Restoring Mesquite Mounds (*nebkhas*) in the Colorado Desert

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Abstract

*A*ccretion dunes or mounds (also known as *nebkas* or *nebkhas*) are formed when plants capture and then are partially buried in wind-blown sand. In the San Felipe drainage in the western Colorado Desert, mesquite (*Prosopis glandulosa* Torrey *var. torreyana* (L. D. Benson) M. C. Johnston)) forms dunes up to 5 m high. These are ecologically important for both ecosystem structure (primarily habitat) and function (soil accumulation, moisture retention and nutrient cycling). The widening of California state highway 86 damaged and removed several mesquite mounds and the California Department of Transportation asked us to explore techniques for recreating them to reduce sediment movement in high winds, enhance soil fertility, promote reestablishment of the original surrounding vegetation, and provide improved habitat. We created sand mounds and planted small mesquite seedlings on them in 1995. Followup research was conducted on site to address problems with irrigation identified in the early years of the project and monitoring and work on the site continued for 18 years. We have learned a great deal about mesquite dunes, plant establishment in severe deserts <67 mm annual rainfall, and remote site irrigation from this project. Knowing what we know now we feel confident in recommending a set of mound recreation strategies.

Figure 1. Mesquite mound

1. Introduction

Plant accretion mounds *(nebkhas)* form when plants capture and are partially buried in wind-blown sand (Lancaster, 1995). As plants grow the mounds increase in size. In the San Felipe drainage near the Salton Sea in the western Colorado Desert, mesquite (*Prosopis glandulosa*) forms dunes up to 5 m high, figure 1. These mesquite mounds are ecologically rich and appear to be very important for both ecosystem structure (primarily habitat) and function (soil accumulation, water retention and nutrient cycling). They provide locally increased nutrient inputs, high-energy foods, moisture, thorn protected nesting sites, improved microclimate, and protected and elevated burrow sites for wildlife.

Although rare today, mesquite mounds were common in the Imperial Valley before agricultural development (Brown, 1923). However, very high levels of traffic in this area beginning with the California Gold Rush in the mid-1800s led to extensive mesquite cutting for fuelwood (Bainbridge, 2007). The flooding of the Salton Sea in 1905 (deBuys and Myers, 1999), farming, settlement, and road building have also erased large areas of mesquite mounds. Today the remaining mounds continue to be ground away by agricultural expansion, land development and off road vehicle recreation, figure 2. Mesquite mounds occur alone or in small clusters near San Felipe Creek in the western Colorado Desert. Brown (1923) noted a heavy growth of mesquite for two miles along San Felipe Creek.

Figure 2. Off road vehicle damage is increasing

The extensive invasion of salt cedar *(Tamarix ramosissima*) in the riparian areas has also been detrimental to mesquite establishment. The widening of highway 86 west north of Westmoreland, CA damaged and removed a number of the surviving mesquite mounds and in 1992 the California Department of Transportation asked us to explore techniques for recreating these valuable habitat islands to offset losses to highway construction. The goals of mesquite mound creating included soil improvement (fine particle accumulation and microbial inoculation by capture of wind transported particles, nitrogen accumulation by fixation), promote re-establishment of native surrounding vegetation, and improve habitat for local fauna and flora.

Pandey and Rokad (1992) found that *nebkha* development is related to canopy architecture. Shrubs with complex net-like canopies, like mesquite, are best at capturing wind-blown sediments. Similar plant associated dunes have been studied in coastal areas and deserts of Africa and China (Le Houérou, 1986; Doughill and Thomas, 2002; Wang et al., 2006). The mesquite mounds appear to be anchored by a single mesquite tree, with the coppice formed by branches protruding from the sand. Sediment is deposited around the mesquite tree creating an oval shaped accumulation with the major axis and larger tail pointing downwind. A loose net of adventitious roots are encountered close to the surface directly beneath the exposed mesquite and in the bare tops and lee faces of the mounds. Mesquite branches typically cover much of the windward and side mound faces, while the top and lee slopes of the mounds are more commonly thin or bare. Viewed from above, the vegetation sometimes takes on the appearance of a horseshoe with the horns facing downwind. Deposits formed about shrubs generally contain fine sands, silts, and clays in addition to the coarser saltating sands (Tsoar, 1990). In addition to increasing mound stability, these fine particles also increase soil fertility (Bainbridge, 2007).

Mesquite mound development and growth requires both sediment supply and establishment of the stabilizing trees or shrubs. Aerial photos taken almost 50 years ago show that the mesquite mounds in the project area undamaged by ORVs have changed very little (in both shape and size). These photos did help us identify a few mesquite trees that established in the area during the same period; but these have not formed significant accretion dunes. Little sand transport was observed in sand traps set up on site in 1994. This suggests that sand accretion may not be continuous, but pulsed, perhaps occurring primarily after several years of drought coinciding with unusually high winds in the spring when mesquite leaf volume is greatest. The mounds may also reflect increased sand mobility during the most recent retreat of Lake Cahuilla, about 400 years ago. Salt balance studies suggest this may have been a period of mesquite establishment at nearby Harper's Well (Jarrell and Virginia, 1990). The exposed lake bed would have led to mobilization of large volumes of dust and sand.

Mesquite mounds are sites of increased nutrient concentration (Virginia et al., 1984; Jarrell and Virginia, 1987). Virginia and Jarrell (1983) found that the upper 30 cm of soil beneath mesquite in the woodland at Harper's Well had an average total nitrogen content of 1,680 mg kg^{-1} soil. The concentration of nitrate, the form of nitrogen most readily available for plant uptake, was 309 mg kg^{-1} soil at Harper's Well, 18% of the total nitrogen. Total nitrogen and nitrate concentrations were 7.6 times and 3.5 times higher, respectively, than adjacent open soil. Through their nitrogen fixing root symbioses the mesquite mounds contribute nitrogen to the desert ecosystem and increase primary productivity. The high nitrogen levels in mesquite soils was well known by Native Americans who utilized these soils for farming (Nabhan, 1982).

Wind speed reduction by shrubs also captures biological propagules, including arbuscular mycorrhizal fungal spores (Allen, 1988). These fungi form symbiotic associations with plant roots, including mesquite, to increase the soil volume exploited by roots and improve phosphorus uptake (Allen, 1991, 1992). The primary effect of arbuscular fungi infection is to enhance phosphorus availability to plants (Hayman, 1982; Allen, 1988). This association may be critical for mesquite which can obtain its nitrogen from the atmosphere, but requires increased uptake of phosphorus to meet the high energy demands of nitrogen fixation (Allen, 1991; Azcón-Aguilar and Barrea, 1992).

