thickets in swales at the interface between the dune system and the valley floor. The _Tamarix_ thickets often form long "strand lines", usually on the slip-face side of individual dunes that extend to the north into the valley floor. The actual dunes are largely devoid of perennial vegetation, with only an occasional large _Larrea tridentata_ present

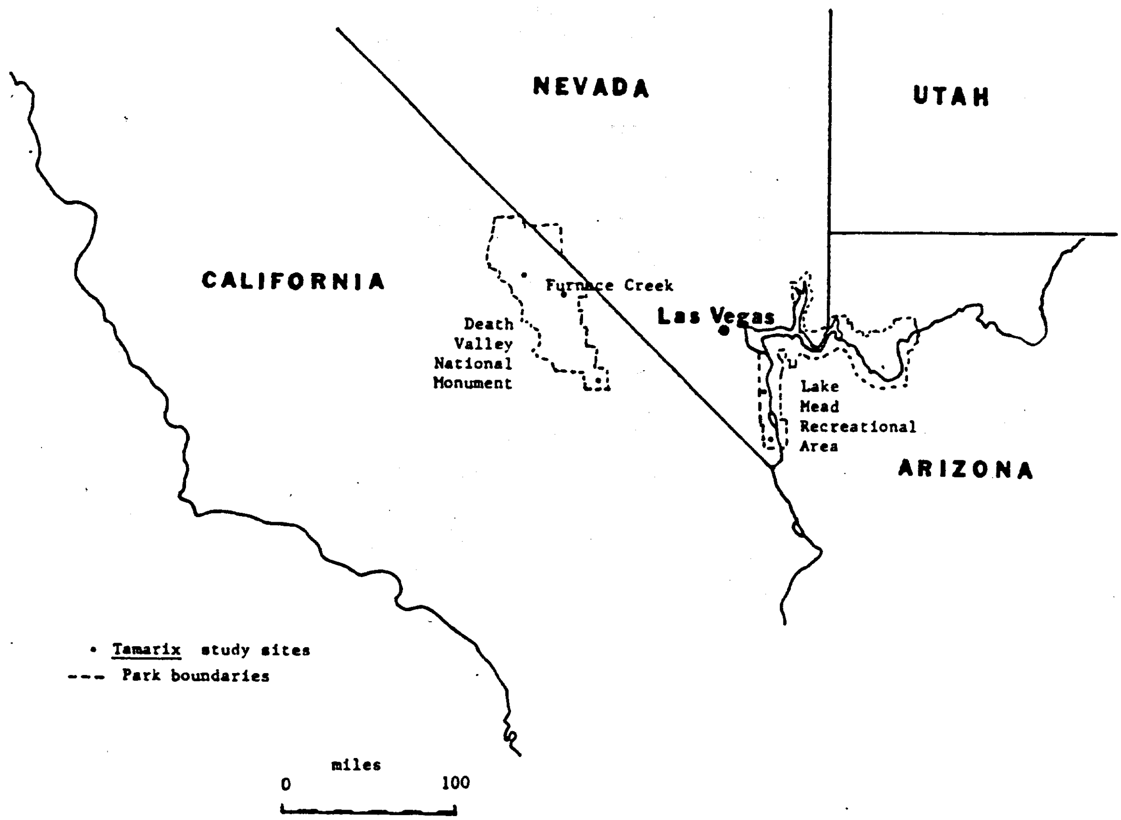

Figure 1. Location of Death Valley National Monument and Lake Mead National Recreation Area within the southwestern United States. Note location of _Tamarix_ study sites within each park unit.

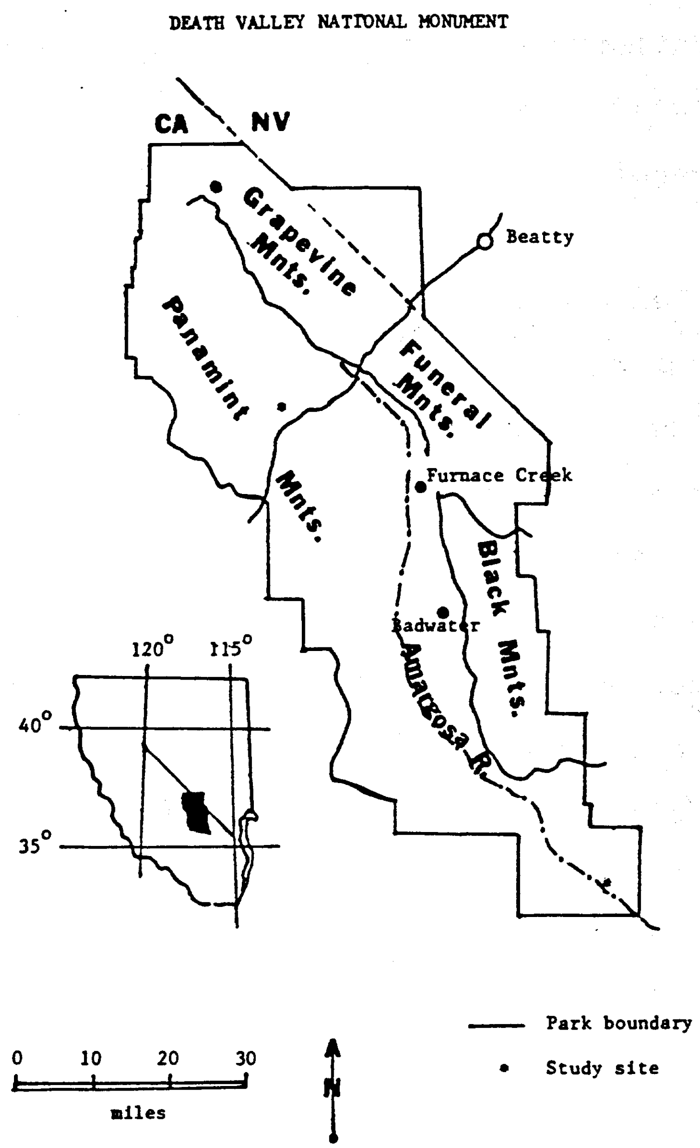

Figure 2. Location of Tamarix study sites within Death Valley National Monument. The Sand Dunes site is just east of the Panamint Mountains and the Amargosa River site is in the far southern end of the Monument.

on the smaller dunes. The valley floor is made up of a very open mixture of Larrea and Atriplex polycarpa. Several extremely large Prosopis glandulosa-dominated dunes are also present on the site. In the eastern periphery of the site, Larrea and Atriplex give way to Suaeda fruticosa, which often grows along the ridge-tops of small dunes.

At the Amargosa River site, Tamarix occurs as scattered thickets along the margins of the numerous river channels that dissect the floodplain. These channels tend to be devoid of vegetation, except for scattered seedlings of various species, with most of the vegetation restricted to small sandy benches that occur between the active channels. Most of the bench areas have a distinct surface crust of salt, resulting in the vegetation being composed almost entirely of halophytes such as Atriplex, Distichlis, Allenrolfea and Suaeda. A strand of Prosopis glandulosa occurs along the floodplain boundaries on each side of the river, but above the saline benches within the floodplain. Thus, Prosopis forms a distinct belt of vegetation that is largely separate from the Tamarix-halophyte assemblage that occurs within the floodplain.

Within Lake Mead, two sites were established in the southern part of the Recreation Area (Figure 3). These sites were chosen because they are representative of Tamarix encroachment into desert montane canyons that contain critical water sources for wildlife, particularly bighorn sheep. The first site was located at Aztec Wash in the Eldorado Mountains (35°40'N, 114°44'W, 630 m elev.). Aztec Wash is a west-to-east flowing ephemeral water course that is apparently fed by several springs, one of which maintains a perennial seep area near the mouth of the canyon. Tamarix occurs as isolated

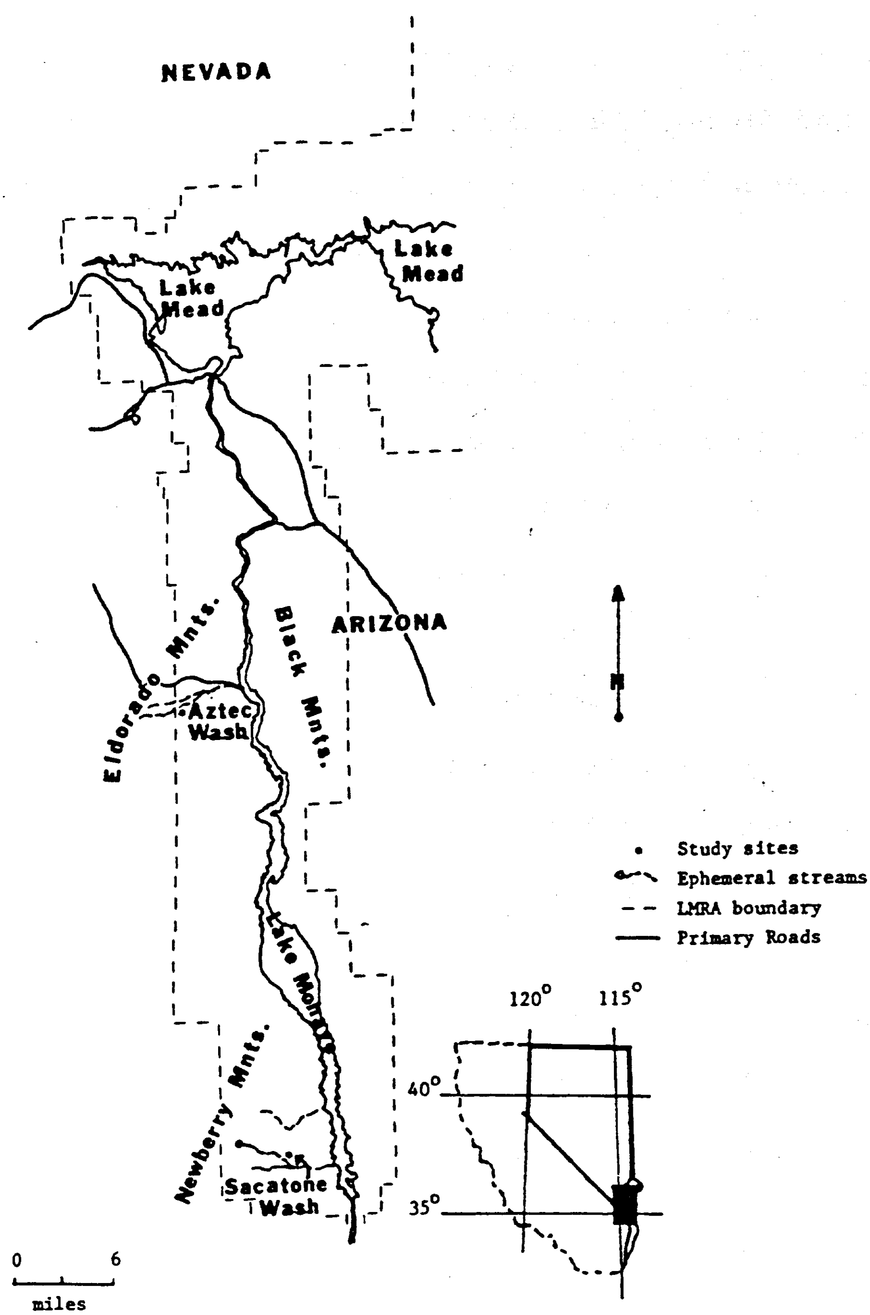

Figure 3. Location of _Tamarix_ study sites within Lake Mead National Recreation Area. Aztec Wash is located in the Eldorado Mountains and Sacatone Wash is located in the Newberry Mountains at the southern end of Lake Mead NRA.

seedlings near the mouth of the canyon, but develops into occasionally dense thickets in the upper sections of the wash. The remaining vegetation in the wash is composed of a diverse assemblage of Mojave Desert shrubs, grasses and cacti.

