EFFECTS OF MESQUITE CONTROL AND MULCHING TREATMENTS ON HERBACEOUS PRODUCTIVITY AND SOIL PROPERTIES

By

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ABSTRACT

The objective of this study was to evaluate the effects of mesquite overstory removal and modifications of soil properties due to mulching treatments on herbaceous production. The three overstory treatments were complete removal of mesquite overstory with no removal of regrowth, complete removal of mesquite overstory with removal of regrowth and an untreated control. The mulching treatments included applications of chip mulch, commercial compost, lopped-and-scattered mesquite branchwood and a control. Both overstory treatments resulted in an increase of over 20% in total annual herbaceous production. The overstory treatment of complete removal of mesquite overstory with no removal of regrowth had the greatest impact on fall production of native herbaceous species during years of relatively high precipitation, at times increasing production by almost 2-fold. Mulching treatments had no effect on herbaceous production; however, soil pH and plant available phosphorus was affected by some of the mulching treatments.

INTRODUCTION

Increased densities of mesquite (*Prosopis spp.)* have been threatening the productivity of rangelands and have been a significant concern for land managers in the southwestern United States. The encroachment of mesquite onto rangelands has been documented since the early 1900's and has been attributed to excessive grazing of livestock and changes in the natural fire regime. Mesquite trees possess a variety of characteristics that allow them to out-compete herbaceous species, and an inverse relationship exists between mesquite tree density and perennial grass production. Reductions in herbaceous production can negatively impact livestock operations and wildlife management, and can increase soil erosion. As a result, natural resource managers are attempting to control mesquite invasions through the use of prescribed burning, chemical treatments and mechanical removal. These management approaches have focused on reducing mesquite densities; therefore, previous research has focused on the effects of killing mesquite. Limited information exists on how top removal of mesquite, and subsequent resprouting of mesquite, affects herbaceous production and soil properties.

An additional method that can be used to increase herbaceous production is the use of mulches to increase soil moisture. The use of mulches can effectively reduce evaporation at the soil surface by intercepting solar radiation and reducing wind speed close to the soil surface. Mulching practices have been traditionally used for agricultural production and limited research has been conducted on how mulches affect herbaceous production on rangelands. Research evaluating the effectiveness of mulches on rangelands could be an asset to natural resource managers, especially in situations of mechanical removal of shrubs in which an excess of woody material is available.

The objective of this study was to evaluate the effects of mesquite overstory removal and possible modification of soil properties due to mulching treatments on herbaceous production. The information provided by this study can be incorporated into management practices to enhance the productivity and stewardship of semi-desert grass-shrub rangelands.

BACKGROUND

Semidesert rangelands provide an assortment of valuable resources in the southwestern United States; however, increased densities of mesquite trees (*Prosopis spp.*) have threatened the productivity of these rangelands. Researchers in the early 1900's first documented increased stands of velvet mesquite (*Prosopis velutina*) and burroweed (*Haplopappus tenuisectus*) in southern Arizona (Griffiths 1910; Thornber 1910). More recent research has confirmed that encroachment of shrubs onto grasslands is occurring at alarming rates (Glendening 1952; Buffington and Herbel 1965; Hastings and Turner 1965; Hennessy et al. 1983). Mesquite trees possess a variety of characteristics that allow them to have a competitive advantage over herbaceous plant species. Mesquite trees have an extensive root system that allows them access to permanent sources of groundwater; they can grow in a wide range of soil types and climatic conditions; and they have the ability to indirectly access nitrogen through a symbiotic relationship with nitrogen-fixing microorganisms. In addition, mesquite can consistently extract soil moisture to a depth of 3 m and an outward distance of 10 to 15 m. As a result, mesquite trees are commonly in direct competition with perennial grass species for soil moisture, especially in the upper 38 cm of the soil (Cable 1977).

Additional research has shown that an inverse relationship exists between the density of mesquite trees and perennial grasses (Parker and Martin 1952; Cable and Tschirley 1961; Reynolds and Martin 1968; McDaniel et al. 1982; Herbel et al. 1983; Heitschmidt and Dowhower 1991; Martin and Morton 1993; Laxson et al. 1997). Cable and Tschirley

(1961) observed a 3-fold increase in forage production as a result of mesquite control, and McDaniel et al. (1982) found control of mesquite trees resulted in a 6 to 17 % increase in grazing capacity over a 4 year period. Likewise, Parker and Martin (1952) concluded that production of perennial grasses more than doubled and annual grass production increased 5-fold as a result of mesquite removal in southern Arizona.

The reduction in perennial grass production that is commonly associated with increased densities of mesquite is a concern for natural resource managers. A reduction in herbaceous production can negatively impact livestock operations, wildlife habitat, and soil erosion. Some researchers suggest that the increase in mesquite, and subsequent decrease in herbaceous production, results in a positive feedback loop that consequently leads to the desertification of formerly productive rangelands. The reduced herbaceous production can leave interspace areas between shrubs bare and vulnerable to fertility losses as a result of increased erosion and gaseous emissions which, in turn, contributes to less herbaceous production and a build up of sand dunes (Herbel et al. 1983; Schlesinger et al. 1990).

Given the competitive advantage that mesquite has over perennial grass species, it is unclear why mesquite encroachment onto grasslands has been occurring at accelerated rates within the last century. Livestock grazing and the alteration of the natural fire regime are likely to be the major causes of mesquite encroachment. Overgrazing of livestock reduces the competition of perennial grasses and provides an improved environment for mesquite seedlings. In addition, cattle have been considered to be a primary factor in the dispersal of mesquite seeds by ingesting the mesquite beans and depositing the seeds (Brown and Archer 1987). Livestock grazing has also contributed to the reduction in fire frequency by reducing the fuel loads. Prehistoric fire regimes are difficult to determine for mesquite savannas; however, evidence suggests that fires occurred about every 10 years prior to Anglo settlement (McPherson 1997). Since Anglo settlement, fire suppression and a reduction in fuel loads have reduced the frequency and intensity of fires that once controlled the encroachment of mesquite by killing the younger, smaller trees (Humphrey 1953).

Natural resource managers have been attempting to determine the most effective and efficient method to control mesquite invasion. Reduction of mesquite stands can be difficult to achieve due to the ability of mesquite trees to withstand disturbances and resprout vigorously. Management approaches have included prescribed burning, chemical treatments and mechanical removal. Fire has been a common management tool in controlling woody species. A significant amount of research has been focused on the effects of fire on mesquite stands, and results suggest that fire is useful in controlling the spread of mesquite, but oftentimes is ineffective in reducing preexisting stands (Wright et al. 1976; Martin 1983; Archer et al. 1988). Studies indicate that fire is effective in killing young trees; however, trees that are 3.5 years or older can become tolerant to fire (Wright et al. 1976; Archer et al. 1988).

Chemical treatments have also been used to control the encroachment of mesquite onto grasslands. Application of herbicides will frequently kill a significant amount of mesquite trees and will result in increased herbaceous production (Cable and Tschirley 1961; McDaniel et al. 1982; Herbel et al. 1983; Martin and Morton 1993). However, treatment effects can be variable and relatively short term. Heitschmidt et al. (1986) observed that there was no difference in herbaceous production between chemically treated and untreated plots 6 and 7 growing seasons after the treatment. Likewise, Scifres and Polk (1974) found that forage production increased on areas chemically treated for brush control only in years of average or above average precipitation. Herbicide treatments often not considered feasible due to the varying results and the multiple treatments that are required to effectively control mesquite invasion. Chemical treatments have also been criticized because of negative side effects such as limiting biodiversity, inhibiting the growth of plants other than the target species and site contamination.