Mesquite establishment

Although persistence and growth of mounds is directly related to the presence of mesquite, little is known about mesquite establishment or persistence in this area. Mesquite has been continuing to spread in the Chihuahuan desert and eastern Sonoran deserts (Brown and Archer, 1989; Gibbens et al., 1992), but we believe it has been in decline in the western Sonoran and Colorado deserts. The presence of a few younger mesquite trees without dunes near the site suggests that flood events or local concentrations of water in animal burrows or low spots can provide sufficient moisture for limited mesquite recruitment. When hurricane remnants cross this area from Baja California rainfall amounts can be very high and flash flooding occurs (NOAA, 2012). When these coincide with higher temperatures seeds scarified in the churning floodwaters may germinate and grow, following the drying front down to groundwater. Mesquite is often found where the ground water is within 15 m of the surface (Brown, 1923; Meinzer, 1927), and at this site it varies from 3-5 m. Mesquite roots can grow very rapidly under good conditions, up to 5 cm in 12 hours (Cannon, 1917). Rooting depths of 12 to 46 m have been observed (Havard, 1884; Phillips, 1963), yet very little is known about how these deep roots develop in the field and reach groundwater.

Mesquite mounds provide an important and significant food source (pods, leaves) during early summer, add structural diversity, provide moist more easily excavated soil, thorny protection and valuable habitat for a wide range of organisms (Dahl, 1982). A survey of seven native mesquite mounds in the project vicinity found an average of seven burrows per mound, with one containing 15 burrows.

Mesquite was also a very important food crop and was planted and transplanted by the native Californians (Shipek, 1989). The nutritious mesquite pods once provided an essential food (Bell and Castetter, 1937; Bean and Saubel, 1972; Zolfaghari and Burden, 1982; Meyer, 1984; Bainbridge et al., 1990). This area was once the site of indigenous agriculture (Lawton and Bean, 1968) and some lithic fragments were found on site. Perhaps human intervention was important in establishment of the mesquite. The larger mesquite woodlands near San Sebastian Marsh are also associated with heavy lithic scatter, potsherds and other signs of ancient settlement.

2. Materials and methods

The project goal was to better understand and to recreate mesquite mounds (Tiszler et al., 1995). Literature and field research led to a better understanding of mounds, but no clear answer about how this should be done. Our team considered two options: grow the trees, plant them in the open and after establishment partially bury them in sand, or create sand mounds and plant them with mesquite seedlings. We selected the second approach to better meet funding, implementation and timing demands; to reduce risk of impact on archeological resources in the area; and in recognition of limited sediment drift across the site. The field implementation phase of the project was started in 1995 and ended in 5 years, after funding ran out monitoring continued for another 7 years.

The project location is two abandoned borrow pits at the southwest corner of the intersection of state highways 86 and 78, adjacent to lower San Felipe Creek (33°07'30.81 N, 115°51'46.29 W) at an elevation of -52 m. Soil had been removed from the site for emergency highway repairs. The borrow pits were both shallow, with typically 1-3 meters of soil removed. Flow in the adjacent San Felipe creek is intermittent through much of its length, but perennial flow is common near the site. Hand drilling and an existing well tube confirmed the water table is within 3 to 5 m of the surface, little changed since 1917 (Brown, 1923).

The firm lacustrine soils in the area are composed of flood deposited lenses of sands and clays. With the exception of the mesquite mounds and nearby barchan dunes (about 4 km away), there is little accumulated sand.

The site microclimate is very challenging with very high temperatures, low rainfall, and high winds. Average annual precipitation is only 67.3 mm for the 97 year record at Brawley, 20 km SE (WRCC, 2012). The precipitation pattern is bimodal with nearly equal maxima occurring in January (10.4 mm) from winter frontal storms off the Pacific and August (10.2 mm) from summer storms moving north from the Gulf of California. Heavy precipitation (<2.5 cm) with subsequent flooding occurs only rarely, but can recharge the soil moisture for many months (Virginia and Bainbridge, 1988). The precipitation and evapotranspiration for the first ten years are shown in figure 3. ET_o exceeded precipitation in every month except one, and over the first ten years the precipitation equaled only 5% of ET_o (CIMIS, 2006). From October 1996 to July 2005 only 40 mm of rain fell per year.

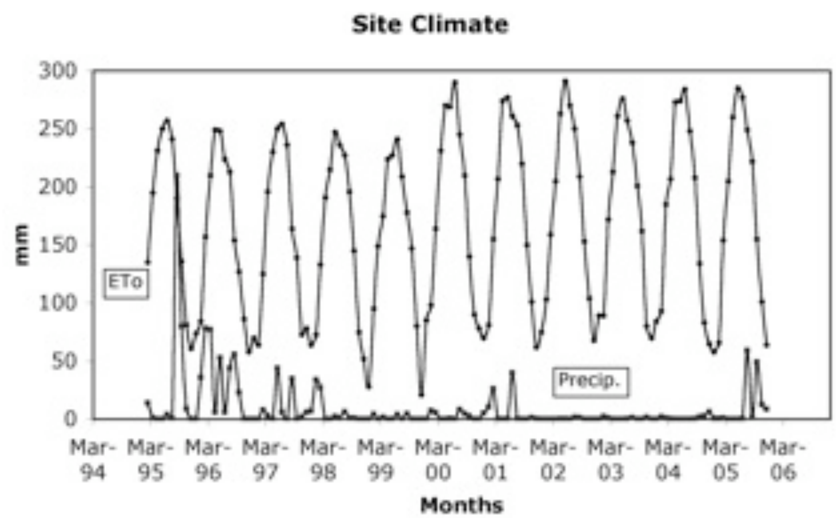


Figure 3. Rain and evapotransiration

Several high wind events occurred over the 18 years of the study, predominantly from west winds, and more rarely from the south- southeast. In Borrego Springs, a nearby location, wind speeds over 100 kmh occurred in 1999, 2000, 2004 and reached 136 kmh in 2013 (NOAA, 2012; NWS, 2013).

The key objective was mesquite establishment, which would be evaluated by survival and growth. The effects of five wind erosion control treatments on mound stability were measured against untreated controls using a set of erosion pins. Each of these treatments was replicated four times: 1) rice straw crimped into the sand with shovels; 2) coir (coconut husk fiber) netting covering the windward two thirds of the mound; 3) xanthan gum sprinkled onto the sand and subsequently moistened to create a crust; 4) pine bark chunk mulch covering the mound; and 5) plastic barrier fence placed immediately upwind of the mound. Habitat value would be estimated by counting burrows.