The second site was Lower Sacatone Wash, located in the Newberry Mountains (35°14′N, 114°40′W, 560 m elev.). Lower Sacatone Wash primarily runs east toward Lake Mohave, but eventually enters Grapevine Canyon before entering Lake Mohave. There is no perennial flow in the upper reaches of Lower Sacatone Wash, but a perennial flow develops in the middle stretch of the canyon, presumably due to spring activity or groundwater being forced to the surface. The canyon bottom has a dense, almost impenetrable cover of phreatophytes including <u>Tamarix</u>, <u>Tessaria</u> (arrowweed) and scattered native riparian species such as <u>Populus</u> <u>fremontii</u> (cottonwood) and <u>Salix</u> <u>gooddingii</u> (willow). The lower part of the wash opens up into a <u>Sporobolus</u> <u>airoides</u> (alkali sacaton) dominated meadow. Large, isolated <u>Prosopis</u> and <u>Acacia</u> <u>greggii</u> trees occur along the margins of the wash.

Water relations observations on <u>Tamarix</u> plants were conducted in Flamingo Wash (36°07′N, 115°08′W, 610 m elev.) near the University of Nevada, Las Vegas campus. Historically, Flamingo Wash only flowed during moist periods or flash floods, but now maintains a perennial surface flow due to urban run-off. A dense stand of woody vegetation, primarily <u>Tamarix</u>, <u>Populus</u>, and <u>Prosopis</u> occurs on the edges of the wash. The wash bottom, which is periodically scoured by flash floods, is composed of <u>Typha</u>, <u>Phragmites</u>, dicot weeds, and scattered <u>Tamarix</u> and <u>Populus</u> seedlings.

Vegetation Analysis

Plant cover of perennial species in the primary study sites was assessed via permanently-placed one hectare (100 x 100m) plots. Plots were subjectively placed in each site in order to quantify the vegetative cover of habitats that are impacted by Tamarix. For each plot, corner 4′ x 0.5" rebar stakes were placed in the ground. Five random lines were then established in each plot using a random numbers table, and were similarly marked with rebar stakes. All stakes were fitted with yellow end caps and labeled for plot number and orientation (corner stakes) or transect number (random lines).

In Death Valley, six 1 ha plots were established in the Sand Dunes site and 2 1 ha plots were established at the Amargosa River site; in the latter plots random lines were oriented perpendicular to the direction of the river channel. Plot orientation and distances for the random lines are given in Appendix 1. At Lake Mead, two plots were established in Aztec Wash and one plot was established in Lower Sacatone Wash. Each plot was 100 m in length, but varied in width as a function of canyon dimensions. In each plot, random lines were oriented perpendicular to the primary drainage channel. Because Aztec Wash and Lower Sacatone Wash change direction the random sampling lines were not all parallel as at Death Valley. The single plot at Lower Sacatone Wash had eight random lines, rather than the normal five.

Vegetation sampling was accomplished using a line intercept technique. We initially proposed analyzing vegetation with belt transects and randomly spaced quadrats, but after discussions with Dr. Peter Rowlands (Resource Manager, Death Valley National Monument), we opted for line intercepts, which are easier to use in dense, thicket-type vegetation. In the line intercept technique, each line is stretched across the plot at a predetermined random location, and the distance for which each species intercepts the line is recorded. This gives an estimate of the vegetative cover, by species, of the plot. Because individual plants are not tallied by this method, no density estimates can be formulated. Frequency can be estimated if multiple lines are used, but it is not advisable to use them for the derivation of an Importance Value. Because each line intercept was staked in the field with rebar, we have provided a mechanism to return and accurately resample all lines, particularly if a durable 100 m tape can be secured to each rebar stake.

Age/Size Structure

Stem diameter-age relationships for Tamarix were estimated from populations at the Sand Dunes and Amargosa River sites. Twenty plants were randomly selected from the Sand Dunes site (10 each from plots A and B) and 10 plants from the Amargosa River site. For each plant, a size series of 5 stems were selected, and a basal cross section obtained for subsequent analysis. All stems were sectioned diagonally, polished with fine sandpaper, and the annual growth rings counted twice (independently) with the aid of a stereoscope. One ring was assumed to equal one year's growth (Brotherson et al. 1984). Stem diameter was obtained by two perpendicular measurements using a millimeter ruler.

Stand demography was quantified for Tamarix at the Sand Dunes and Amargosa River sites. At each site, 150 random plants were chosen using a point-quarter technique. For each plant, the canopy height and width (mean of two perpendicular measurements) and basal diameter of the largest stem were measured. To estimate canopy volume from height and width measurements, we determined the canopy of Tamarix to approximate a spherical segment. The equation for the volume (V, in m^3) of a spherical segment (non-hemisphere) is:

$$V = 1/6\pi h(3r^2 + h^2)$$

where h is canopy height and r is canopy radius in meters.

Water Relations

Plant water potential and stomatal conductance were measured throughout the 1988 growth season for Tamarix, Populus fremontii, and Prosopis pubescens growing together in Flamingo Wash. Three individual plants of each species were chosen for the study. Water potentials were recorded for 3-4 detached shoots per plant utilizing a pressure chamber (PMS, Corvallis, OR). After being detached from the plant, shoots were immediately placed in zip-loc plastic bags and placed on ice for transport back to the laboratory, where they were measured. Water potential measurements were conducted at pre-dawn and then at 2-3 hour intervals throughout the day.

For stomatal conductance measurements, four random leafy shoots were tagged on each plant prior to measurements in order to facilitate repeat sampling over whole days. Stomatal conductance and transpiration were measured with a Lambda Instruments LI-1600 steady state porometer (LI-COR, Lincoln, NE) fitted with a LI-1600-07 "conifer cuvette", which also works well with microphyllous desert shrubs such as Tamarix and Prosopis. Conductances and transpiration rates were measured for both abaxial and adaxial leaf surfaces, but expressed for one leaf side only (i.e., m^2 part of conductance and transpiration units are based on a single leaf side). Stomatal conductance and transpiration were measured at 2-3 hour intervals over whole days, commencing 60-90 minutes after dawn. Tagged shoots used for the measurements were harvested at the end of the day, and leaf areas were determined for each shoot using a leaf area meter (Delta-T Devices, Pullman, WA). This allowed conductance and transpiration estimates to be calculated per unit leaf area on each shoot.

RESULTS AND DISCUSSION

Community Composition

The woody species composition and vegetative cover of the Sand Dunes site are summarized in Table 1. Only four perennial species were recorded in the six 1 ha plots at the site: Tamarix chinensis (saltcedar), Larrea tridentata (creosotebush), Atriplex polycarpa (desert saltbush) and Suaeda fruticosa (seepweed). Prosopis glandulosa (mesquite) also occurred on site as very large mounded plants, but were not in any of the samples. Total cover in the plots was ca. 31%, 86% of which was made up of Tamarix. It should be noted that plots were subjectively aligned in order to describe Tamarix-impacted vegetation in the area; strict random sampling would undoubtedly have resulted in lower Tamarix cover. Even so, total Tamarix cover was much lower than that attained in other internal drainage basins of the Great Basin; for example, Utah Lake where Tamarix attained a cover of 50-60% (Brotherson and Winkel 1986). Coefficients of variation and frequency indicate that Tamarix is distributed across the site in a moderately consistent fashion; Larrea and Atriplex intermediately so, and Suaeda in a highly clumped fashion.

Six permanent plots, designated Plots A-F, were analyzed on this site. Plots A and B, on the western edge of the distribution of Tamarix at the Sand Dunes, are typical strand-line stands of Tamarix that extend in dense belts along the slip-face of north-south running dunes. Large Tamarix thickets extend well into the dune swale, but the densest thickets are congregated against the dune faces. Much of the swale in each plot is made up of clay hardpan that cracks during the dry season. Plot C is a large swale area that is almost

Table 1. Frequency and cover estimates of perennial species at the Sand Dunes site, Death Valley National Monument.

Species	Frequency[1]	Cover (%)		
		Mean	CV[2]	Maximum[3]
Tamarix chinensis	90	26.7	85	75.0
Larrea tridentata	27	1.9	194	11.9
Atriplex polycarpa	40	1.5	181	10.9
Suaeda fruticosa	23	1.0	288	15.0
Total Cover		31.1	64	75.0
Species Richness		1.8	44	3

1 Percentage of 100 m line intercepts for which measureable cover of the species was recorded
2 Coefficient of Variation
3 Maximum cover recorded for single 100 m line intercepts

completely covered with a dense, impenetrable Tamarix thicket that measures ca. 90m in length and 65-75m in width. No other woody species were recorded on the plot. Plot D is an open interdune area that has the highest cover of Larrea and Atriplex on the site, and only a 5% cover of Tamarix. Tamarix occurs as isolated, large thickets, but apparently has not invaded this area to the extent that it attains extensive, closed thickets. Plots E and F occur at the far eastern edge of Tamarix distribution in the Sand Dunes area, and consist of more level, gently rolling sand dunes than for the earlier plots. Here Tamarix varies between widely scattered large thickets (Plot E) to large belts of dense thickets along dune edges or in swales (Plot F). Suaeda becomes an important member of the community on these latter two plots, suggesting that this area of the dune field may be more saline than in the other plots (Marks 1950, Haase 1972).