Mechanical removal is an additional management approach that can be applied to reduce mesquite stand densities. Mechanical removal can be employed in situations where the use of chemicals is prohibited or is not feasible; standing biomass is insufficient to carry a moderately intense fire; the stand structure is such that the majority of trees are tolerant to fire; or other constraints exist that require tree removal to be selective. Mechanical treatments can be applied uniformly, over large areas and can include root plowing, roller chopping, chaining or dozing. These treatments can be successful in killing mesquite; however, the remaining woody debris can make the area impractical for livestock use (McPherson and Wright 1986). Other, more selective techniques can be used on smaller areas without as much disturbance to the soil and understory vegetation. These techniques include hand grubbing or top removal and are effective in reducing stand density and canopy cover, can improve the efficiency of managing livestock, permits reseeding to more desirable forage plants, and does not present a hazard to susceptible crops or ornamentals (Fisher et al. 1973).

Management concerns have typically been focused on reducing mesquite densities; therefore, previous research has focused on the effects of killing mesquite. Limited information exists on how top removal of mesquite, and subsequent resprouting of mesquite, affects herbaceous production and soil properties. Management situations that may call for a top removal treatment include management for wildlife habitat that requires tree removal to be selective and disturbance to be minimal; physical removal of mesquite to increase herbage cover prior to prescribed burning; or to restore a small, denuded watershed.

The documented increase in herbaceous production as result of mesquite control is evidence that competition occurs between mesquite trees and understory herbaceous species in semidesert rangelands. However, the exact nature of this competition is unclear. Studies have shown that mesquite trees may actually provide improved soil conditions under their canopy for herbaceous plant growth. For example, Tiedemann and Klemmedson (1973) discovered that organic matter, total nitrogen, total sulfur and total soluble salts were more than 3 times higher in the top 4.5 cm of soils under mesquite canopies compared to soils in open areas. Similar studies concluded that the amount of nitrogen and organic carbon in the soil decreased as the horizontal distance from the shrub increased (Barth and Klemmedson 1978; Virginia and Jarrell 1983). Paulsen (1953) concluded that soils between mesquite canopies were deteriorated in both chemical and physical properties in comparison to nearby, uninvaded grass stands. The soils between mesquite crowns were coarser, lower in pore volume, and higher in volume weight, and this contributed to reduced water-holding capacity and general fertility of the soil. Obtaining an understanding of plant competition for soil nutrients in mesquite-dominated ecosystems is further complicated by the possible symbiotic N_2 fixation by leguminous plants such as mesquite. *Prosopis spp.* have been observed to nodulate and fix N_2 under glasshouse conditions, yet few nodules have been recovered from the field and in-field fixation of N_2 by mesquite has never been reported (Virginia and Jarrell 1983).

In addition to soil properties, shrubs and trees have been noted to affect herbaceous plant production by providing shade for herbaceous species. Shreve (1931) observed that soil temperature was considerably lower in the shade of trees in comparison to those areas in direct sunlight. However, he was also noted that evaporation did not differ between shaded and open areas and soil moisture at 15 cm was usually greater in the shaded areas, but only after heavy summer rains or lighter rains in cooler months. In addition, Tiedemann et al. (1971) evaluated the response of four perennial grasses to varying levels of shade in southern Arizona. They concluded that all four species of native grasses made their best growth in full sunlight.

Plants compete for many resources; however in semidesert rangelands, moisture is typically the major factor limiting growth. In these environments, low precipitation in combination with high temperatures and evapotranspiration rates create a significant moisture deficit. The amount of annual potential evapotranspiration is commonly 2-3 times greater than the annual rainfall (McClaran 1995). The mulching of soil surfaces has been a common practice for increasing soil moisture and crop production for agricultural lands; however, limited research has been conducted on how mulches affect herbaceous production on rangelands. Mulching has been found to be effective at reducing the constant rate stage evaporation by intercepting the solar radiation and reducing wind speed close to the soil surface (Prihar et al. 1996). In addition, mulches can improve soil structure, water infiltration and add some nutrients to the soil (Kemmerer 1979). Several studies have evaluated the effects of straw mulch on herbaceous production in the Southwest. Glendening (1942) found that the use of straw litter mulch in southern Arizona increased soil moisture and resulted in increased germination and emergence of grass seedlings. He attributed this finding to more effective moisture intake as a result of reduced runoff, and reduced evaporation rates due to decreased soil surface temperatures. Similarly, other studies have found that straw mulch improves forage production, reduces moisture losses, and lowers soil temperatures (Aldon 1978; Day and Ludeke 1987). Limited research has been conducted on the effectiveness of mulches created from localized woody debris on herbaceous production. The use of wood chips as a mulching treatment has been found to have favorable effects by reducing soil moisture and improving growth of woody plant species (Fraedrich and Ham 1982; Kraus 1998). Lavin et al. (1981) found that using juniper slash as mulch extended the growing season of forage species and protected these species from excessive grazing by rabbits. Commercial compost can also be used to influence soil moisture. Gagnon et al. (1998) found that large amounts of compost raised soil moisture content 3-5%, especially under dry climatic conditions. Additional research evaluating the effectiveness of mulches created from localized woody debris could be an asset to natural resource managers, especially in situations where mechanical removal of shrubs produces an excess of woody material.

DESCRIPTION OF STUDY

Objectives

The purpose of the study was to provide understanding of the relationships between existing shrub-grassland ecosystems and determine the effect of modifying soil conditions on herbaceous production. The specific objectives were:

- To determine changes in herbaceous production in response to mesquite overstory removal and modification of soil properties due to mulching treatments.
- To provide management recommendations for modifying shrub encroachment and maximizing herbaceous production.

Study Area

Background of Study Area

The Santa Rita Experimental Range is located about 10 km east of Green Valley, AZ, and about 48 km south of Tucson, AZ. It borders the northwestern portion of the Santa Rita Ranger District of the Coronado National Forest and is bordered on the south by the Santa Rita Mountains. The range is located on a broad, sloping bajada, which is strewn with washes draining to the northwest into the Santa Cruz River. Elevations range from below 885 m at the northwest corner to over 1,370 m in the Santa Rita foothills. This area, spanning 21,530 hectares, represents the over 8 million hectares of semidesert grass-shrub range in Arizona, Texas, and New Mexico.

Established in 1903, the Santa Rita Experimental Range is the oldest, still operating, research area of its type. At conception, the range was developed in an effort to combat the effects of overgrazing. The area was fenced off and cattle were excluded from the property until about 1915. Native and introduced grass species were artificially seeded in 1903 and have been intermittently reseeded to the present (Reynolds and Martin 1968).