B. Mound Construction

In August 1994, locally collected seeds were placed in supercells containing a sand:perlite: organic potting soil (21:2:2) mix after scarification (immersed in concentrated sulfuric acid for 5 minutes and rinsed with deionized water) and sterilization (immersed in 95% ethanol for 1.5 minutes and rinsed with deionized water). In September, 230 seedlings were transplanted to plant bands (4 x 4 x 15 cm) containing a sand:perlite:organic potting soil:mesquite dune soil (7:1:1:1) mix. Mesquite dune soil was added to inoculate the seedlings with site adapted nitrogen fixing rhizobia bacteria and arbuscular mycorrhizal (AM) fungi. Later examination of mesquite roots showed that nodulation had occurred. A 1/5 strength complete Hoagland's fertilizer solution was applied twice during the greenhouse propagation period.

Twenty-eight mounds were created on March 15, 1995 by dumping 11.3 metric tons of sand for each dune. Before the sand was dumped, 7.5 cm diameter holes were augered to ~1 m under half of the mounds, to evaluate possible benefits from faster root extension. The dumped sand created mounds about 1.2 m high and 4.3 m diameter, figure 4. The shapes were refined with hand tools. The commercially available sand was coarser than natural mounds with lower silt and clay content. The very fine "blow sand" that comprises naturally occurring mesquite mounds was not commercially available and a coarser sand of lower silt and clay content was used (Table 1).

Figure 4. Sand dumping and shaping to create mounds

Table 1. Grain size distribution

Classification	Grain size, mm	Project area mesquite mounds	Purchased
Gravel	>2.00	0	0.6
Coarse sand	0.50-2.00	1.6	12.4
Medium sand	0.25-0.50	6.7	61.7
Fine sand	0.063-0.25	84.1	24.9
Silt and clay	<0.0063	7.7	0.5

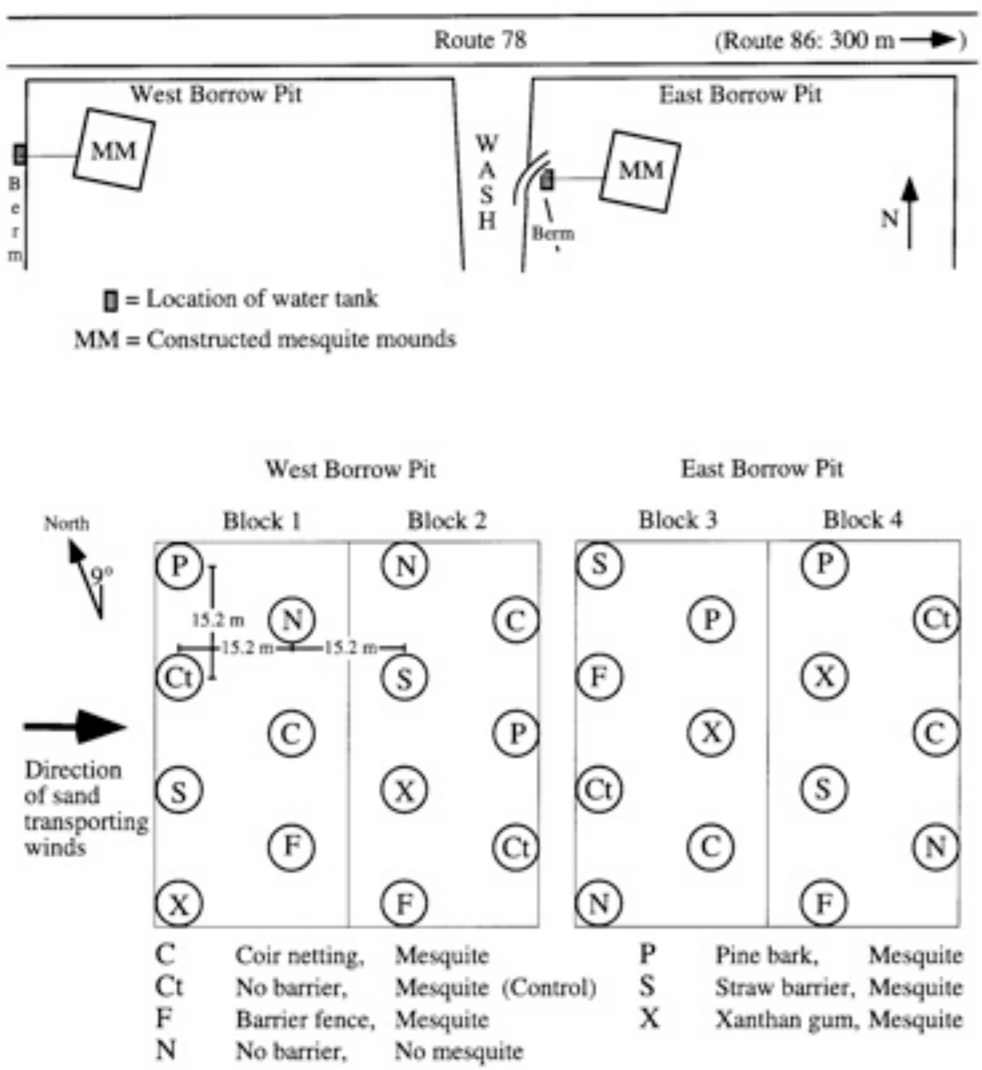


Figure 5. Plot mound layout

Figure 6. Treatments

Mounds were placed in four blocks of seven, figure 5. Preexisting plant cover was very low. The mound axis was oriented 9˚ east of north, perpendicular to the prevailing sand transporting wind (as determined by the orientation of sand beneath nearby shrubs). No mound within a block stood directly downwind from another in that block. The five sand stabilization treatments and an unprotected control were replicated four times in a randomized complete block design, figure 6. An additional mound in each block was left unprotected and unplanted to assess the role of mesquite plants alone in mound stabilization.