The species composition and vegetative cover of the Amargosa River site are summarized in Table 2. Eight perennial species were recorded on this site, and all but Prosopis are considered to be strongly halophytic in habit. Prosopis occurred on the upper benches only and was largely absent from the flood plain proper where the plots were established. The smaller benches that occur between the active channels with the flood plain were all covered with a surface crust of salt, so it is not surprising that the site is dominated by halophytes. Distichlis spicata (saltgrass) had the highest total cover on the site, but tended to occur in dense patches, as evidenced by its higher C.V., lower frequency and maximum cover values (Table 2). In contrast, Tamarix and Suaeda occurred throughout the site at moderate to low cover. The fourth co-dominant species on the site

Table 2. Frequency and cover estimates of perennial species at the Amargosa River site, Death Valley National Monument.

Species	Frequency[1]	Cover (%)		
		Mean	CV[2]	Maximum[3]
Tamarix chinensis	100	5.5	76	13.0
Distichlis spicata	80	8.1	128	27.8
Suaeda fruticosa	100	3.9	46	6.6
Allenrolfea occidentalis	80	2.6	135	9.0
Atriplex polycarpa	50	0.7	186	3.7
Atriplex canescens	40	0.4	147	1.7
Atriplex lentiformis	10	0.1	52	1.5
Prosopis glandulosa	10	1.2	317	12.0
Total Cover		23.0	47	38.3
Species Richness		4.7	26	6

1 Percentage of 100 m line intercepts for which measureable cover of the species was recorded
2 Coefficient of Variation
3 Maximum cover recorded for single 100 m line intercepts

was Allenrolfea occidentalis (pickleweed), an obligate halophyte that reaches its greatest development on wet, strongly saline soils (Haase 1972).

A comparison of the two Death Valley sites indicates the wide variety of conditions that Tamarix may be found in. Previous analysis of saltcedar habitats have shown Tamarix to occur in a wide range of soil conditions, both for texture and for salinity (Brotherson and Winkel 1986), and so it can be found associated with Larrea on relatively non-saline, coarse-textured dune sites and with Distichlis, Allenrolfea and Suaeda on heavy, highly saline soils of floodplain sites. Prior to removal, Tamarix was also common on fine textured, inundated soils associated with marshes in the vicinity of Eagle Borax and Saratoga Spring. Finally, although total plant cover was lower at the Amargosa River site than at the Sand Dunes site, species richness was higher. Due to the evenness of cover among several co-dominants, species diversity would be much higher on this site than for the Sand Dunes site.

The perennial species and vegetative cover of the Aztec Wash site are summarized in Table 3. Fourteen species were recorded on this site. Phreatophytes are present on the site (e.g., Tamarix, Prosopis), but most of the species at Aztec Wash are characteristic of Mojave Desert dry wash and hillside communities. Although not recorded in any line intercepts, several species of cacti are present in Aztec Wash. Tamarix was the dominant perennial of the wash bottom, making up 45% of the total plant cover. However, each 100 m (or less) line intercept averaged over 6 species, indicating that species diversity is quite high on the site despite the apparent dominance in cover by Tamarix.

Table 3. Frequency and cover estimates of perennial species at the Aztec Wash site, Lake Mead National Recreation Area.

Species	Frequency[1]	Cover (%)		
		Mean	CV[2]	Maximum[3]
Tamarix chinensis	100	19.2	33	27.1
Vigueria deltoidea	50	5.4	135	22.5
Hymenoclea salsola	80	4.1	93	10.3
Baccharis sarothroides	60	3.4	174	18.7
Larrea tridentata	50	2.5	124	7.6
Prosopis glandulosa	10	2.8	314	28.0
Bebbia juncea	50	1.9	142	8.0
Acacia greggii	50	1.8	161	8.6
Encelia farinosa	70	1.2	92	3.1
Ambrosia eriocentra	30	0.4	144	1.8
Ephedra nevadensis	10	0.2	310	2.5
Aristida glauca	30	0.1	180	0.6
Eriogonum fasciculatum	10	0.1	286	0.9
Sphaeralcea ambigua	10	0.1	265	0.7
Total Cover		43.0	24	58.6
Species Richness		6.1	46	12

[1] Percentage of 100 m line transects for which measureable cover of the species was recorded
[2] Coefficient of Variation
[3] Maximum cover recorded for single 100 m line intercepts

The perennial species and vegetative cover at the Lower Sacatone Wash site are summarized in Table 4. Sacatone Wash has a semi-permanent flow in the wash channel, resulting in the vegetation of Lower Sacatone Wash being largely riparian/phreatophytic in habit. Total plant cover was very high on the site, averaging 82% and approaching 100% on several transects. Fifteen species were recorded on the site, with ca. 8 of the species being riparian/phreatophytic in habit. The presence of *Populus fremontii*, *Salix exigua*, and *Prosopis* spp. indicates that this site may have supported a well developed gallery forest or woodland of native riparian trees, or at least a mixture of riparian woodland and mesquite bosque, prior to the introduction of *Tamarix*. The vegetation is now primarily an assemblage of disturbance-oriented phreatophytes such as *Tamarix*, *Tessaria* (arrowweed) and *Baccharris* (seepwillow). These three species collectively make up 69% of total site cover, and often intermingle to form dense, impenetrable thickets. The *Tamarix*-*Tessaria* association is a common one in disturbed riparian habitats throughout the Southwest, reaching its greatest development on bottomland soils of undifferentiated alluvium subject to varying periods of surface moisture (Haase 1972). Within this association, *Tamarix* dominates on finer textured soils with shallower water tables (Gary 1965), which appeared to be the case in Sacatone Wash.

Although *Tamarix* is the dominant plant in Lower Sacatone Wash, it has a relative cover of only 28%. In the upper section of the wash, above the perennial flow section, *Lycium pallidum* (wolfberry) dominates the vegetation in the form of dense, thorny thickets.

Table 4. Frequency and cover estimates of perennial species at the Lower Sacatone Wash site, Lake Mead National Recreation Area.

Species	Frequency[1]	Cover (%)		
		Mean	CV[2]	Maximum[3]
Tamarix chinensis	100	22.5	48	39.3
Baccharis sarothroides	75	18.7	85	36.2
Tessaria sericea	88	15.4	114	50.0
Lycium pallidum	63	9.0	132	30.5
Sporobolus airoides	25	7.3	186	32.0
Prosopis glandulosa	25	1.9	258	14.0
Prosopis pubescens	13	1.7	282	13.6
Populus fremontii	13	1.2	292	10.0
Larrea tridentata	25	1.1	182	4.7
Salix exigua	13	0.7	298	5.9
Bebbia juncea	38	0.6	167	2.8
Hymenoclea salsola	25	0.4	190	2.0
Juncus acutus	13	0.3	230	2.1
Acacia greggii	13	0.2	250	1.4
Senecio douglasii	13	0.1	300	0.8
Total		81.6	17	100.0
Species Richness		5.6	32	9

[1] Percentage of 100 m line intercepts for which measureable cover of the species was recorded
[2] Coefficient of Variation
[3] Maximum cover recorded for single 100 m line intercepts

The lower part of the wash is a Sporobolus airoides (alkali sacaton) meadow. Species richness and diversity were again quite high at Lower Sacatone Wash, although the growth habit of the vegetation is substantially different than that observed at Aztec Wash.

Population Structure

The stem diameter-age relationships of Tamarix populations at the Sand Dunes and Amargosa River sites are shown in Figure 4. In each population, a highly significant ($p < 0.01$) regression-based relationship was derived between stem diameter and number of growth rings (i.e., stem age). Stem harvests from the Sand Dunes site were divided into separate plots (A and B) and were found to have identical regression slopes. Comparison of the two primary sites indicates a slightly steeper slope for the Amargosa River site than for the Sand Dunes site. No harvests were made at the Lake Mead sites prior to clearing activities on those sites.

The number of growth rings per unit stem diameter can be compared between sites to give a potential site productivity estimate. These data, as well as data from the literature, are given in Table 5. The number of growth rings per unit stem diameter were 3.44 rings cm^{-1} at the Sand Dunes site and 3.32 rings cm^{-1} at the Amargosa River site, indicating essentially equal growth potential at the two sites. These sites show significantly fewer rings per cm when compared to Tamarix from Central Utah, but more than in Tamarix from Navajo National Monument, Arizona. A probable explanation for this difference in growth rates is that the Great Basin climate of Central Utah results in a shorter growing season (and thus thinner