Climate and Growing Season

The majority of precipitation on the Santa Rita Experimental Range comes in the form of rainfall. During the summer months, southeasterly winds bring rain across the Santa Rita Mountains. On the northwest side, the moisture-laden air meets the hot desert air, creating convective currents; this causes the rains to fall heaviest on the high elevations near the mountains and decrease with distance from the mountains (Greene and Martin 1967). The summer rains, July 1 to September 30, provides 60% of the annual precipitation. April, May, and June, are the driest months of the year. Annual and seasonal rainfall varies widely and successive years of above or below average rainfall are common (Reynolds and Martin 1968). This study was located in the Desert Grassland Enclosure (Figure 1), which is equipped with a standard weighing rain gauge. The average annual precipitation during the term of the study, from 1995 to 1999, was 369 mm (standard error of ± 43 mm) (Figure 2). A comparison of the average annual precipitation from 1985 to 1994 to the average annual precipitation during the term of the study revealed that average annual precipitation during the study was 31% below

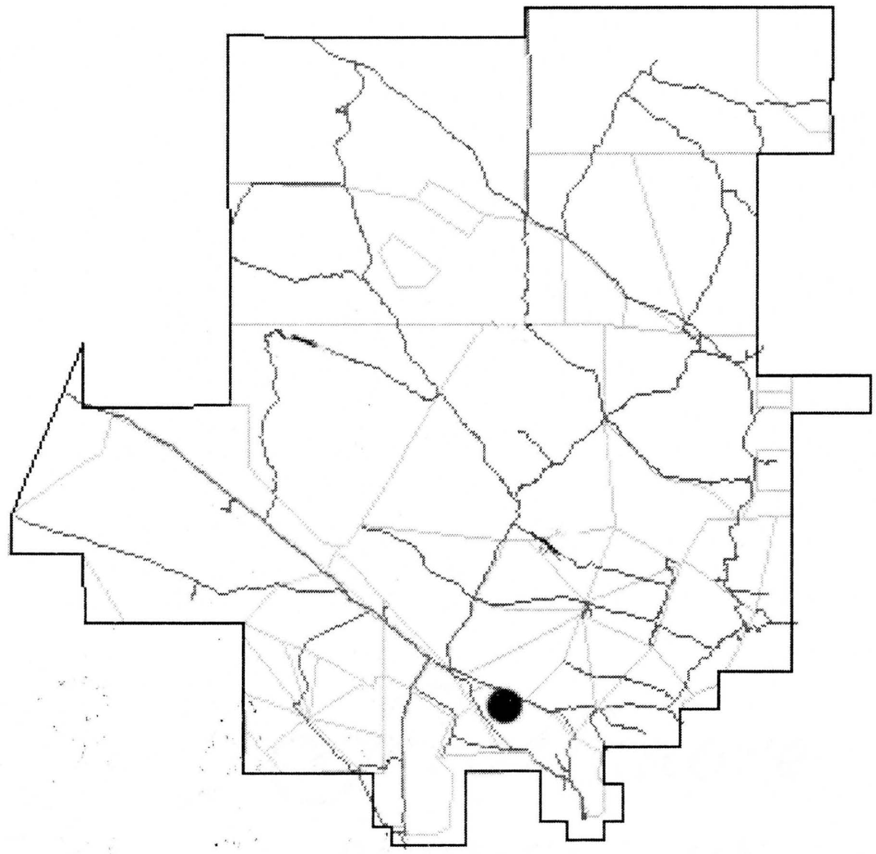

Figure 1. The Santa Rita Experimental Range indicating location of study.

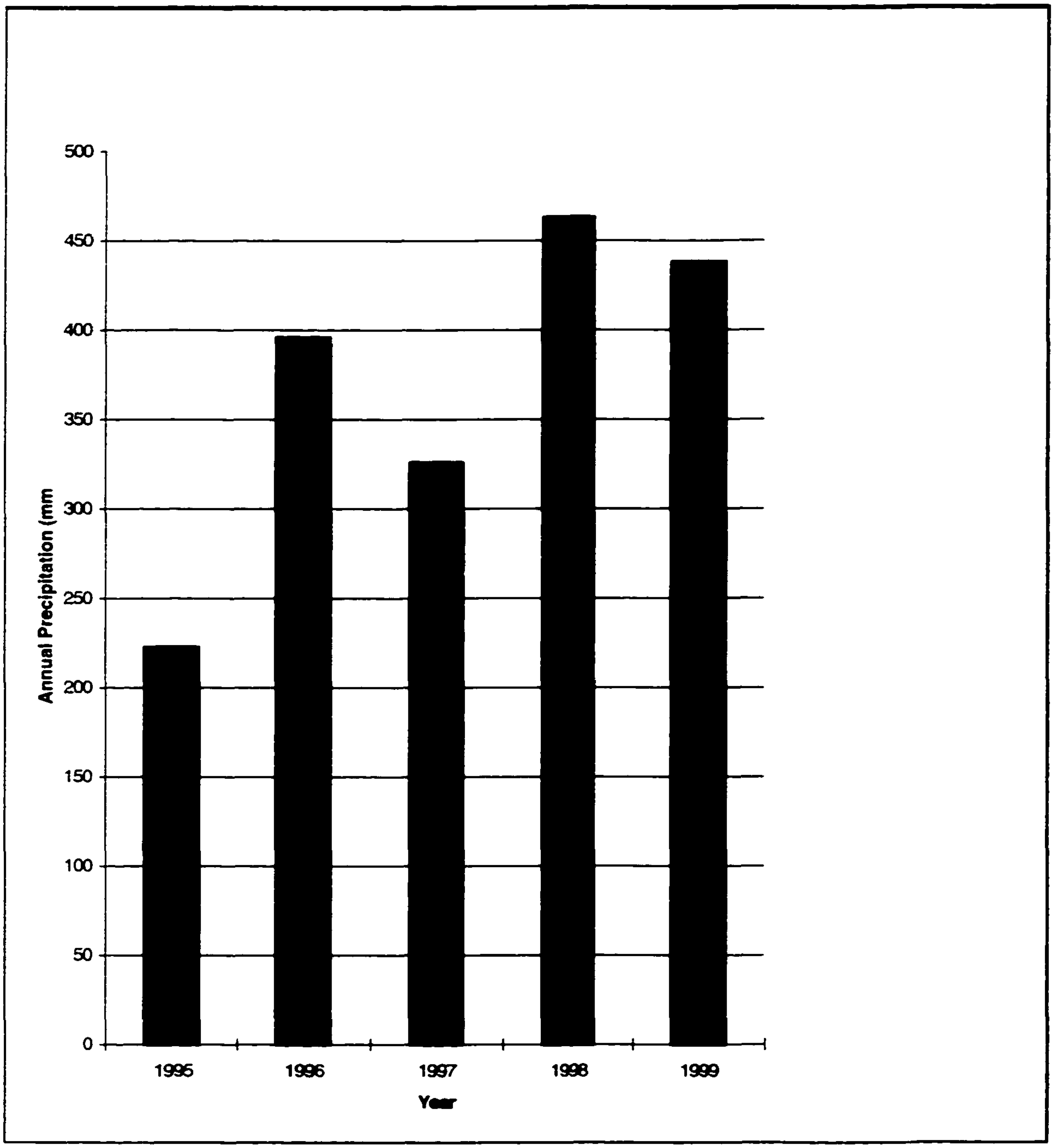

Figure 2. Annual precipitation over the term of the study.

average. The average annual precipitation from 1985 to 1994 was 443 mm (standard error of ± 32 mm). In addition, winter-spring (November-May) precipitation during the study was 48% below average, while summer-fall (June-October) precipitation during the study was 14% below average (Figure 3). It is not unusual for over half of the summer rains to be lost in the form of surface runoff. Therefore, the intensity of rain is as important as the frequency in providing usable moisture for plant production.

The Santa Rita Experimental Range is typical of most semi-arid climates, with an average of 175 cloud-free days per year, low humidity and light winds. Evaporation averages 1900 mm per year from open water. Most of the dissipation takes place in June when daily temperatures reach an excess of 100°F. A study conducted within the Desert Grassland Enclosure in 1940 found a mean daily evaporation rate of 8 mm during the months of July and August (Glendening 1942). Plant growth is limited by lack of moisture, not low temperatures, therefore, the nine-month frost-free period from March to November cannot be considered a growing period (Reynolds and Martin 1968).