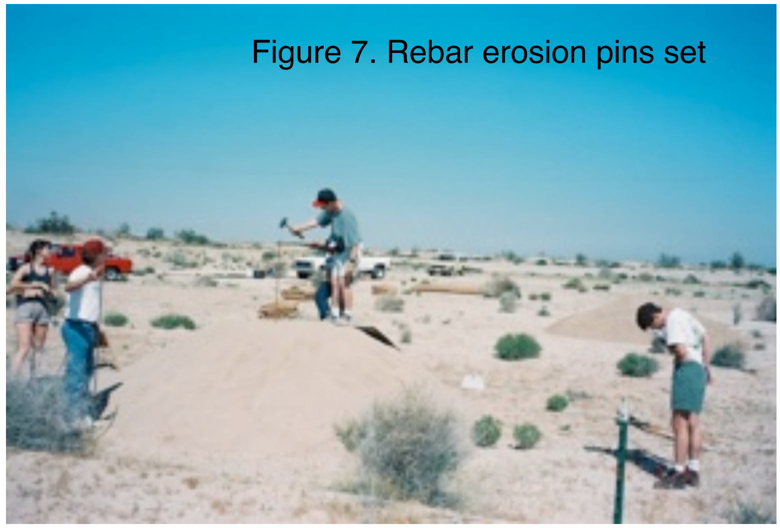


Figure 7. Rebar erosion pins set

The erosion control materials included: 1) rice straw punched into the sand with shovels and McLeods; 2) coir (coconut husk fiber) netting covering the windward two thirds of the mound; 3) xanthan gum sprinkled onto the sand and subsequently moistened to create a crust; 4) large pine bark mulch; and 5) plastic barrier fence placed immediately upwind, figure 6. The xanthan gum was free, but if it had been purchased straw would have been the least costly treatment ($3.50 per mound material cost) and coir was most expensive (about $35 per mound). The gum was applied as a powder and then moistened to form a crust.

Rebar pins were placed in grids within and around the dunes to monitor sand accumulation or loss and possible movement, figure 7. A 1.8 m tall pin was placed in the center of every mound with a goal of 40 cm exposed and four 15.2 cm pins were placed in soil at the edge of each mound at the head and tail and each side (variable distances from the center pin depending on the exact shape of the sand mound). In addition, four 1.2 m tall pins were placed within each of fourteen mounds (two of each treatment) 1.2 m from the center pin in order to more intensively monitor displacement of sand within the mound. Upwind and downwind pins were placed along an axis running through the center pin and oriented 9˚ north of west (parallel to prevailing wind). Side pins were placed along a perpendicular axis running through the center pin. Sand was allowed to settle for three weeks before initial measurements were made by determining the length from the top of each bar to contact with the sand surface.


Figure 8. Drip irrigation

Nine mesquite seedlings (height approximately 25 cm) were planted on each mound. Five seedlings were planted on each mound on March 20 and four planted more were planted three weeks later on April 13. Left over seedlings were planted about the site in open areas. Five plants on each mound were initially protected with treeshelters of varying heights recycled from previous projects (Bainbridge et al., 1995).

Plants were hand watered, with each plant receiving 2.5 l of water per week until two gravity fed drip irrigation systems could be installed by a subcontractor in early May, figure 8. These each supplied two blocks from a 1325 l polyethylene tank on a 3 m tall tower. The water refill delivery was provided by another subcontractor.

The goal of supplying approximately 7.5 l of water to each plant biweekly was not met, with some mounds getting much less water than others, and all getting less than intended. The operation of the drip system was problematic almost from the start and efforts to maintain water delivery required constant attention. In June 1996 an effective solution was finally developed with fittings added to allow operation of a small in-line gas pump to clear the emitters and drive water through the system, but considerable mortality had already occurred.

The problems with drip irrigation at this and other sites led to our research on more efficient alternatives, see for example deep pipe, clay pot and wick irrigation systems (Bainbridge et al., 2001; Bainbridge, 2006a,b; Bainbridge, 2012), and PPTs and text at bainbridge bepress. The drip irrigation systems were discontinued in fall 1996. The mounds were watered twice in 1997 by spraying from a fire truck, and watered twice by hand in 1999. Some surviving trees received limited hand watering in 2001 and 2002.

3. Results

Mesquite nebkha ecology

The mean slope of the windward slope of the naturally occurring mesquite mounds in the area, 24.7 degrees (n=20), was more than double the steepness of barcan dunes in the area, 10.5 degrees (n=2). The downwind slopes for mesquite dunes were 21.7 degrees compared to 57.5 degrees for the barcans. The steeper upwind slopes are apparently sustained by the fine roots and mycorrhizae, algal crusts, and increased aggregate stability created by the presence of clay (7% silt and clay) and organic matter (Kemper, 1966; Harter, 1977). In addition to increasing mound stability, these particles also increase soil fertility (Brady, 1990).

Soil samples from established mounds at the our study site averaged total 220 mg kg^{-1} soil N with nitrate only 16.5 mg kg^{-1} soil, just 7.5% of the total nitrogen. Nevertheless total and available nitrogen were 2 times and 2.6 times higher respectively than the content of nearby open soil. Open sands along the upwind and lee edges of the mound had even lower nitrate levels, < 2 mg kg^{-1}. The nitrate increased with depth, suggesting either transport by percolating water or buildup over time as the mound grew. Ammonium concentrations were lower than nitrate at the top of the mound and slightly higher at the edges, reducing the concentration disparity between mound and adjacent soils. Plant available ($NaHCO_3$ extractable) phosphorus was low (< 1.7 mg kg^{-1}) and differed little between the mound top and periphery.

Europium staining was used to analyze samples from the top, middle, and bottom of the windward and lee faces of a single undisturbed mesquite mound to 10 cm depth (Conners et al., 1994). Samples were also collected in open soils approximately 10 m from the windward and lee edges of the mound. Europium staining does not discriminate between mycorrhizal and other fungal hyphae, but ratios of hyphal length to soil weight are good indicators of mycorrhizal fungal activity. The two off- mound soils had an average active hyphal length of only 0.23 m g^{-1}, while hyphal lengths were as high as 1.26 m g^{-1} on the nebka.

Although mesquite mounds may improve moisture availability, nutrient status, and create higher levels of beneficial microsymbionts compared to surrounding soils, few plant species coexist with mesquite on the mounds. Creosote bush (*Larrea tridentata*) was found on four of the seven dunes we surveyed, with the largest dune supporting 12 individuals. Grasses occur in scattered clumps on the lee slopes and at the base of the mounds.

Mesquite Survival and Growth

One of the most striking features of this study was the intense herbivory, both above and to a lesser extent below ground, by rabbits and other animals, figure 9. As McAuliffe (1986) discovered in palo verde (*Parkinsonia*) herbivory may be the key factor in establishment of mesquite. Some plants had been kept to the 15 cm height of plant shelters for more than 12 years.

Figure 9. Herbivory

This led us to install cages or tree shelters on all surviving plants but even this proved unable to fully protect plants. After the first year overall survival was 76%, with no significant differences among erosion control treatments. The problems with irrigation water delivery and herbivory limit the value of the survival results.