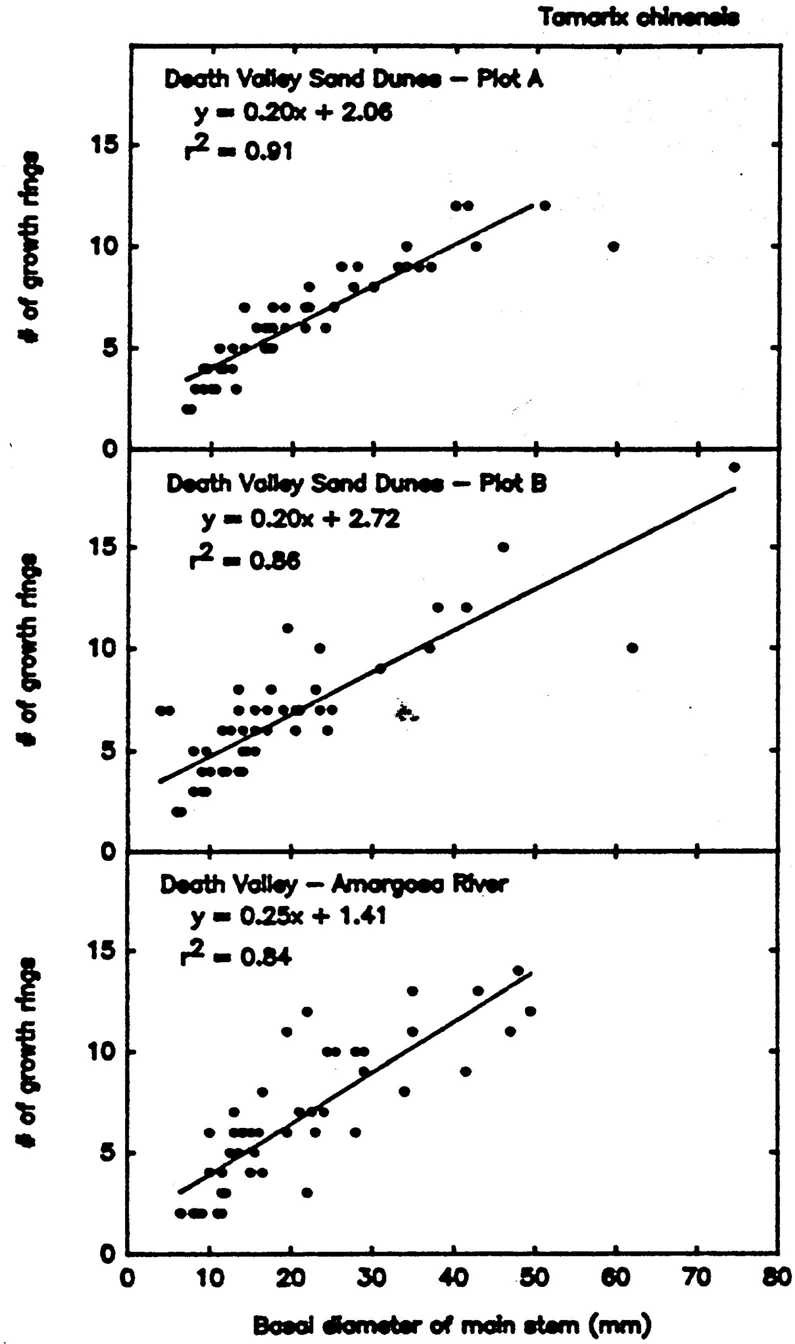

Figure 4. Number of growth rings as a function of basal stem diameter in _Tamarix chinensis_ from Plot A (top) and Plot B (middle) in the Death Valley Sand Dunes site and from the Amargosa River site (bottom).

Table 5. Number of annual growth rings per centimeter stem diameter for main stems of *Tamarix chinensis* from various locations in the Southwest.

Location	Growth Rings Per Unit Stem Diameter (number cm^{-1})	Source
Death Valley Sand Dunes (California)	3.44	This study
Amargosa River (California)	3.32	This study
Navajo National Monument (Arizona)	2.36	Brotherson et al. (1980)
Utah Lake (Utah)	7.68	Brotherson et al. (1984)

growth rings). Death Valley populations have a potentially long growing season, but growth is undoubtedly reduced by the extremely high temperatures that occur there during the summer months (Van Hylckama 1969). The intermediate elevations at which Tamarix occurs in Navajo National Monument, together with perennial surface water supplies, results in ideal conditions for high productivity of the species.

To further examine growth potential in Tamarix, the relationship between estimated thicket age (from stem diameter measurements taken in the field and regression relationships from Fig. 4) and calculated canopy volumes (from canopy height and width measurements taken in the field; see Methods) for each site are shown in Figure 5. Canopy volume increases in a curvilinear fashion as the thicket ages, with most canopy volume increase occurring after the thicket is ca. 10-12 years old. This data appears to support Everitt's (1980) observation that Tamarix is a "slow starter", although an alternative explanation is that aboveground canopy development lags behind development of the root system. Unfortunately, there is no adequate quantitative data on root system development or root/shoot ratios in developing Tamarix plants, only descriptive information. The increase in canopy volume per unit age appears to be much greater at the Sand Dunes site than at the Amargosa River site (Fig. 5), which contrasts with the similar growth ring/diameter relationship between the two sites (Table 5). This may be a consequence of the growth habit of many thickets at the Sand Dunes site, where shifting sand dunes may stimulate production of new rhizomes, which in turn result in new vertical stems being produced from the base. This results in potentially shorter, but "bushier" thickets at the Sand Dunes site,

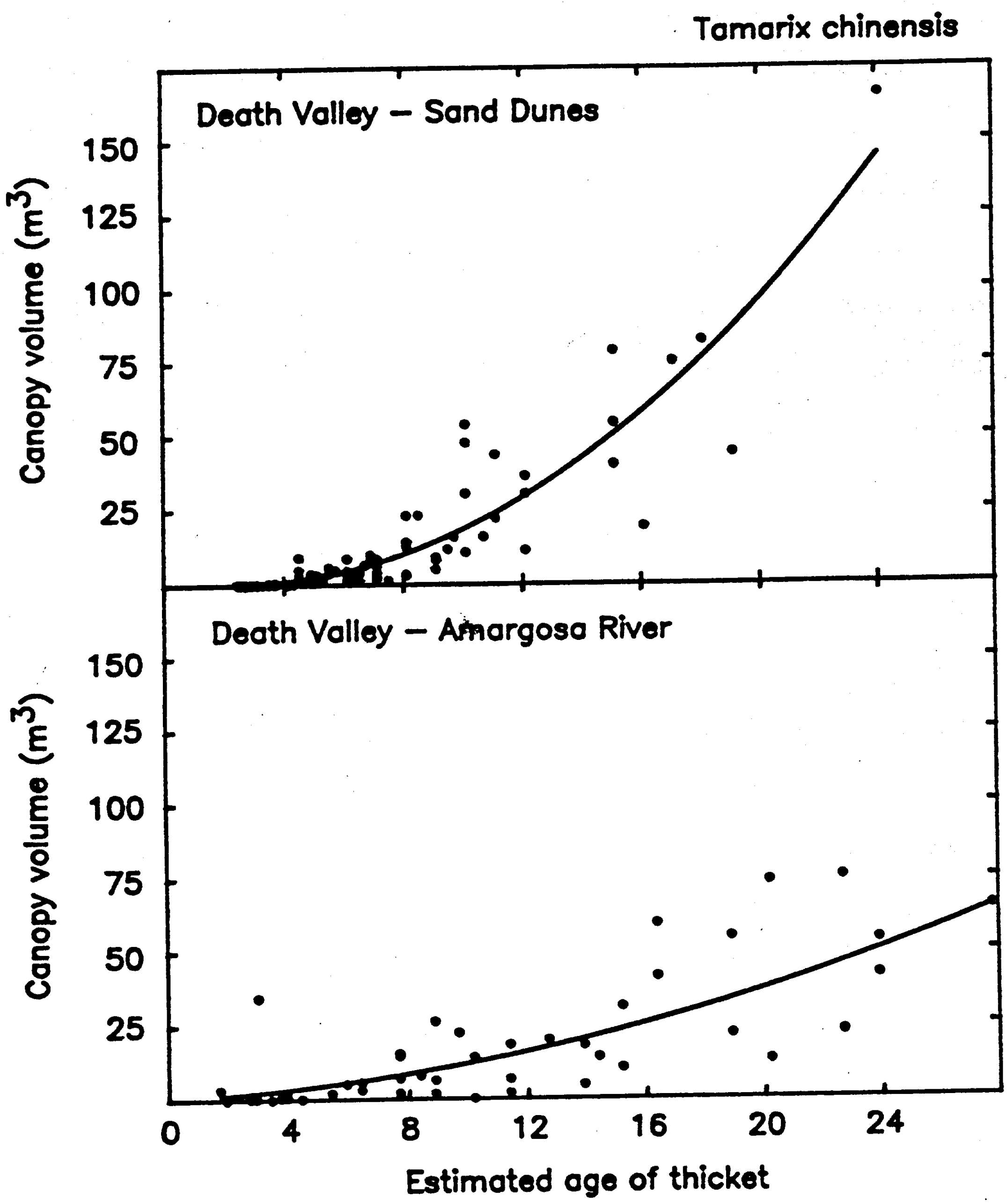

Figure 5. Canopy volume as a function of estimated thicket age for _Tamarix chinensis_ from the Death Valley Sand Dunes site (top) and Amargosa River site (bottom).

which indeed appears to be the case. In contrast, older *Tamarix* plants at the Amargosa River site are often solitary and of considerable height, and have much more moderate lateral rhizome-induced canopy development.

Frequency histograms of the number of plants in various canopy volume (i.e., size) classes for the Sand Dunes and Amargosa River sites are shown in Figure 6. The frequency distributions are very similar for the two sites, and are strongly skewed toward smaller size classes. For example, 73% of the plants measured at the Sand Dunes site were less than $25m^3$ aboveground canopy volume (less than 8-10 years old; see Fig. 5), and 71% of the plants at the Amargosa River site were less than $25m^3$. (Note: a *Tamarix* plant that measures 3m high and 3m wide has a canopy volume of ca. $25m^3$). This indicates that both populations are still in the growth phase. However, several plots at the Sand Dunes site, particularly plots C and D, were devoid of small plants. Plot C, made up of dense impenetrable *Tamarix* thickets, apparently has no microsites available for the recruitment of new plants from seed. Plot D appears to be the most xeric of the *Tamarix* plots, and presently has only isolated, older *Tamarix* plants interspersed between *Larrea* and *Atriplex* shrubs.

The Sand Dunes population apparently became established in 1969, which was an extremely wet year (P. Rowlands, personal communication). This agrees well with the maximum estimated ages of thickets on the site (see Figs. 4,5). We visited the Sand Dunes site after a heavy rainfall event in January, 1988 and found standing water in most of the swales of the site. Of interest was the observation that the outline of standing water in each swale was a very close approximation of the current distribution of *Tamarix* on