There are two major growing periods on the Santa Rita Range. The first is in early spring, when temperatures become favorable, and the other occurs after the summer rains begin. The summer-season extends from 5 to 12 weeks and produces 90% of the perennial grass herbage (Martin and Cable 1974). Usable forage appears about a week after the first effective rain (Reynolds and Martin 1968).

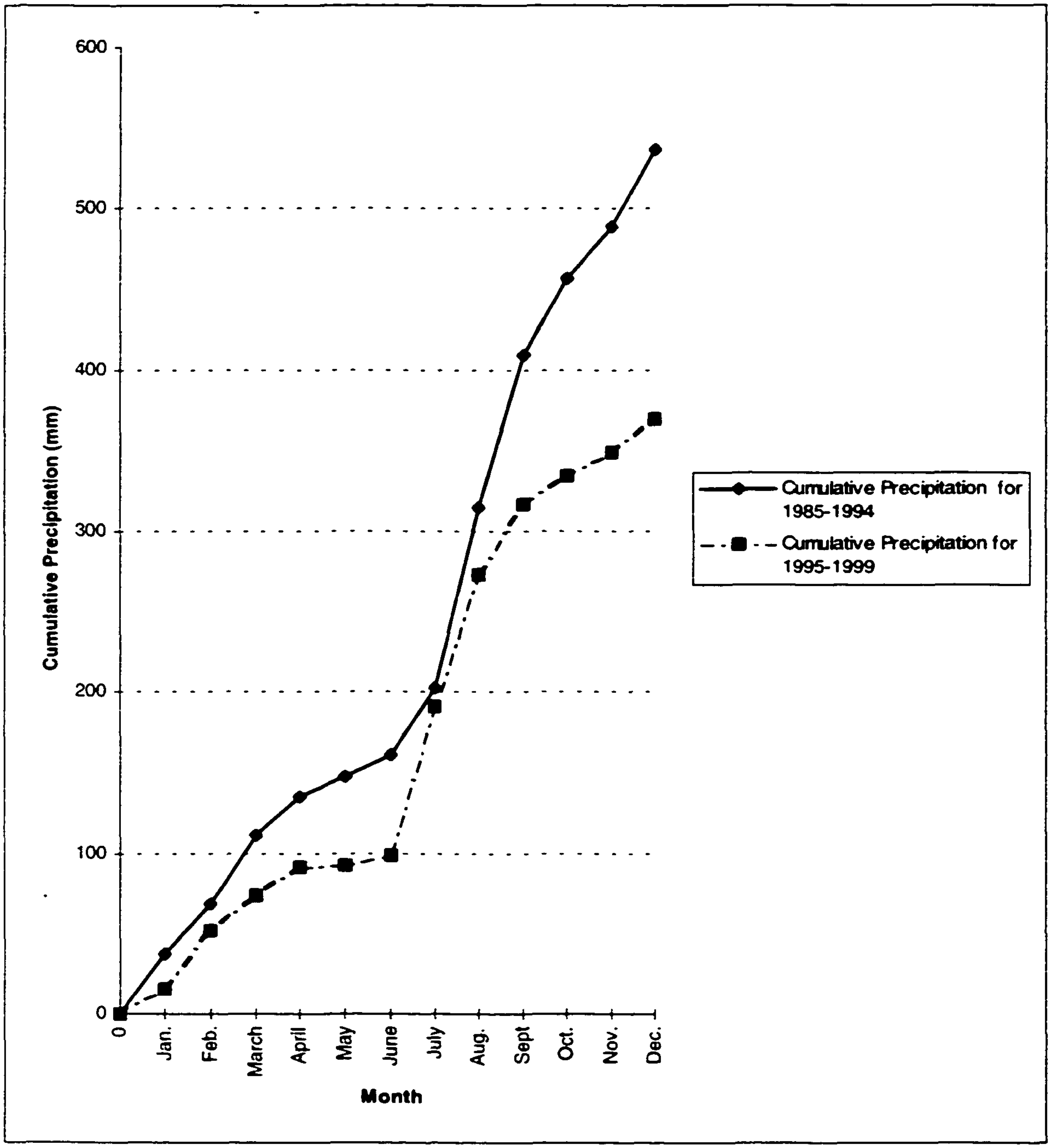

Figure 3. Comparison of cumulative monthly precipitation for the 10-year average and the term of the study.

Geology and Soils

The Santa Rita and Patagonia mountains to the south and east are the main sources for the alluvial fans of the Santa Rita Experimental Range (Drewes 1971b). During the later Cenozoic age, the mountains were eroded to their present state. Some lime cementation is present, but caliche-rich beds are mostly restricted to deposits rich in carbonates such as limestone (Drewes 1972b). The Santa Rita Experimental Range is located on what is known as the Madera Canyon fan. This fan has a 16 km radius and is composed of very hard siliceous volcanics.

The soils of the Santa Rita Range are composed of Pleistocene alluvium. Fifteen soil series are mapped on the range, and are broken down into 19 different mapping units (Clemmons and Wheeler 1970; Martin and Reynolds 1973). The soil texture on-site was classified as loamy sand. The pH of these soils averaged 5.9. The characteristics of the soils on-site are typical for soils in the Continental series (Hendricks 1985). These soils are Typic Haplargids and are deep, well drained soils. In addition, these soils have moderate available water capacity and slow permeability.

Vegetation

Much of the Santa Rita Experimental Range is dominated by invasion stands of mesquite (*Prosopis spp.)*. As early as 1904, dramatic increases in velvet mesquite (*P. velutina*), burroweed (*Haplopappus tenuisectus)*, and jumping cholla (*Opuntia spp.)* were noted on the range. Figures 4 and 5, photos taken from a permanent photo point within