After irrigation was discontinued and the drought deepened survival dropped further to just 14% by year 10, figure 10. This compares to close to 100% in recent wick studies.
At year 10 in paired comparisons, the only significant differences ($p<0.05$) in survival were be

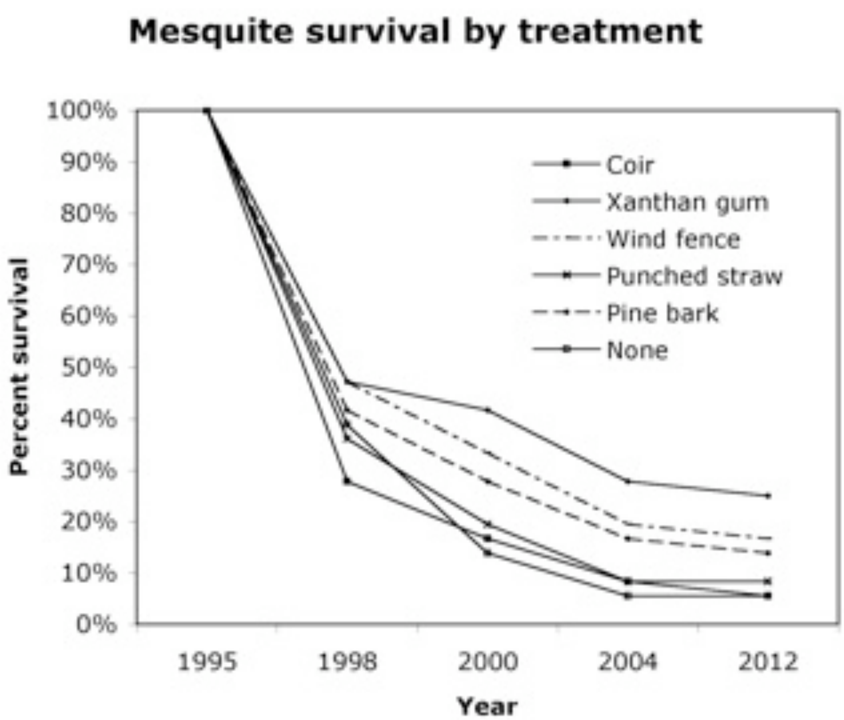


Figure 10. Survival by treatment

tween bare mounds and xanthan gum, coir and xanthan gum, and crimped straw and xanthan gum. The drilled holes beneath mounds had no effect on survival. Additional plants were added to some barren mounds using wick irrigation systems in 2007.

Mound Stability

After some settling and reshaping under strong spring winds in 1995, the mounds appeared to stabilize. After one year, height measured at the center of the mound dropped an average of only 5.6 cm, or about 6%. The coir and punched straw were most effective, Table 2, 3. High wind events caused some sculpting of mounds, figure 11. Erosion of the mounds left some plant roots exposed and it is possible some plants literally blew away in high winds, figure 12.

Several mounds formed small east-pointing "tails" of finer materials after the first year, suggesting some downwind movement had occurred. There was an initial general settling and spreading of the mounds, in part due to foot traffic from watering and measurement as can be seen from the performance of the no plant control treatment.

Table 2. Sand Mound Stability, mean decrease in mound height, cm

Year	1	2	3	4	5	Cumulative	SD
Coir mat	1.8	0.0	**25.4**	5.1	3.3	35.6	10.4
No plant, bare	2.5	2.5	**14.7**	2.5	1.5	23.7	5.6
Straw	4.1	2.0	**17.0**	4.8	5.6	33.5	5.9
Xanthan gum	6.6	4.8	**14.2**	6.1	3.6	35.3	4.2
Barrier fence	6.6	4.8	**9.1**	6.6	4.3	31.4	1.9
Bark	6.9	5.1	**5.6**	7.6	9.9	35.1	1.9
Bare, plants	10.9	8.9	**9.1**	10.9	8.4	48.2	1.2

Figure 11. Wind scouring of mound

Figure 12. Erosion exposes roots

Table 3. Increase or decrease () sand mound height after one and eight years at the downwind (east) pin, cm.

Year	Year 1			Year 1-8	
Erosion treatment	mean	SD	$p<0.05$	mean	SD
Crimped straw	0.9	1.3	a	(-7.9)	4.8
Coir netting	2.3	1.7	ab	(-3.4)	7.9
Bark chip	3.4	2.5	abc	(-7.0)	1.8
Barrier fence	4.3	1.5	bc	+6.0	3.2
Xanthan gum	4.3	3.5	bc	(-0.4)	2.5
None (no mesquite)	4.9	2.3	bc	(-1.2)	6.0
None (with mesquite)	5.7	2.7	c	0	7.3

With the exception of the barrier fence and coir netting the pins set upwind show relatively small changes in erosion even after 8 years, table 4. The only significant difference ($p<0.05$) was the paired comparison of barrier fence and xanthan gum.

Table 4. Mean increase or decrease ()change in sand mound height from 1996-2003 at the up-wind (west) and pin, cm.

Year	mean	SD
Erosion treatment		
Crimped straw	(-7.5)	1.5
Coir netting	(-3.5)	7.1
Bark chip	(-7.8)	1.2
Barrier fence	(-1.0)	11
Xanthan gum	(-10.3)	4.4
None (no mesquite)	(-6).0	2.8
None (with mesquite)	(-8.3)	3.4

Habitat value

Burrows were monitored by counting visible burrows, figure 12. Several burrows may be formed by a lizard or rodent so the total burrow count is likely to be much higher than “lived in” burrows. Colonization was relatively quick and burrow density continued to increase, fluctuating in response to rain, food, and perhaps other factors, Table 5. The punched rice straw had the most burrows.

Mesquite pod production was limited over the first ten years and growth was slow during the prolonged drought; but after the heavier rains of August 2005 pods were set on several trees. This is reflected in the much larger burrow numbers for August 2006, bold. A careful burrow count in the flat ground within the west fenced plot found only 60 burrows, all small, compared to 503 in the west mounds.