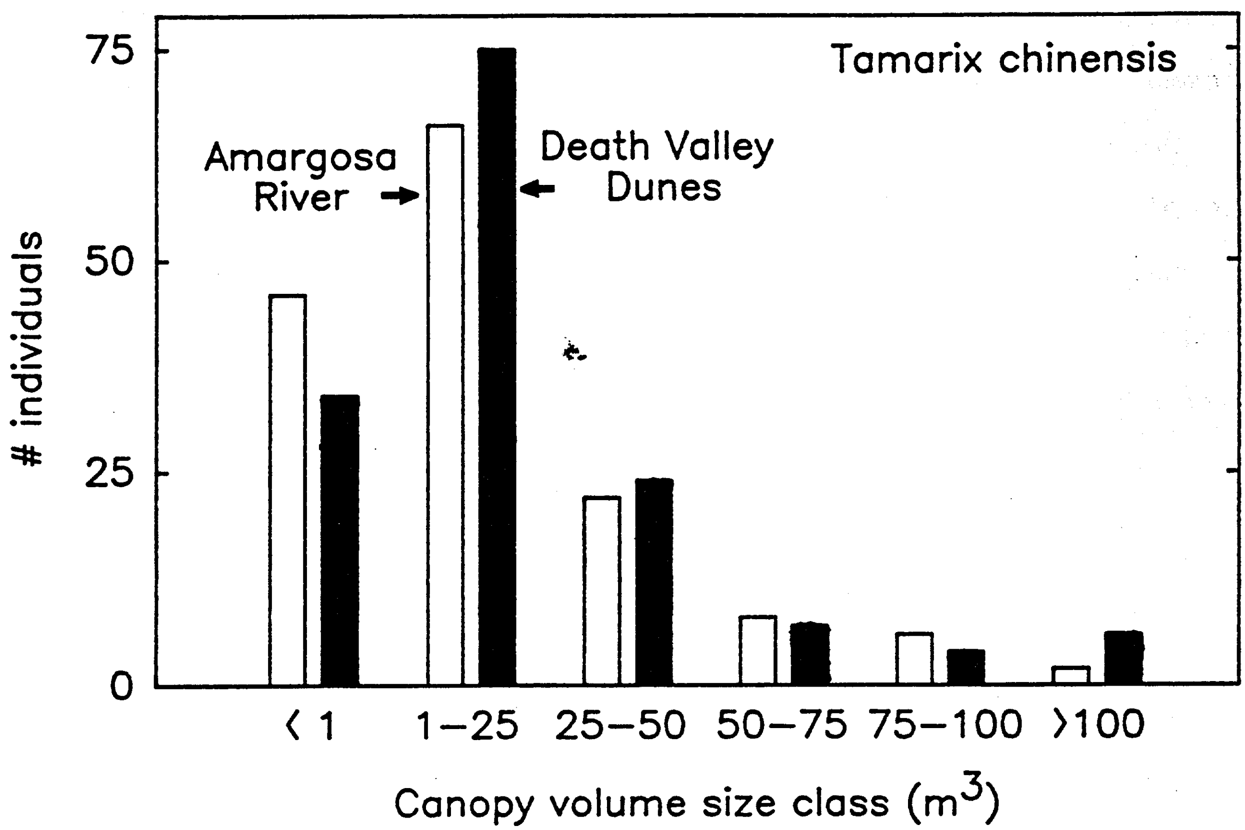

Figure 6. Frequency histograms for the distribution of <u>Tamarix chinensis</u> into various canopy volume size classes for populations from the Death Valley Sand Dunes site (closed bars) and Amargosa River site (open bars).

the site. The establishment of _Tamarix_ seedlings depends on high moisture levels at or near the soil surface, after which the primary root rapidly grows downward to the water table (Merkel and Hopkins 1957; Tomanek and Ziegler 1960). Thus, the conditions necessary for recruitment (i.e., periodic floods or high water) appear to be continuing to occur at the Sand Dunes site, resulting in periodic new cohorts of seedlings. Since the frequency distribution of plant sizes is similar at the Amargosa River site (Fig. 6), recruitment of new seedling cohorts also appears to be periodically occurring there. At Amargosa, almost all new seedlings and small plants were found in the active channels, whereas the mature trees and thickets were confined to the saline benches between the active channels. Thus, a mosaic of age groups may be forming across the Amargosa River flood plain as the active channels meander.

Water Relations

Seasonal patterns in the plant (xylem) water potentials of _Tamarix_, _Populus_ (cottonwood), and _Prosopis_ (mesquite) in Flamingo Wash are shown in Table 6. _Tamarix_ consistently maintained the lowest (most negative) water potentials during the year, with dawn (maximum) water potential ranging from -1.8 MPa (megapascals; 1 MPa = 10 bars) in May to -3.3 MPa in October; midday (minimum) water potentials ranged from -2.6 MPa in April to -3.9 MPa in October. _Populus_, a native riparian tree, had the highest seasonal water potentials, maintaining predawn values above -1.0 MPa and midday values above -2.0 MPa. _Prosopis_ consistently exhibited intermediate predawn and midday water potentials throughout the year; seasonal minimum values occurred in the fall and were -2.4 MPa and -3.3 MPa

Table 6. Seasonal water potentials of *Populus fremontii*, *Prosopis glandulosa* and *Tamarix chinensis* from Flamingo Wash, southern Nevada. Data are means ± one standard deviation.

Date	Taxa	Water Potential (MPa)	
		Dawn	Midday
19 April	*Populus*	-0.68 ± 0.15	-1.21 ± 0.13
	Prosopis	-1.18 ± 0.14	-1.94 ± 0.08
	Tamarix	-2.25 ± 0.20	-2.58 ± 0.32
20 May	*Populus*	-0.73 ± 0.17	-1.64 ± 0.33
	Prosopis	-1.44 ± 0.08	-2.28 ± 0.06
	Tamarix	-1.78 ± 0.25	-2.69 ± 0.21
10 July	*Populus*	-0.90 ± 0.15	-1.70 ± 0.16
	Prosopis	-2.03 ± 0.26	-3.13 ± 0.10
	Tamarix	-3.28 ± 0.39	-4.05 ± 0.40
31 July	*Populus*	-0.71 ± 0.07	-1.68 ± 0.06
	Prosopis	-1.74 ± 0.22	-2.98 ± 0.06
	Tamarix	-2.96 ± 0.21	-3.79 ± 0.37
21 October	*Populus*	-0.76 ± 0.03	-1.65 ± 0.12
	Prosopis	-1.83 ± 0.13	-3.28 ± 0.09
	Tamarix	-3.30 ± 0.24	-3.92 ± 0.36
30 November	*Populus*	-0.93 ± 0.10	-1.03 ± 0.26
	Prosopis	-2.44 ± 0.23	-3.11 ± 0.46
	Tamarix	-3.07 ± 0.21	-3.86 ± 0.47

for dawn and midday, respectively. The water potentials for *Tamarix* are lower than those observed by Anderson (1982) for *Tamarix* stands in New Mexico; his values in June were -0.9MPa at dawn and -2.6 MPa at midday. In contrast, our values for *Prosopis* are higher than those observed by Nilsen et al. (1981) from the Salton Sea area of Southern California. Finally, the water potentials of *Populus* from Flamingo Wash are quite similar to those reported by Smith and Nachlinger (1987) from the Owens Valley of California.

Of primary interest and applicability to the present study was the fact that *Tamarix* occurred at substantially lower water potentials in Flamingo Wash than did sympatric populations of *Populus* and *Prosopis* even though all three taxa were apparently extracting water from the same water source. The explanation for this may be that *Tamarix* is capable of actively pumping salts from the soil solution through the plant, and then depositing the salts onto its leaf surfaces via salt glands (Decker 1961). This salt pumping mechanism may result in significantly lower osmotic potentials in the plant tissues, either by direct uptake of salts into the symplast (intracellular spaces) or by stimulating the production of organic solutes in the tissue symplast in order to balance salt load in the plant apoplast (intercellular spaces and xylem). In contrast, *Populus* appears to exclude salts from its tissues, presumably at the root, and so does not have a large osmotic contribution to water potentials in the shoots. *Prosopis* is probably also effective in excluding salts from its tissues, but has the ability to seasonally osmoregulate in response to water stress (Nilsen et al. 1981).

Seasonal salinities of the water source in Flamingo Wash and salt concentrations in the tissues of each of these species would help to confirm these speculations.

Each of the three species show consistent declines in plant water potential between dawn and midday (Table 6) due to transpirational water loss exceeding the rate at which water is supplied to the shoot via the plant vascular system. To validate this pattern, diurnal patterns in plant water potential were measured on 10 July and 30 November, 1987 for the three species. Maximum daily water potential was confirmed to occur at predawn in each of the species, and minimum water potentials to occur around midday (Figure 7). Populus was again found to have the highest water potential throughout the day, and Tamarix the lowest. These curves from Tamarix also agree well with the diurnal trends observed by Anderson (1982), although the morning declines observed in Flamingo Wash were more gradual than he observed in New Mexico. The mean decline in plant water potential between dawn and midday, when averaged over the whole year (see Table 6), was 0.69 MPa in Tamarix, 0.82 MPa in Populus, and 1.08 MPa in Prosopis. Thus, although Tamarix exhibits the lowest water potentials of any of the three species, it exhibits the smallest dawn to midday reduction in water potential. This indicates that Tamarix has either: (1) greater stomatal control of water loss; (2) a more efficient hydraulic system; or (3) a more favorable root/shoot ratio for meeting transpirational water loss from the plant canopy.

To investigate stomatal control of water loss, diurnal patterns in stomatal conductance and transpiration were obtained in April and late May, 1988 at Flamingo Wash for the three species. Stomatal