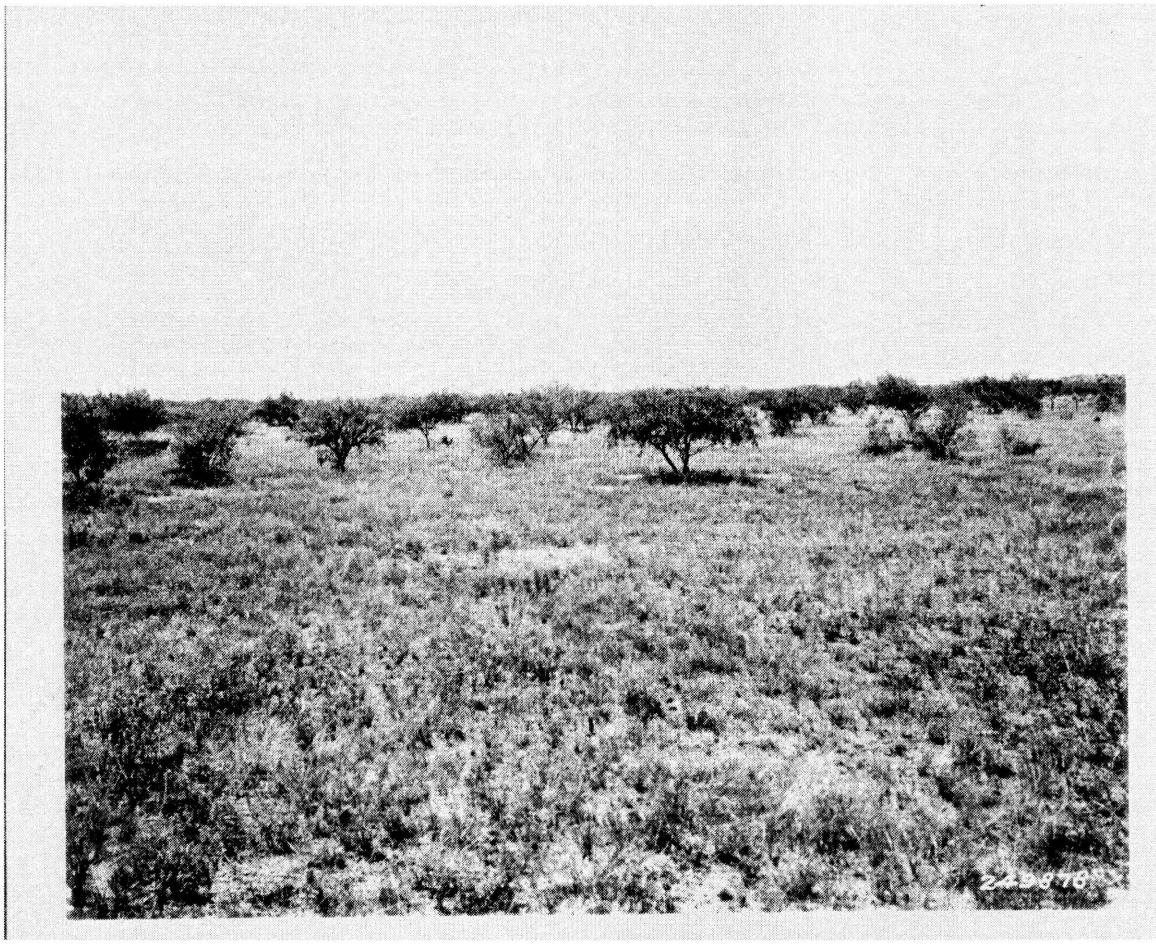

Figure 4. Photo taken in 1930 from permanent photo station within the Desert Grassland Enclosure at the Santa Rita Experimental Range.

Figure 5. Photo taken in 1985 from permanent photo station within the Desert Grassland Enclosure at the Santa Rita Experimental Range.

the Desert Grassland Enclosure, illustrate the increase in mesquite trees on this site over a 50-year span. Mesquite is a competitor for soil moisture and, along with cholla cactus and burroweed, reach their highest densities between 975 and 1,220 meters in elevation. Mesquite trees have a central taproot and an extensive lateral root system and, as a result, are classified as facultative phreatophytes. They are capable of utilizing permanent groundwater and, when necessary, extract surface percolating water. Mesquite trees flower in the spring and summer and their fruits mature in summer. The study site had an average pre-treatment density of 506 mesquite trees/ha, and a pre-treatment mesquite volume of 26.2 m^3/ha/plot. Lehmann lovegrass (*Eragrostis lehmanniana*) is the dominant herbaceous species, comprising 80% of the annual herbaceous production. Lehmann lovegrass, an introduced species from South Africa, was first seeded at the Santa Rita Experimental Range in 1937. Since its introduction, Lehmann lovegrass has spread aggressively throughout the area and has been observed to displace native herbaceous species. Lehmann lovegrass is a perennial bunchgrass that can set seed in the first year after germination. Each plant produces large amounts of small, wind and water dispersed seeds in the fall (Anable et al. 1992). The majority of the plant's growth occurs in the summer; however, it is able to produce more growth from winter moisture than warm season native grasses (Cable 1971). The remaining 20% of herbaceous production that occurred within the study plots was from native species (Table 1). Common woody species were *Acacia greggii*, *Calliandra eriophylla*, *Ambrosia confertiflora*, and *Haplopappus tenuisectus*. Common native perennial grass species were *Eriogonum wrightii*, *Solanum elaeagnifolium*, and *Gnaphalium purpureum*, and the common annual

Table 1. List of plant species found within study plots.

PERENNIALS	ANNUALS
Acacia greggii	*Amsinckia intermedia*
Ambrosia confertiflora	*Chenopodium album*
Calliandra eriophylla	*Cirsium arizonicum*
Cucurbita spp.	*Datura meteloides*
Desmanthus spp.	*Daucus pusillus*
Ditaxis spp.	*Descurainia pinnata*
Eragrostis lehmanniana	*Drymaria spp.*
Eriogonum wrightii	*Eragrostis cilianensis*
Gnaphalium purpureum	*Erigeron divergens*
Gutierrezia sarothrae	*Eschscholtzia mexicana*
Haplopappus tenuisectus	*Evolvulus pilosus*
Krameria parvifolia	*Ipomoea spp.*
Lycurus phleoides	*Kallstroemia grandiflora*
Mimosa laxiflora	*Lupinus spp.*
Mimosa spp.	*Mentzelia spp.*
Sarcostemma spp.	*Plantago spp.*
Setaria spp.	*Portulaca oleracea*
Sida spp.	*Setaria spp.*
Sitanion hystrix	*Simsia spp.*
Solanum elaeagnifolium	*Viguiera annua*
Trixis californica	*Zinnia spp.*
Proboscidea parviflora	
Prosopis velutina	

species were *Chenopodium album*, *Eschscholtzia mexicana*, *Descurainia pinnata* and *Amsinckia intermedia*.

Field Methods

Treatments

Sixty, 5x5 m plots were established in June of 1995, with a minimum of a 1 m buffer between each plot. Large herbivores were excluded from the site prior to and during the term of this study. A pretreatment inventory of mesquite overstory volume (Chojnacky 1988) was conducted on each plot. The sample plots were then blocked based on the overstory inventory and the treatments randomly assigned to the plots. The overstory treatments consisted of complete removal of mesquite overstory with no removal of subsequent sprouts, complete removal of mesquite overstory with periodic removal of sprouts, and retention of mesquite as a control. The four mulching treatments were wood chip mulching, lopped-and-scattered mesquite branchwood, commercial compost, and a control. Each combination of the three overstory treatments and four mulching treatments was replicated 5 times.

Prior to treatment application, herbaceous production and the soil chemical composition on the sample plots were determined. The application of treatments was completed by July 19, 1995. The mesquite overstory was removed by means of manual cutting within 15 cm of the soil surface and the woody debris was removed from site. The mesquite resprouts were later controlled by cutting and removal in July of 1997 and April of 1998.

The wood chip material was composed of local mesquite branchwood that was chipped using a portable wood chipper. Chipped materials were <100 mm in diameter and were layered to a 15 to 25 mm depth on the treated plots. The lopped-and-scattered material was locally cut mesquite branchwood that was applied to completely cover an entire plot. The amount of lopped-and-scattered material applied to the treated plots, estimated using an inventory for downed woody material (Brown 1974), was 6 m^3/ha/plot. The commercial compost was fir based with 0.5% nitrogen, 0.1% iron, and 0.2% sulfur. Approximately 0.25 m^3 of commercial compost was applied to cover an entire plot at a depth of approximately 12 mm.

Data Collection

Herbaceous production was measured biannually during May and October from 1995 to 1999. The herbage collection in May captured the production that occurred in the early spring growing season, while the collection in October represented the production that occurred in the late summer and early fall growing season. Herbaceous production was determined by weight estimate (Pechanec and Pickford 1937). The technique outlined by Frischknecht and Plummer (1948) was used for collection of herbage. The 5x5 m plot was divided into quadrants and the 105 cm wire hoop used for herbage collection was divided into thirds. The three selected quadrants of the plot and the selected third portion of the sampling ring were rotated in such a manner that sampling never occurred in the same location of a plot throughout the term of the study. All rooted, standing biomass within the sampling area was clipped at the soil surface, air dried, and standing biomass for each herbaceous species was determined. Because the herbage collection took place after the growing season, air-drying was deemed acceptable (Pechanec and Pickford 1937).