Table 5. Burrow density (mean per mound)

Year	1997	1998	1999	2000	2003	2006	2007
Treatment							
Crimped straw	4	9.5	7.25	11.3	2.5	**45.3**	27
Barrier fence	3	6	7.3	13.5	4.3	**30.5**	13.3
Xanthan gum	3	10.5	6.8	9.3	4.2	**30.5**	16.5
Bark chunks	2.5	7.5	4.8	7.5	4.8	**30**	22.3
None, plants	1.5*	7.3	7	7	1.8	**26.8**	11.8
Coir netting	1	6	3	11.5	3.8	**43.8**	11.3
None	1.5*	7.8	5.5	13.3	3.5	**44.5**	10.5

*combined data 1997 only

Figure 13. Burrows

4. Discussion

Mesquite survival and growth

The sustained drought with only a few ecologically significant rain events in the first 10 years made it difficult for mesquite to establish and grow. Only 44 cm of rain fell at Brawley through the project's first eleven years, but ET_o nearby was 2,194 cm during this period. Precipitation met only 2% of potential evapotranspiration demand. From October 1996 to July 2005 there were only 6 days with 2.5 cm of rain or more. Finally in fall 2005 two rains occurred with rainfall exceeding 10 cm total. Had this rain occurred in the first two years the survival story would have been different. The limited rains during the drought failed to deeply wet the mound soils and the water storage benefit sometimes provided by dunes was not realized. In addition shallow surface roots were exposed and damaged by deflation, limiting response to the brief, light rains. The coir and straw may have limited survival by intercepting and re-evaporating light rains before moisture could reach the soil and plant roots. However, in a sustained rain or cloudburst they would provide some benefits over more vulnerable surface treatments. Two flooding events from flash floods occurred between 2005 and 2012 putting standing water over part of the plots. These flood events may be essential in helping roots reach groundwater.

Mesquite seedlings have suffered consistent and intense herbivory, primarily by jack rabbits (*Lepus californicus*). Herbivory and drought were the primary causes of death. Although tree shelters or cages were eventually added to all survivors damage and death was also caused by burrowing animals as they created extensive burrows under and around some of the plants. mound deflation also exposed the roots of some of the plants and led to their death. The overall differences in survival between erosion treatments were not dramatic. The xanthan gum and pine bark had taller surviving trees than the worst treatments: control (no erosion control), barrier fence and crimped straw. The small numbers make the significance uncertain. Over the long term there appeared to be some benefit from the bark treatment as all of the largest trees were on bark mounds. Growth increased after the first significant rain event and larger trees are all now assumed to be in contact with the groundwater, figure 14.

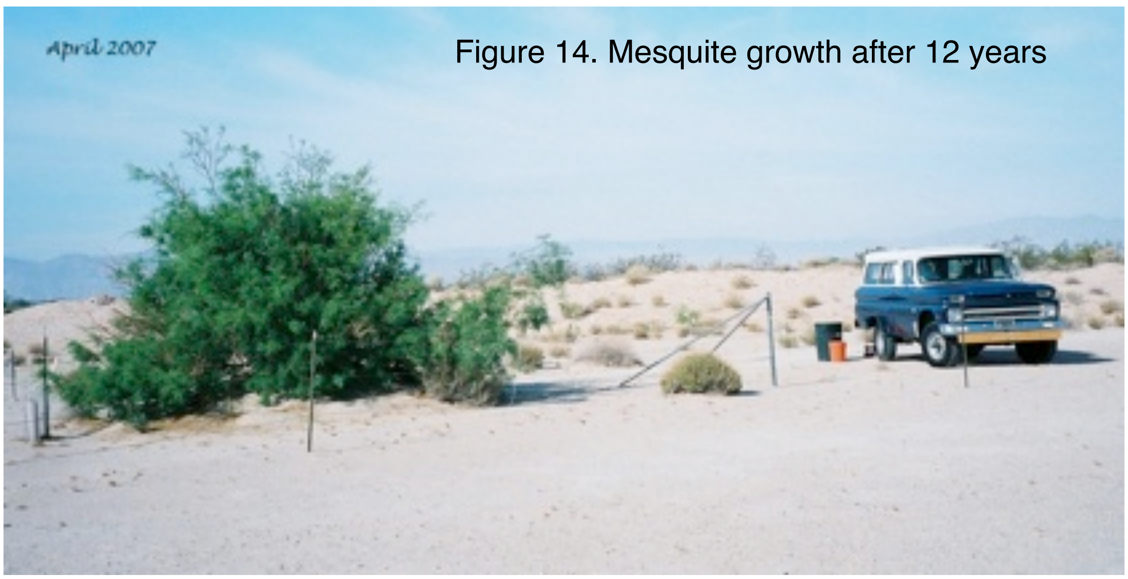


Figure 14. Mesquite growth after 12 years

Erosion control

The untreated mounds *without* mesquite or irrigation showed the smallest initial declines in height, illustrating the unanticipated erosional impacts of walking on the mounds (even using a ladder) during irrigation maintenance and herbivory protection installation. The low number of replications (n=4) and the confusing effect of foot traffic makes significance weak. In the early years when all the erosion materials were functioning effectively the east pins (downwind from the predominant sand transporting winds) showed a small increase in accumulation, 3.7 cm versus an average of 1.2 cm for all other compass points. The east base pins were the only base pins to show a significant difference among treatments. Based on mean sand accumulation on the downwind side after year one it appears that the intact crimped straw was most resistant to wind transport of fines. The variation from year to year limits understanding, but over the first two years coir at 1.8 cm, and straw at 6.1 cm were clearly effective. A high wind event led to a major loss of material in year 3, see bold column in table 2. The erosion pins were pulled in 2005 as part of a cleanup of the site. Windspeed at Thermal airfield (south of Indio) average 14 mph for the year, but peaks in March, 20 mph, and November, 25 mph (USA.com, 2014); but winds of close to 100 mph may occur, moving even small gravel. These rare events may be most important for sediment movement and the creation of nebkhasmesquite mounds.

The pine bark and coir were least effective over 5 years but ironically pine bark mounds had all the largest trees, table 6. The numbers are so low that significance is limited, but still perhaps instructive. The best erosion control choice for a particular location will depend primarily on the desired goals and predicted weather patterns. If short term stabilization of erosion is critical (especially for just 1-2 years) the coir mat may be suitable. If a more complex goal of erosion control, plus revegetation and burrows is the goal then straw, pine bark, barrier fences, and/or xanthan gum may be more appropriate. Punched straw was inexpensive and with rice straw proved to be very durable and supported maximum burrow development. Although termite activity was gradually consuming the straw punched in straw flakes were still visible after 12 years. Slightly lower survival with the straw and coir may reflect the effect of these surface mulches in intercepting light rains before they reached the soil and wicking moisture to the surface (Bainbridge, 1996).