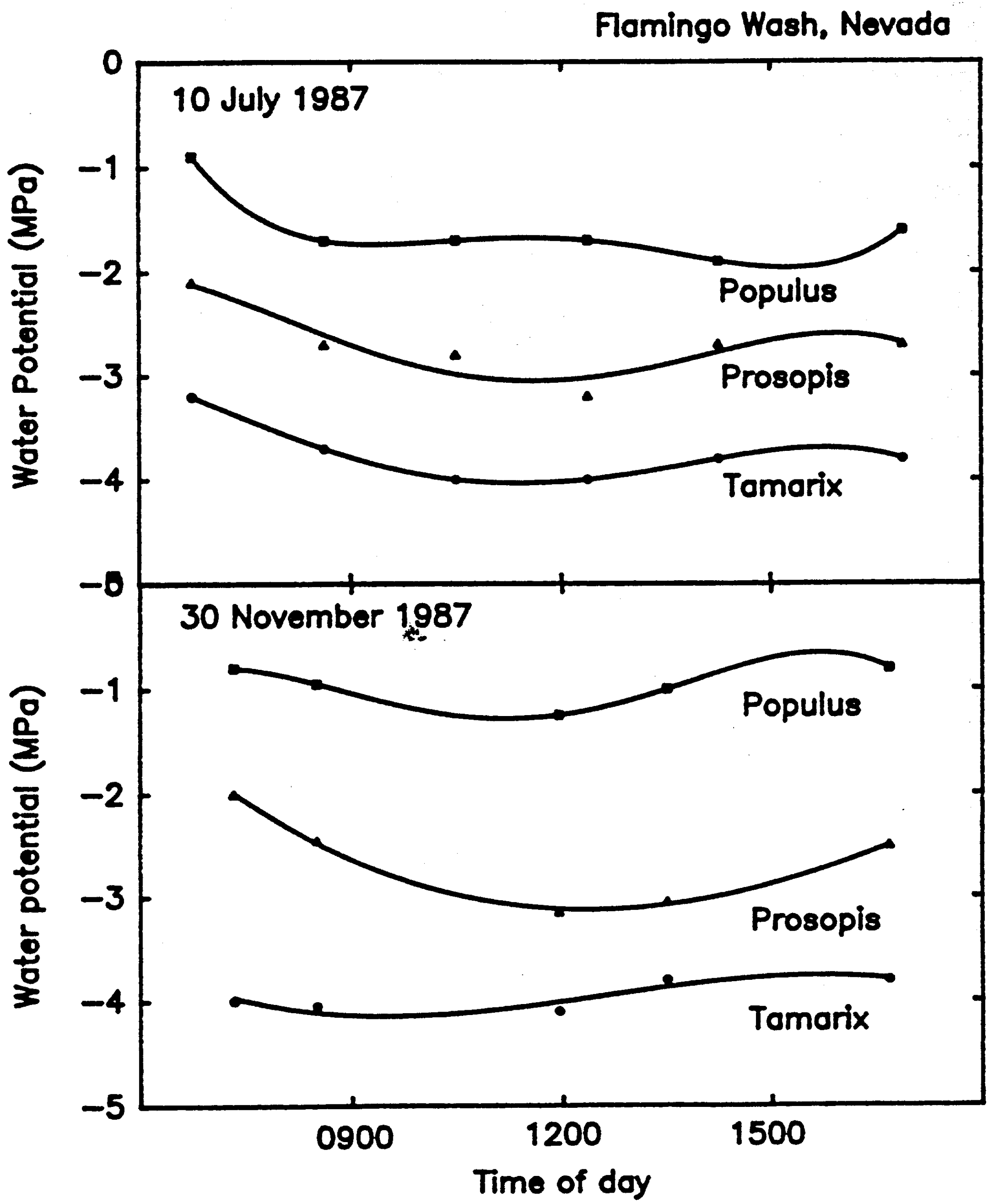

Figure 7. Diurnal patterns in plant water potential on 10 July 1987 (top) and 30 November 1987 (bottom) for Tamarix chinensis (circles), Populus fremontii (squares) and Prosopis pubescens (triangles) from Flamingo Wash, NV.

conductance (Figure 8) and plant transpiration (Figure 9) showed contrasting diurnal trends at different times of the year for the three species. In April, when maximum air temperature was 26°C and midday relative humidity was 22%, each species showed bell-shaped conductance and transpiration curves. Maximum conductance occurred in late morning, and maximum transpiration occurred in early afternoon in concert with maximum VPD (vapor pressure deficit). Tamarix exhibited the highest stomatal conductance, but not transpiration, of the three species at this time of year. By May when maximum air temperature had risen to 32°C and midday RH had fallen to only 8%, stomatal conductances and transpiration rates were much higher in all three species. However, maximum conductances occurred in the early morning, when VPD is lowest, in all three species; this behavior was most pronounced in Tamarix (Fig. 8). This resulted in diurnal reductions in transpiration in Tamarix and Prosopis, but not in Populus, which maintained relatively constant transpiration throughout the day (Fig. 9). Midday stomatal closure was even more pronounced in Tamarix and Prosopis in late June under very hot, dry conditions (midday air temperature of 44°C, RH of 4%), but much less so in Populus (data not shown due to humidity sensor problems with porometer), further supporting the above trends and species differences.

The results of this water relations study confirm the observations of van Hylckama (1980) and Anderson (1982), who found that Tamarix exhibits effective stomatal control of water loss when exposed to high temperature or low humidity, and that the transpiration rates of Tamarix are similar to that of co-occurring phreatophytes. Thus, the prodigious water losses previously

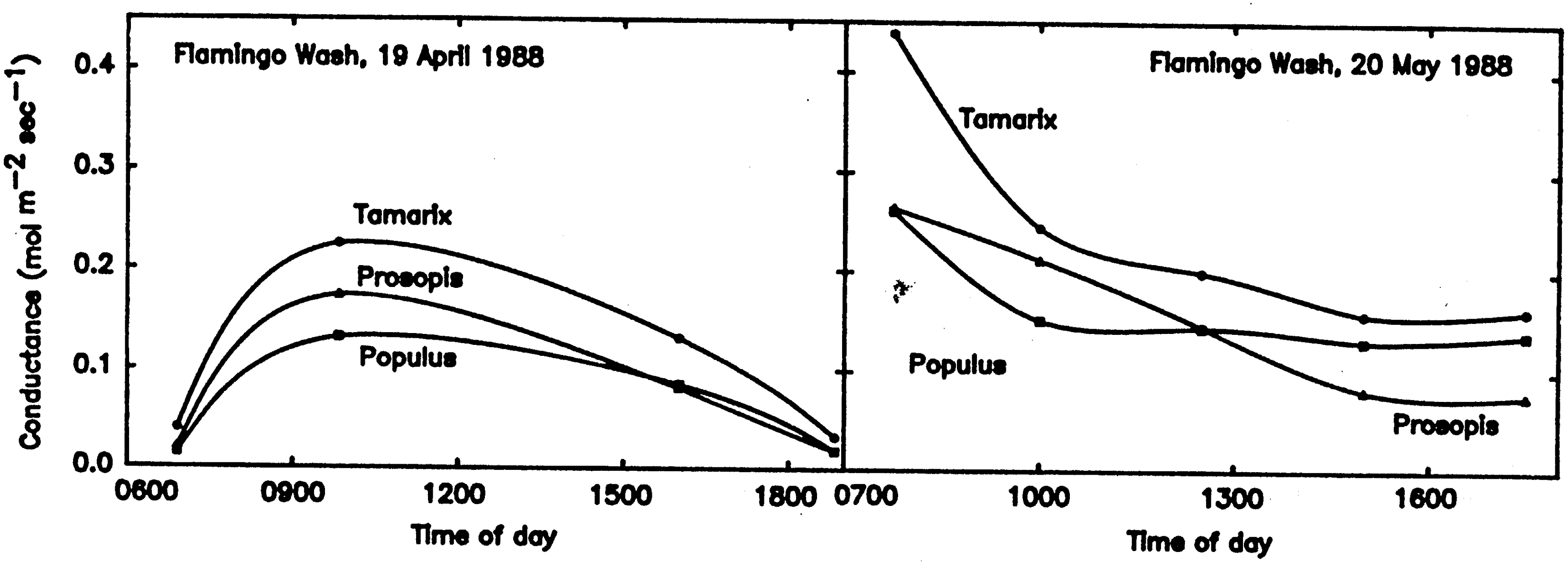

Figure 8. Diurnal trends in stomatal conductance on 19 April 1988 (left) and 20 May 1988 (right) at Flamingo Wash. Species and symbols are same as in Fig. 7.

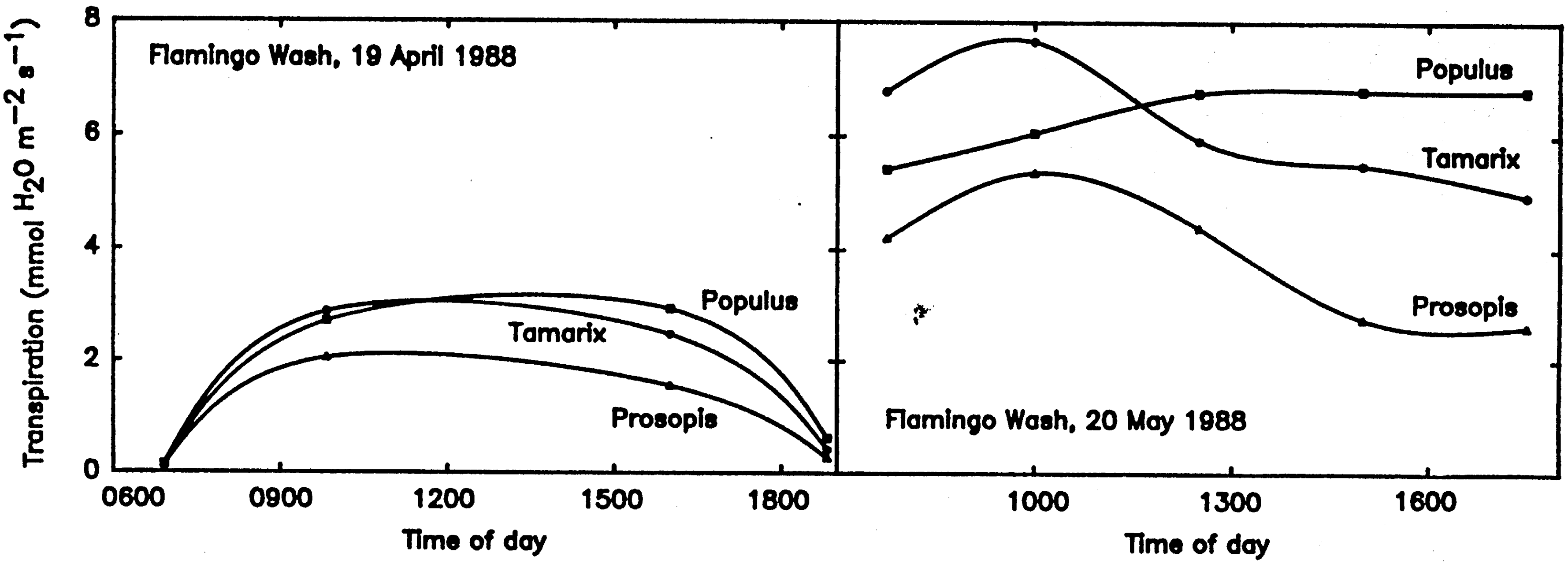

Figure 9. Diurnal trends in transpiration at Flamingo Wash. All figure legends are as in Fig. 8.

attributed to saltcedar (Gatewood et al. 1950; Robinson 1965) may not be the case under many conditions (Culler 1970; Graf 1980). In addition to climatic conditions, also of importance in determining transpiration in _Tamarix_ are total canopy leaf area or volume (Hughes 1972; Gay and Fritschen 1979; Davenport et al. 1982), and subsurface conditions such as depth to groundwater and soil salinity (van Hylckama 1974; Hagemeyer and Waisel 1987). Obviously, the nature of the vegetation which replaces saltcedar after successful clearing efforts will determine how much water is annually saved in the process (Culler et al. 1982; Weeks et al. 1987).