The volume of mesquite overstory was determined by utilizing the technique outline by Chojnacky (1988). A pretreatment inventory of all mesquite trees on site was made in June 1995. A post-treatment inventory of mesquite trees within the overstory control plots was performed in October 1999.

Soil samples were collected annually during the month of May from 1995 to 1999. A composite sample was collected from each plot and consisted of 12 sub-samples collected from the top 5 cm of the soil (Carter 1993). The 12 sub-samples were collected along a diagonal transect across the plot with 0.3 m between samples. In most cases, the composite sample contained soil from both under the mesquite canopy and the open areas. All soil analyses of chemical and physical properties were performed at the Soil, Water, Plant Analysis Laboratory of the University of Arizona, Tucson, Arizona. Soils were analyzed for total nitrogen, nitrate, total organic carbon, total phosphorus, plant available phosphorus (Olsen phosphorus), and pH. In addition, soil texture was determined on 5 randomly selected plots in 1996. Standard hydrometer particle size distribution analysis was used to classify texture.

Precipitation was measured monthly using a standard weighing rain ga uge located on-site. Seasonal precipitation was delineated for conducting correlation coefficient analysis. Spring precipitation included precipitation that fell from November through May. Fall precipitation was considered to be the precipitation that fell from June through October.

Analytical Procedure

A one-way analysis of variance, completely randomized design with fixed effects (Milton 1992) was used to determine if significant differences in herbaceous production and soil properties occurred as a result of overstory treatments, mulching treatments or between the years of 1995 to 1999. ANOVA was also used to determine if the mulching treatments significantly affected mesquite overstory production. When appropriate, interaction effects were evaluated using two-way analysis of variance. The Tukey-Kramer Honestly Significant Difference test was used in making multiple comparisons (Williams 1993). Correlation coefficient analysis was used to determine if a significant relationship existed between precipitation and herbaceous production, precipitation and soil properties, soil properties and herbaceous production, and pH levels and soil properties. The level of significance for all analyses of variance and correlation coefficient analyses was set at 0.10. All analyses were performed using the statistical program JMP (SAS Institute Inc. 1996).

RESULTS AND DISCUSSION

Response of Herbaceous Production

Overstory Treatments

Total Herbaceous Production

An evaluation of herbaceous production from 1995 to 1999 in response to the overstory treatments revealed that these treatments resulted in higher herbaceous production than the control plots. The treatment plots that received complete removal of mesquite overstory with no control of regrowth had an average production of 1,911 kg/ha/year (standard error of ± 125 kg/ha/year), which was a 23% increase over the production on the control plots, while plots that received the treatments of complete removal of mesquite overstory with removal of regrowth had an average production of 1,882 kg/ha/year (standard error of ± 106 kg/ha/year), a 22% increase in production over the control plots. The average herbaceous production for the control plots was 1,554 kg/ha/year (standard error of ± 94 kg/ha/year). The increased herbaceous production was most likely due to the reduced competition for soil moisture between mesquite trees and herbaceous vegetation. However, the increased herbaceous production was considerably less than that observed in similar studies (Cable and Tschirley 1961; Reynolds and Martin 1968; McDaniel et al. 1982; Herbel et al. 1983; Heitschmidt and Dowhower 1991; Martin and Morton 1993; Laxson et al. 1997). This difference is partially because previous research involved overstory treatments of killing the mesquite trees; the treatments in this study involved only top removal. Therefore, the mesquite trees were still competing with herbaceous plants for soil moisture. In addition, the below average precipitation that occurred during the study may have contributed to the diminished response of herbage production to the overstory treatments. Scifres and Polk (1974) made similar observations as they concluded that increases in forage as a result of mesquite control occurs only in years of average or above average precipitation. Competition for soil moisture between mesquite trees and herbaceous plants is probably diminished during times of below average precipitation because extraction of water from the soil by mesquite roots decreases linearly as soil water content decreases (Cable 1977). In addition, the production of perennial herbaceous species is positively correlated to annual precipitation (Cable 1975); therefore, during times of below average precipitation, the effects of overstory control on herbaceous production are diminished due to reduced competition between mesquite trees and herbaceous species.

Spring Versus Fall Herbaceous Production

Further analysis of herbaceous production was conducted by evaluating production in terms of spring herbage production versus fall herbage production (Table 2). When examining the response of spring herbage production over the duration of the study, the overstory treatments had no significant effect on the level of production. The lack of response of spring herbage production to the overstory treatments might be because of the 48% below average precipitation during this growing season. However, the overstory treatments did have an effect on fall herbaceous production. The treatment of complete

Table 2. Total annual, spring and fall herbaceous production from 1995 to 1999.

Year	Total Herbaceous Production	Spring Herbaceous Production	Fall Herbaceous Production
		kg/ha/year	
1995	584 ± 62	94 ± 5	490 ± 60
1996	1608 ± 77	201 ± 20	1407 ± 73
1997	1422 ± 76	842 ± 55	580 ± 48
1998	2350 ± 111	660 ± 45	1690 ± 85
1999	2947 ± 138	1172 ± 67	1775 ± 100

removal of mesquite overstory with no control of regrowth was found to have higher fall herbaceous production than the control treatment. The average fall production for the control plots was 1,042 kg/ha/year (standard error of ± 69 kg/ha/year), while the treated plots averaged 1,278 kg/ha/year (standard error of ± 89 kg/ha/year), a difference of 23%.

The treated plots of complete removal of mesquite overstory with no removal of regrowth may have exhibited higher production compared to the treated plots of complete removal of mesquite overstory with removal of regrowth due to the shade provided by the resprouting mesquite. The shade provided by the resprouting mesquite trees averaged 7.5% cover of the treated plots in 1997. This increased to an estimated 15-20% cover by 1999. Shreve (1931) found that the environment under the canopy of trees was more favorable for production of annual species and perennial seedlings in comparison to open areas. He concluded that soil temperature was significantly lower and soil moisture at 15 cm was significantly higher under the canopy of trees. In addition, Tiedemann (1970) found that perennial grasses in the semidesert grassland increased production as a result of artificial shade treatments.

The significant effect of the overstory treatment on fall production in comparison to spring production can be explained by the reduced water uptake by mesquite during the summer and fall months in comparison to the spring months, and the majority of perennial herbaceous growth takes place during the summer months. Mesquite trees have the highest level of growth during the spring as it is involved in leaf, twig and trunk growth and, therefore, requires more water during this time (Haas et al. 1973; Cable 1977). Mesquite reduces growth after the onset of summer drought; as a result, those trees that were treated with the overstory removal would require less water to support the reduced biomass in comparison to those trees that were untreated. The effect of the overstory treatment would also be more evident in the fall because the bulk of perennial herbaceous production on site occurs in late summer and fall as a result of late summer rainfall. Fall herbaceous production was determined to be 72% higher than spring herbage production. Cox et al. (1990) observed that the peak of Lehmann lovegrass production occurred in August, and Cable (1975) concluded that most native perennial grass species on the Santa Rita Experimental Range were primarily summer growers.

When evaluating the herbaceous production from year-to-year, the overstory treatments were found to have an effect on spring herbaceous production between the years of 1997 to 1998, and fall production between the years 1998 to 1999. This finding was seemingly due to the increased precipitation during these years. A difference in production was observed between the treatment plots of complete removal of mesquite overstory with no removal of regrowth and the control plots. The treatment resulted in a 34% increase in spring production over the control between the years 1997 to 1998, and a 23% increase in fall production over the control between the years 1998 to 1999.