Table 6. Tallest tree per mound, means per treatment after 5 years

Treatment	Cm
Bark chunks	161.8
Xanthan gum	135.3
Coir netting	90.7
Barrier fence	88.8
Crimped straw	79.5
None	68

Habitat value

The mounds provided an immediate improvement in habitat diversity and many organisms colonized the mounds. Burrow density overall was comparable to natural mounds after three years. After significant rains burrow density increased significantly in 2006. Species that have been observed on the mounds or in burrows include: sidewinder (*Crotalus cerastes*), several species of lizards including a horned lizard (*Phrynosoma platyrhinos*) and desert iguanas (*Dipsosaurus dorsalis*), figure 15, and rodents. Insects and spiders were also seen in and around burrows. A number of birds have also been observed sitting on the mesquite trees. Pod formation became significant after ten years. Pod debris left on the ground confirms tha they have become a food source for insects, animals and birds. It is clear that the presence of the mounds have added richness to the once flat and largely barren borrow pits.

5. Conclusion

The strategy chosen for creating mesquite mounds was limited by constraints of the site and budget but was clearly inappropriate for this set of weather conditions. If heavy rains and flooding had occurred in the first year instead of the tenth year the story might have been different, but the lack of rainfall pattern must be expected in these very dry desert areas (Bainbridge, 2007). Planting on the mounds proved problematic. Mesquite seedlings planted at the same time in a

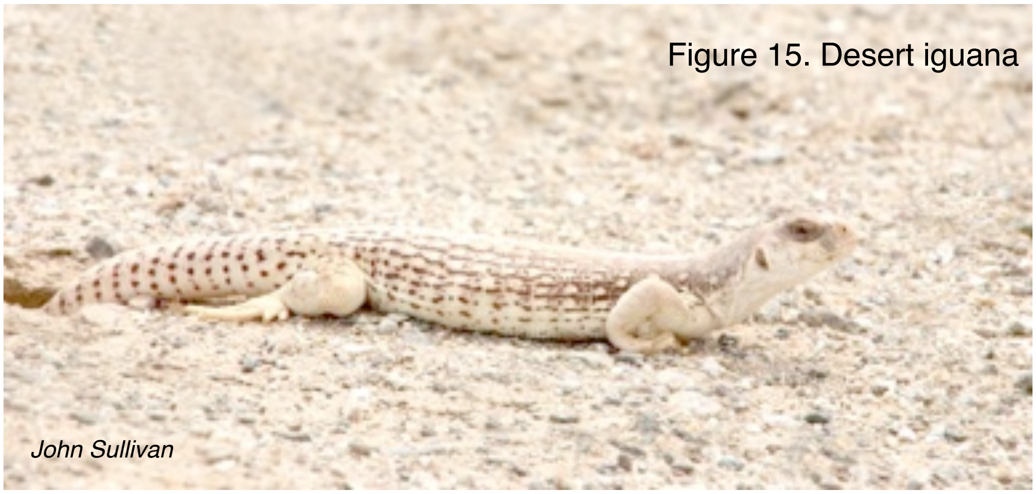


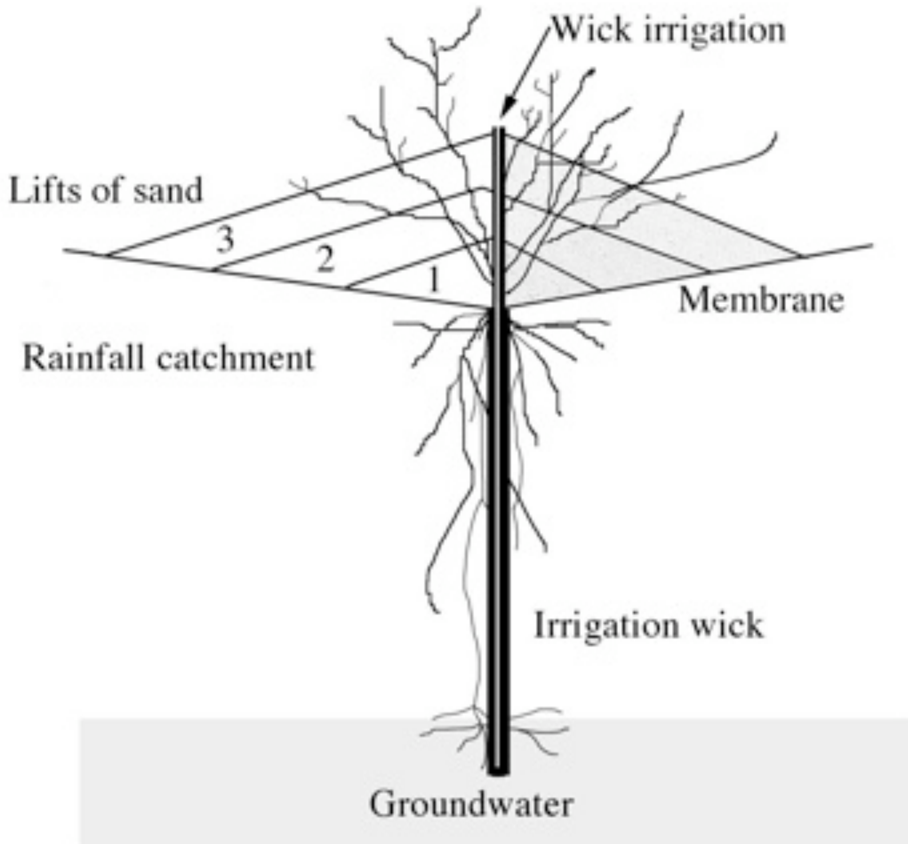
Figure 15. Desert iguana

natural catchment area on site with no protection or support have done better than the plants in the mound experiment.

We would suggest that to recreate mounds the plants should be grown in deep containers (Bainbridge, 2012) in a nursery to 1-3 meters height and then planted in ground shaped to create rainfall catchments, figure 15, perhaps with a rainwater harvesting membrane (see Bainbridge, 2007; Edwards et al., 2000; Shanan and Tadmore, 1979). Gravity wick irrigation with the wick inserted into a hole drilled to groundwater would be used to maintain the trees (Bainbridge, 2011). All seedlings would get a double-walled tree shelter (such as Tubex or Plantra) with multiple ties to resist high winds and a 1 m high rabbit-proof fence around each mound would be installed to further reduce herbivory. As the plant grows we would bury the plants in several lifts of sand leaving the branch tips exposed, and perhaps adding punched straw or bark to reduce erosion.