SALTCEDAR CONTROL EFFORTS IN THE PARK SYSTEM

Background

Prior to describing the efforts that have been undertaken to date for control of saltcedar in the individual park units, it may be worthwhile to initially discuss control of saltcedar from a more general perspective. An analysis of the harmful, beneficial, and ecological values of saltcedar, and its potential for biological control is presently being conducted (J. Deloach, personal communication). This study will, in the near future, outline the prospects for various control measures of saltcedar in the Southwest. No economic comparisons have been made of the relative values of the harmful versus beneficial aspects of the presence and potential dominance of saltcedar in native communities. Saltcedar has both harmful and beneficial aspects (Everitt 1980; D. Busch, Bureau of Reclamation, personal communication). Harmful effects include its utilization of large amounts of groundwater, increased sedimentation of stream channels, salinization of occupied habitats, disruption of native plant communities, reduced wildlife habitat due to the displacement of native vegetation; and reduced recreational and aesthetic values of occupied wetlands in parks and natural areas. Beneficial aspects include it being good nesting habitat for white-winged doves and several other species of birds, it grows well and so provides cover on saline soils where most other plants will not grow, its a valuable source of nectar and pollen for bees during much of the year, and one species, *Tamarix aphylla*, is a valuable ornamental, shade tree and windbreak species. The athel tree, *T. aphylla*, is a large evergreen tree that should perhaps not be equated, either ecologically or economically, with the deciduous saltcedars, even though it may also be considered an exotic species in NPS areas. Thus, resource managers should consider avoiding *T. aphylla* when initiating clearing efforts directed toward saltcedar, *T. chinensis*.

Saltcedar is an extremely difficult plant to kill by either mechanical or chemical methods. Millions of dollars have been spent on saltcedar control and eradication in Western river basins, as most attempts required repeated chemical and mechanical treatments. Primary control methods that have historically been attempted include bulldozing, root plowing, spraying, burning, and hand cutting (with or without herbicide application). Mechanical treatments alone have rarely been effective due to the deep root system of *Tamarix*. Foliage sprays kill top growth, but plants invariably resprout. Burning similarly results in only short-term elimination of aboveground canopies; the plants then readily resprout. Large-scale burns on the Colorado River have resulted in complete kills of native cottonwood and willow populations, whereas saltcedar vigorously resprouts and assumes even greater dominance in the post-burn community.

Eradication of *Tamarix* from small areas where it has not had time to develop into extensive thickets can be accomplished at modest expense by hand cutting and direct application of herbicide to the cut surface. The herbicide Silvex was historically the one of choice due to its high kill rate, but Silvex is now banned from use. For larger areas of infestation, the most successful technique to date has been using a root plow modified for deep subsurface placement of herbicides (Hollingsworth et al. 1979). These researchers found that one operation, preferably in the spring, that severed the tap roots 35-60 cm below the surface and simultaneously applied residual herbicides, either by soil layering or soil injection (Quimby et al. 1977), was more than twice as effective as spraying with phenoxy herbicides (Hughes 1965) or root cutting alone. However, the Fish and Wildlife Service has apparently had some success with aerial application of "Roundup" on the Bosque del Apache National Wildlife Refuge in New Mexico (D. Busch, Bureau of Reclamation, personal communication).

Death Valley National Monument

An aggressive clearing campaign to eradicate saltcedar from Death Valley has been underway since 1972. As of 1984, Tamarix was known to occur in 19 locations in the Monument (October 5, 1988 memorandum from Peter Sanchez). The largest stand of saltcedar in the Monument is at the Sand Dunes site, where Tamarix is distributed over a 65 ha (160 acre) area. No clearing activities had occurred by 1984, nor have any since then. However, it remains a high priority site.

Primary clearing activities as of 1984 had occurred at the following locations: Eagle Borax; Saratoga springs and the adjacent Amargosa River floodplain; Monarch Canyon in the Funeral Mountains; along ditches near Travertine Springs and Texas Spring; and NE of Tule Spring. At each location, trees or thickets were cut with chainsaws and brushcutters at the soil surface and treated with Silvex-like herbicides until the late 1970's, and then with Tordon RTU thereafter. Cut stems were removed, stacked and burned. This burning activity apparently resulted in a large fire at Eagle Borax in 1981, resulting in the destruction of much of the mesquite bosque in the vicinity of the marshes. Almost none of the mesquite had regenerated as of 1988. However, saltcedar has also failed to regenerate and so the wetland is presently considered by the NPS to be restored. Partial removal of saltcedar was undertaken in the Amargosa River floodplain in 1971 and 1975 and at Saratoga Springs in 1972; athel may also have been removed from Saratoga. Saltcedar reinvaded both sites in 1979. Several other small springs, most of which occur in the Grapevine and Panamint Mountains, were partially or completely cleared of saltcedar between 1972 and 1982. The status of saltcedar at these sites is unknown to us at the present time.

Three primary clearing efforts have apparently occurred since 1984. Although we have not been able to document a date, the saltcedar that reinvaded Saratoga Springs in 1979 has been removed, as there is presently no saltcedar or athel in the immediate vicinity of the wetlands. Prior to our study being initiated, a moderate amount of clearing of both saltcedar and athel occurred at Nevares Spring in 1985. The most significant clearing activities that have occurred during the course of this study were continued removal of saltcedar and athel from Nevares Spring in 1987 and removal of all the saltcedar from the Amargosa River floodplain near Saratoga Springs, in the spring of 1989. Stems were cut at ground level and the herbicide Garlon 3A was quickly applied to the cambial region of each cut stump. Because this treatment occurred recently, follow-up counts of percent mortality have not been conducted. However, of potential concern is that extensive stands of saltcedar occur on BLM land upstream from the site. Unless cleared, these stands may continue to provide "seed rain" into the site, allowing new recruitment to take place in wet years.

Lake Mead National Recreation Area

Saltcedar has been invading the shoreline of Lake Mead since 1941 and the shoreline of Lake Mohave since its formation in 1953. The beach habitats of these two reservoirs are considered ideal for Tamarix due to its ability to tolerate both inundation and dry soil, and hence adapt well to a fluctuating shoreline environment. At many shoreline locations today saltcedar thickets are so dense that recreational access ranges from difficult to virtually impossible. Although this study did not deal directly with these shoreline populations of Tamarix, a brief background concerning control efforts in these areas is instructive (source: several Resource Management reports from Lake Mead NRA). A variety of methods to control shoreline populations of Tamarix have been attempted, including mechanized removal, clear cutting, cutting and burning, and burning in place. Results from these experiments showed that no one method killed saltcedar in one attempt, but a campaign of repeated attacks reduced the amount and vigor of resprouting. Complete kills of root systems were considered feasible if enough retreatment was conducted.

This study concentrated on Tamarix populations and clearing efforts at spring sites in the southern part of the NRA (see Fig. 3). Saltcedar invasion at springs was not documented until a survey was completed in 1974, which identified saltcedar at 36 of the 38 springs within Lake Mead NRA. In 1975 a saltcedar removal project was undertaken at five springs in the Newberry Mountains. Plants were cut at ground level with chain saws or loppers and the stumps were treated with Silvex by direct application using a small oil can. Post-treatment mortality from that clearing effort was not documented in the report.

Coincident with the present study, new clearing efforts were conducted in April-May 1988 at several springs: Aztec Spring in the Eldorado Mountains, and Lower Sacatone Wash and Willow Spring in the Newberry Mountains. At each site all plants were removed at ground level with a chain saw, but no herbicide was applied. The strategy in this effort was to return to the sites on a monthly basis and remove regrowth via flaming in an effort to eventually starve the root system. Flaming was done with a propane torch, which tended to also ignite adjacent uncut vegetation. A small fire was started in this way at Lower Sacatone Wash, and a large (ca. 0.2 ha) fire was started at Aztec Wash. Flaming was thus suspended in Aztec Wash and Lower Sacatone Wash, and regrowth was only cut at each monthly visit.

At each treatment site, all plant heights (initial pretreatment and monthly regrowth) were recorded and pre-/post-treatment photographs were taken at permanent photographic locations. Regrowth data at Willow Spring where both cutting and flaming techniques were used, are given in Table 7. The results indicate that moderate regrowth occurred after each treatment, but there were indications that regrowth was becoming less after repeated treatments, particularly in the smaller size class categories. All plants displayed decreased regrowth after a fourth flaming (data not shown), and 18 out of 38 plants showed no sign of regrowth. However,

Table 7. Mean height (in meters) of <u>Tamarix</u> regrowth after various treatments during the 1988 growth season at Willow Spring. Dates listed correspond to the following activities: April 25, initial height prior to cutting; June 14, regrowth 49 days after initial cutting; July 12, regrowth 28 days after second cutting and prior to first flaming; September 13, regrowth after two monthly flamings; and October 17, regrowth after third flaming. Plant data are categorized by initial height classes. Data collected by Lake Mead NRA personnel.

		Date				
Size Class	Number	April 25	June 14	July 12	Sept 13	Oct 17
> 3 m	5	3.70	0.45	0.61	0.71	0.40
2-3 m	7	2.33	0.29	0.64	0.68	0.54
1-3 m	21	1.39	0.26	0.37	0.35	0.25
< 1 m	9	0.73	0.25	0.13	0.15	0.03
All plants	42	1.68	0.28	0.37	0.35	0.26

these data were collected in mid-November, when normal winter dormancy mechanisms may have limited regrowth potential. Even so, the results appear encouraging.

Petrified Forest National Park

In Petrified Forest, saltcedar forms dense thickets along the Puerco River and Ninemile Wash in the central part of the Park, where it has been established since 1937, and dense stands were first noted in reports in 1951. However, these low elevation drainages form a small percentage of the Park. Of greater interest from a resource management perspective are the extensive, but scattered stands of Tamarix that occur along the Lithodendron, Jim Camp, and Cottonwood washes in the upper part of the Park (Bowman 1987). Tamarix also occurs around stock tanks remaining from former grazing in the Park.

Initial control efforts in the Park occurred in 1979-80 (Johnson 1985). In one test plot, plants were physically pulled from the soil, removing as much of the root system as possible, with a backhoe and hand tools. This technique resulted in a 54% kill rate. In a second plot, plants were cut at ground surface and either left untreated or treated immediately with Garlon 3A or Garlon 4. After one year, mean kill rates were 23% for untreated plants, 76% for Garlon 3A, and 79% for Garlon 4 treated plants.