Lehmann Lovegrass Versus Native Species Production

Additional analyses were conducted on the response of the introduced species, Lehmann lovegrass, versus native herbaceous species to the overstory treatments (Table 3). Again, total annual production, spring production, and fall production were evaluated. The overstory treatments had no significant effect on total annual, spring, or fall production of Lehmann lovegrass. These results indicate that Lehmann lovegrass was not

Table 3. Total annual, Lehmann lovegrass and native herbaceous species production from 1995 to 1999.

Year	Total Herbaceous Production	Lehmann Lovegrass Production	Native Herbaceous Species Production
		kg/ha/year	
1995	584 ± 62	439 ± 53	145 ± 28
1996	1608 ± 77	1511 ± 77	97 ± 22
1997	1422 ± 76	1292 ± 68	130 ± 27
1998	2350 ± 111	1873 ± 105	477 ± 57
1999	2947 ± 138	2756 ± 134	191 ± 63

competing with mesquite trees for soil moisture during the term of the study. This conclusion is further supported by research that suggests Lehmann lovegrass is capable of persisting and spreading in areas where the average precipitation within 40 days of summer is 90 mm (Anable et al. 1992); and it is well adapted to areas where summer precipitation is 203 mm or more (Robinett 1992). Annual precipitation during most years of the study was well above this amount, therefore, it may be that Lehmann lovegrass production was not constrained by lack of soil moisture.

In contrast, the total annual and fall production of native herbaceous species was affected by the overstory treatments. A difference in total annual production of native species occurred between the treatment of complete removal of mesquite overstory with no removal of regrowth and the control plots. The control plots averaged 140 kg/ha/year (standard error of ± 20 kg/ha/year) and the treatment plots resulted in an average production of 251 kg/ha/year (standard error of ± 47 kg/ha/year), which was a 79% increase in total annual production of native species. Similarly, the treatment of complete removal of mesquite overstory with no removal of regrowth had significantly higher fall production of native species than both the treatment of complete removal of mesquite with removal of regrowth and the control plots. The treatment of complete removal of mesquite with no removal of regrowth had an average fall production of native species of 167 kg/ha/year (standard error of ± 40 kg/ha/year), which was a 2-fold increase over the other two treatments. The treatment of complete removal of mesquite with removal of regrowth averaged 78 kg/ha/year (standard error of ± 22 kg/ha/year), and the control plots averaged 56 kg/ha/year (standard error of ± 12 kg/ha/year). The overstory treatments had no effect on spring production of native species. It appears the native herbaceous species were in competition with mesquite for soil moisture and responded well to the reduction in mesquite.

Production of Perennial Versus Annual Herbaceous Species

Analyses were also conducted to evaluate the response of perennial herbaceous species versus annual herbaceous species to the overstory treatments (Table 4). The total annual, spring, and fall production were analyzed for both the perennial and annual species. The treatment of complete removal of mesquite overstory with no removal of regrowth resulted in higher total annual production of perennial species. The average perennial production for this treatment was 1,838 kg/ha/year (standard error of ± 125 kg/ha/year), while the average production for the control plots was 1,517 kg/ha/year (standard error of ± 94 kg/ha/year). This treatment resulted in a 21% increase in annual production of perennial species. However, the overstory treatments had no effect on either spring or fall perennial production. The overstory treatments were had no effect on the total annual production of annual herbaceous species. The evaluation of the overstory treatment effects on spring and fall production of annual herbaceous species was a contrast. The analysis revealed a significant difference in spring production of annual species between the two treatments. The treatment of complete removal of mesquite overstory with removal of sprouts had higher levels of production (average 63 kg/ha/year, standard error of ± 15 kg/ha/year) than the treatment of complete removal of mesquite overstory with no removal of regrowth (28 kg/ha/year, standard error of ± 8 kg/ha/year). In addition, the overstory treatments affected the fall production of annual species. The treatment of

Table 4. Total annual, perennial species and annual species production from 1995 to 1999.

Year	Total Herbaceous Production	Production of Perennial Species	Production of Annual Species
		kg/ha/year	
1995	584 ± 62	532 ± 62	52 ± 10
1996	1608 ± 77	1588 ± 77	20 ± 6
1997	1422 ± 76	1421 ± 76	t
1998	2350 ± 111	2106 ± 117	244 ± 27
1999	2947 ± 138	2919 ± 137	28 ± 13

t = trace

complete removal of mesquite overstory with no control of regrowth resulted in an over 2-fold increase in production, while the treated plots averaged 31 kg/ha/year (standard error of ± 8 kg/ha/year) and the control plots averaged 11 kg/ha/year (standard error of ± 4 kg/ha/year) of production of annual species. The response of perennial and annual species to the overstory treatments is unknown and most likely relates to the species-specific requirements for germination and growth.

Mulching Treatments

Total Annual, Spring, and Fall Herbaceous Production

The effects of the understory mulching treatments on total annual herbaceous production, spring herbaceous production, and fall herbaceous production were evaluated for 1995 to 1999. The mulching treatments had no effects on total annual, spring or fall production. The absence of effects from the mulching treatments is likely due to the below average precipitation during the study period and inadequate levels of mulch applied to alter the constant rate stage of evaporation. Biedenbender and Roundy (1996) suggested that during periods of infrequent rainfall, mulching treatments do not sufficiently affect soil moisture availability. In addition, the constant rate stage or first stage of evaporation from the soil surface is primarily controlled by external conditions and is the stage of evaporation that is most affected by surface residues (Lemon 1956; Bond and Willis 1970). Bond and Willis (1970) discovered that as evaporation potential increases, greater surface residue rates are required to slow the first stage of evaporation.

In addition, increasing rates of residue also progressively decrease first stage evaporation. It is likely, therefore, that the rates of mulch applied to the treatment plots were insufficient to affect the first stage of evaporation.

An analysis of production from year-to-year revealed that the mulching treatments did have an immediate response on spring herbaceous production in 1995 and 1996, and an affect on spring production for 1998 and 1999. A difference in spring herbaceous production in 1995 and 1996 was observed between the treatments plots of lopped-and-scattered branchwood and the control plots. The lopped-and-scatter treatment plots experienced lower production than the control plots. The average spring herbaceous production for the control plots was 179 kg/ha/year (standard error of ± 23 kg/ha/year), while the lopped-and-scattered plots averaged 105 kg/ha/year (standard error of ± 23 kg/ha/year). It is unclear why this treatment appeared to hinder spring production by as much as 41%. However, these results correspond to similar findings in a counter-part to this study in Ramat Hanadiv Park, Israel. Perevolostky et al. (1996) found that the lopped-and-scattered and chip mulch treatments reduced herbaceous production in the first post-treatment year. The difference in spring production in 1998 and 1999 was found to be between the chip mulching plots and the control plots. The chip mulching plots averaged 1,033 kg/ha/year (standard error of ± 92 kg/ha/year), which was 41% higher in production compared to the control plots that averaged 731 kg/ha/year (standard error of ± 92 kg/ha/year). The effectiveness of the treatment during this year might be related to the relatively increased precipitation during 1998.

Lehmann Lovegrass Versus Native Species Production

Additional analysis was conducted to examine the effects on mulching treatments on the introduced species, Lehmann lovegrass, versus the native herbaceous species. Again, analysis revealed that the mulching treatments did not affect the total annual, spring or fall production of Lehmann lovegrass or native herbaceous species.