We believe this approach would more rapidly create sustaining and vigorous mesquite mounds. The ecological benefits are clear. The benefits of mound establishment in reducing sand movement are clear (Wang et al., 2006). The cost and difficulty involved in establishing mesquite mounds also supports the need for better protection of existing mesquite mounds. The Bureau of Land Management, California State Off-Highway Recreation department and others could provide signing, fences and educational material to reduce damage to these valuable resources. Additional research is needed to provide confirmation of the value of mounds for sand erosion control, environmental restoration and agroforesty (Bainbridge, 2011).

Figure 15. Planting diagam



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Added information on sand, sand movement and reptiles in the region

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Drilling for soil samples on mound

Punching in the straw with McLeods

Additional photographs

Cutting the coir fabric

Project team camp

Downwind pin almost buried

Monitoring measurements

Monitor wind fence Dec 1995

Monitor coir mound Aug 1995

Bark mound 1997

Mesquite mounds with water tank

Termite tubes
on rice straw

Herbivory bark mound 1999

Coir decay by June 1999

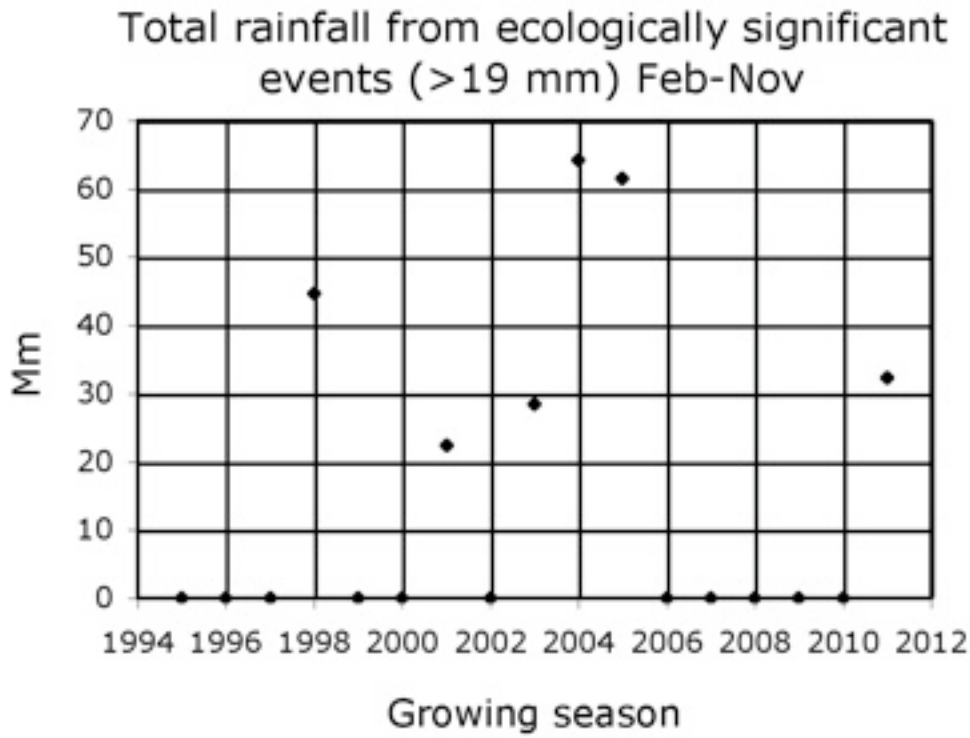
Bark mound tree growth by June 1999

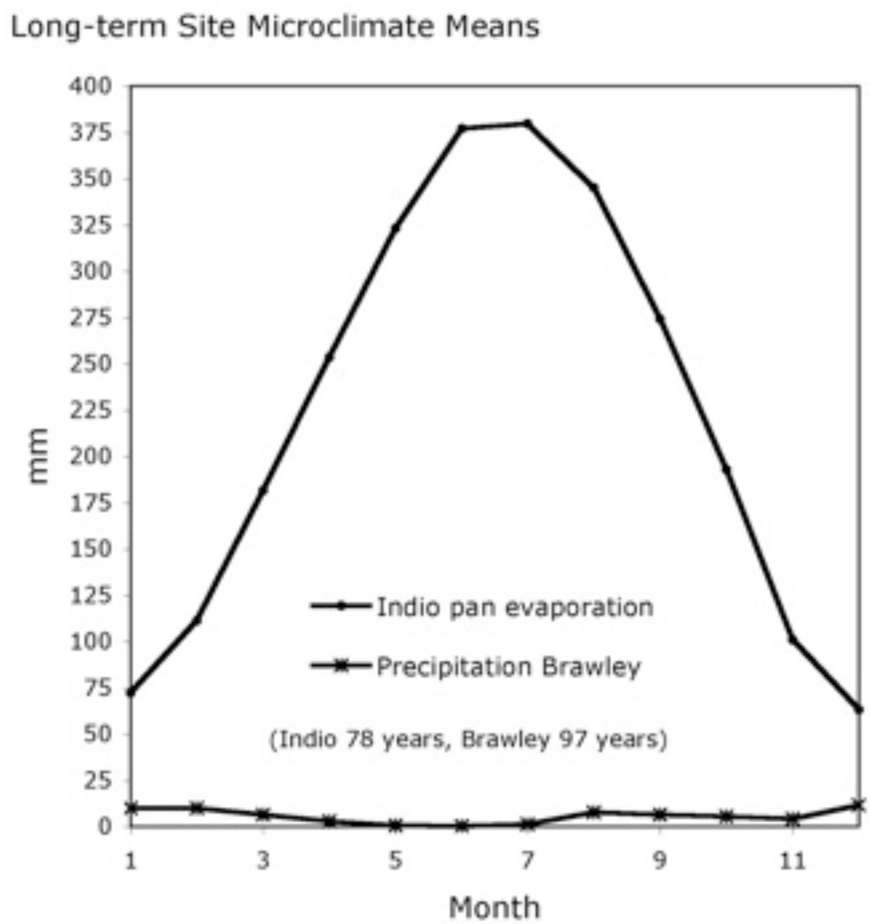
Wind blown survivor - note soil cracking from flood event

Pod production 2007

Irrig x mulch mesquite trees experiment, deep pipe irrigation was most effective with excellent survival and fast growth

ORV damage to natural mounds increases


Total rainfall from ecologically significant events (>19 mm) Feb-Nov
Mm
0
10
20
30
40
50
60
70
1994 1996 1998 2000 2002 2004 2006 2008 2010 2012
Growing season


Long-term Site Microclimate Means
mm
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
400
Indio pan evaporation
Precipitation Brawley
(Indio 78 years, Brawley 97 years)
1
3
5
7
9
11
Month