Recent clearing efforts in the upper washes of the Park were conducted in 1987 and 1988, employing the cut stump/Garlon 3A application method. In 1987, a low kill rate of 21% was obtained; plants cut and treated in 1988 showed a 67% kill rate, however (C. Bowman, personal communication). There are several possible explanations for this discrepancy: (1) cuttings were burned in place in 1987, possibly stimulating resprouting; (2) plants were cut exactly at ground level in 1988 as opposed to various heights in 1987; (3) herbicide was applied much more rapidly in 1988 due to better coordination between cutters and herbicide applicators; or (4) 1988 was a wetter year, potentially resulting in more vigorous plants that would more rapidly and completely translocate the herbicide to the root system. In all likelihood, improved kill rate in 1988 was due to better technique, particularly concerning speed of herbicide application post-cutting. For example, Tamarix control efforts in Canyonlands National Park have included herbicide treatment one day after cutting, apparently resulting in a very low kill rate.

Plants that survived treatment in 1987 at Petrified Forest were re-cut and re-treated in 1988. Kill rate for these plants was only 38-42%, again possibly indicating a higher kill rate for vigorous plants with a larger conducting area for herbicide translocation to the root system. Also, a difference was observed in resprouting between the 1987 and 1988 control work. In 1987, resprouting was frequently near or directly on the treated stump, particularly the larger ones. For clumps treated in 1988, regrowth was usually peripheral to the clump, either because of distal shoots escaped treatment or because herbicide translocation did not reach outlying shoots (C. Bowman, personal communication).

FUTURE RECOMMENDATIONS

Clearing Activities

An analysis of all clearing techniques used during this study and prior to 1987 suggests that the cut stump with herbicide application technique is most cost effective for small infestations. The preferred herbicide is Garlon 3A or 4. It is best applied with either a brush or a small oil can so that the cambial and phloem regions are completely covered (small stems are best covered entirely). Of critical importance for successful treatment is that the herbicide be applied <u>immediately</u> after cutting, i.e. no more than 5 minutes post-cutting. The best way to accomplish this is to work in small crews with one or two cutters per applicator, plus additional personnel to remove and stack cut brush. Ideally, cut brush should probably be removed to an off-site location and burned. However, at Petrified Forest cuttings were piled in the washes and left to dry in 1988. None of the cuttings had sprouted by 1989, but had instead washed down to become lodged on sand bars (or created new sand bars). These sand bars had no new saltcedar growth by mid-1989, but instead were supporting various grasses (C. Bowman, personal communications).

Clearing operations are best conducted in the spring or fall. It is essential that saltcedar be fully leafed out with green foliage, and thus not dormant. In the spring, downward translocation is expected to be high soon after the canopy has leafed out; likewise translocation to the roots tends to be high in the fall prior to the plant becoming deciduous. Summer treating is not advisable simply because it is too hot for crews to work, particularly at remote sites. An experiment should probably be conducted to determine the optimum season for treating saltcedar with Garlon in the event that a major treatment program is anticipated. This would best be accomplished with paired spring- and fall-treated plots.

Cutting without herbicide application may not be feasible, despite the encouraging results at Lake Mead NRA. At Lake Mead, monthly visits were required to keep regrowth cut back in an effort to eventually starve the root systems. Since burning regrowth with torches was abandoned due to fire hazard problems, this method seems to be quite labor intensive. Also, there is not yet an indication how long it will take to completely kill saltcedar thickets with this method. In contrast, cutting followed by herbicide application requires only one annual visit to cut and treat regrowth. Herbicide use was avoided at Lake Mead spring sites because of concern over using herbicide in sensitive wildlife habitats. However, if herbicide is applied directly to cut stumps in a conservative manner, as opposed to spraying, drift of herbicide into the ecosystem should be negligible. Follow-up studies on this question may be advisable. Lake Mead has received permission to use Garlon 3A for cut stump treatment this year, and so will use this method for future treatment activities (A. O'Neill, personal communication).

It remains to be seen if the somewhat labor intensive cut stump with herbicide application method can be applied to dense stands of concern such as the Death Valley sand dunes, beach populations at Lake Mead NRA, and the Puerco River stands at Petrified Forest. In areas where mechanized equipment can gain access, mechanical uprooting followed by herbicide injection into the soil may be feasible. However, this may not be an acceptable method at beach habitats, where herbicide could drift into the aquatic environment.

Although not advised in most recent publications on saltcedar control, a method that may prove cost effective would be to burn dense monospecific stands of saltcedar during the winter (when the plants are deciduous), then revisit the stands each spring and fall to cut and treat regrowth. Although sprouting would be high after fire, the initial burning process would eliminate a vast majority of aboveground biomass that would take months or even years to initially cut using individual small crews. Burning would also remove the dense litter layer that forms under saltcedar thickets; this litter layer may inhibit recruitment of native species onto sites formerly occupied by saltcedar if the layer is not removed. Burning would obviously not be a feasible alternative in mixed communities.

The most promising long-term technique for the reduction of saltcedar is biological control (Pemberton 1985). Surveys of pests and herbivores on saltcedar from numerous habitats have shown native insects, mites, and microorganisms have adapted very poorly to the exotic Tamarix (Watts et al. 1977). However, there is a movement under way in the Park Service to more aggressively investigate the feasibility of biological control of saltcedar. This research would be potentially invaluable, as biological control is theoretically the most ideal way to slow down the saltcedar encroachment process and to eventually reclaim habitats for native vegetation.

Monitoring Community Responses to Saltcedar Control

If a monitoring program is desired by the Park Service in order to determine if native species respond favorably to the elimination of Tamarix, a variety of techniques can be utilized. Prior to treatment of saltcedar, the community structure of the site needs to be documented. We accomplished this with our permanent hectare plots and random line intercepts. It would also be advisable to map the distribution of saltcedar on 7.5' USGS topographic maps or hand drawn maps and to establish permanent photographic locations. These latter two activities have been done at Lake Mead NRA prior to clearing. Quantitative vegetation data can be generated either via line intercepts (as done in this study and now available at Death Valley and Lake Mead), belt transects, random quadrats or circular plots, or walking point-intercepts. If these lines or plots are permanently marked, then precise resampling of the community can be accomplished at regular intervals post-treatment to document successional processes on the site. If plant cover, by species, is all that needs to be quantified, then line intercepts or walking point-intercepts can be used. If density data, and possibly Importance Values, are also desired, then belt transects, plots, or point-quarters may be necessary. Many of these latter techniques, however, are difficult to use in dense thicket-type vegetation. Thus, vegetation structure may largely dictate what methods can be utilized.

Perhaps the most valuable information resource managers could obtain to determine if the native plant community responds to the elimination of Tamarix would be if a shift occurs in the age/size structure of each native population of interest (see Fig. 8). Saltcedar encroachment into native communities often seriously limits the recruitment of new individuals into the community, resulting in a shift in native populations toward older/larger classes. The removal of saltcedar from the habitat may thus result in a shift in the age/size structure of native populations toward younger/smaller classes as new recruitment occurs. If this quantification is deemed to be too time consuming, resource managers should attempt to make qualitative determinations of recruitment of new individuals of native species pre- and post-treatment in order to determine if recruitment is greater than what tended to occur prior to clearing activities. If recruitment significantly increases post-clearing, and those new cohorts survive in the habitat, then that would be unambiguous evidence that the native plant community is responding positively to saltcedar control.

Revegetation

In many habitats, resource managers may find that saltcedar encroachment has been so severe that the native community may not respond to the elimination of saltcedar. This may be due to an irreversible alteration of the habitat by saltcedar, particularly regarding lowered water tables, increased sedimentation, and salinization of the habitat. Dense litter layers from former monospecific stands of saltcedar may also limit the number of microsites available for new recruitment by native species. To ensure that saltcedar does not quickly reinvade these habitats, it may be advisable to initiate an active revegetation program in an effort to encourage native plants to occupy the "saltcedar niche" and also to provide ground cover that will minimize soil erosion and new saltcedar recruitment.

In wet, non-saline habitats it may be possible to plant native riparian trees such as willows or cottonwoods. This could be accomplished by planting cuttings (pre-treated with a rooting hormone to increase viability) in streambank habitats formerly occupied by saltcedar (Bowman 1986). If willow thickets could be established by this method, then the former saltcedar habitat would be replaced by superior wildlife habitat, particularly for birds (due to increased insect usage of willow versus saltcedar). Based on the experience at Eagle Borax in Death Valley former marshes may tend to regenerate without revegetation efforts, following saltcedar control, provided that the marsh was not completely eliminated by saltcedar and thus no propagules or seed sources were available.

In saline sites where willows and cottonwoods would not be successful, the site could be seeded with saltgrass (Distichlis spicata) or alkali sacaton (Sporobolus airoides). These grasses would obviously not provide the thicket-type wildlife habitat that occurred before, but would aid in soil stabilization and probably help minimize recruitment of saltcedar back into the habitat. The germination requirements and time of optimum seed dispersal would need to be determined for these species prior to any seeding programs. In dry sites such as upland washes, native shrubs (e.g., Atriplex, Larrea, Chrysothamnus, etc.) could be introduced to stabilize the community and slow down the reinvasion process.

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APPENDIX: Compass Readings and Location of Line Intercepts for Permanent Plots at Death Valley National Monument and Lake Mead National Recreation Area.

Plot	Compass Readings Plot[1]	Compass Readings Intercepts[2]	Distance to Line Intercepts (m)
<u>Death Valley - Sand Dunes</u>			
Plot A	305°NW	35° NE	8, 42, 56, 68, 95
Plot B	305°NW	35° NE	9, 15, 36, 60, 89
Plot C	Due N	Due E	6, 39, 63, 70, 87
Plot D	315°NW	45° NE	16, 39, 53, 73, 82
Plot E	355°NW	85° NE	15, 33, 49, 69, 91
Plot F	15° NE	105°SE	11, 18, 33, 62, 79
<u>Death Valley - Amargosa River</u>			
Upper Plot	290°NW	20° NE	2, 26, 46, 68, 91
Lower Plot	290°NW	20° NE	11, 20, 56, 77, 90
<u>Lake Mead - Aztec Wash</u>			
Upper Plot	280°NW	10° NE	9, 25, 39, 57, 75
Lower Plot	290°NW	20° NE	7, 16, 57, 77, 92
<u>Lake Mead - Lower Sacatone Wash</u>			
Lower Wash	280°NW	10° NE	9, 14, 27, 45, 58, 63, 89, 95

1 Compass reading for "length" of plot, starting at nearest corner to SW

2 Direction of line intercepts running perpendicular from "length" of plot