Production of Perennial Herbaceous Species Versus Annual Herbaceous Species

The response of perennial herbaceous production versus annual herbaceous production to the mulching treatments was also evaluated. Once again, the results indicated that the mulching treatments had no effect on total annual, spring, or fall production of perennial or annual herbaceous species.

Interaction Effects

Interaction effects between overstory treatments and mulching treatments on total annual, spring and fall herbaceous production were evaluated. There were no interaction effects on spring or fall herbaceous production. However, an interaction effect was observed between overstory treatments and mulching treatments on total annual herbaceous production. The majority of the variability is attributed to the effects of the overstory treatments.

Annual Variability in Herbaceous Production

Variability in herbaceous production occurred among the years 1995 to 1999. Much of this variability was explained by the variation in annual precipitation during these years. A correlation was observed between average annual herbaceous production and annual precipitation. The variability in average annual production of perennial herbaceous species and average annual production of Lehmann lovegrass was also correlated to annual precipitation. Annual production of native herbaceous species was not correlated to annual precipitation and exhibited less year-to-year variability in comparison to Lehmann lovegrass production (Figure 6). In addition, while Lehmann lovegrass production steadily increased from 1997, production of native herbaceous species significantly declined after 1998. This decline might be a result of Lehmann lovegrass displacing native species. There was a lack of correlation between average seasonal production and seasonal precipitation; this would be expected because perennial grass production in southern Arizona is dependent on current summer rainfall, in addition to previous summer rainfall (Cable 1975). Annual variability in herbaceous production could also be related to variability in soil properties. Positive correlations between annual herbaceous production and soil properties such as: pH, total nitrogen, total organic carbon, and nitrate were observed. The nature of these correlations remains undetermined.

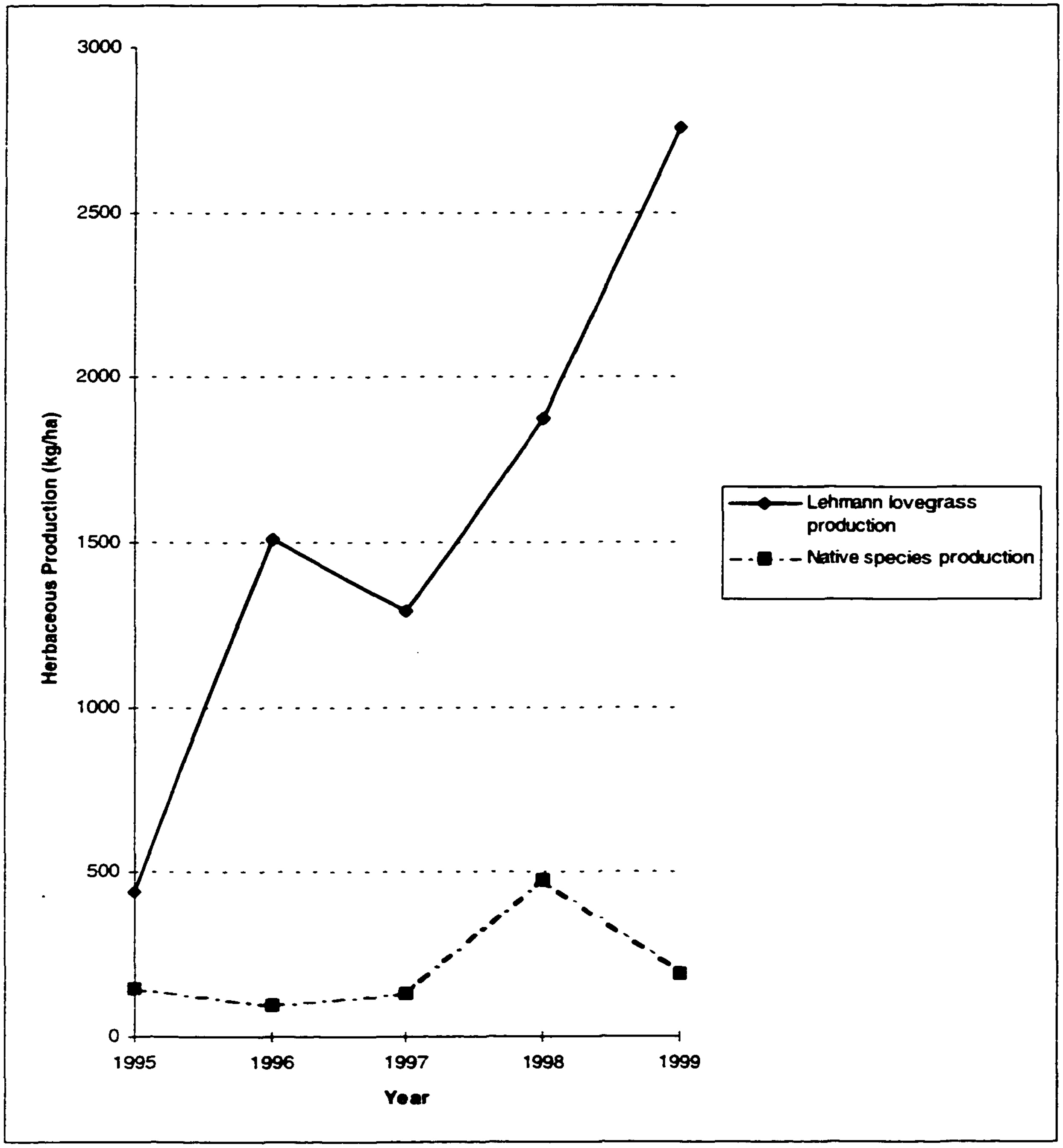

Figure 6. Average annual production of Lehmann lovegrass versus native herbaceous species.

Response of Mesquite Production to the Mulching Treatments

The response of mesquite biomass production to the mulching treatments was evaluated from pretreatment volume measurements in 1995 and a measurement of the overstory trees within the control plots in 1999. The analysis revealed that the mulching treatments had no affect on the growth of mesquite. It appears that the level of mulch applied to treated plots did not significantly influence evaporation rates sufficiently to affect available soil moisture. In addition, this response by mesquite would be expected due to the phreatophytic nature of mesquite trees that allows it to avoid water stress by tapping into soil moisture deep within the soil profile (Nilsen et al. 1983).

Response of Soil Properties

Overstory Treatments

The effects of the overstory treatments on total organic carbon, total nitrogen, nitrate, total phosphorus, plant available phosphorus, and pH in the soil were evaluated for the study period. The treatments had no effect on any of these properties. These results are not surprising given the relatively slow rate of nutrient cycling in semi-arid environments. While numerous studies have observed the effects of mesquite on soil properties (Tiedemann and Klemmedson 1973; Barth and Klemmedson 1978; Virginia and Jarrell 1983), limited research has been conducted to examine the impacts of the removal of mesquite trees on these properties. Klemmedson and Tiedemann (1986) did conclude that the removal of mesquite results in a significant decline in nutrient availability 13 years after removal. The term of this current study may not have been sufficient to reflect the impact of mesquite removal on soil properties.

Mulching Treatments

The response of total organic carbon, total nitrogen, nitrate, total phosphorus, plant available phosphorus and pH in the soil to the mulching treatments was also analyzed. These treatments were found to have no significant effect on total organic carbon, nitrate or total phosphorus. However, these treatments did affect the total soil nitrogen, plant available phosphorus and soil pH. The total soil nitrogen levels were higher with the lopped-and-scattered plots than the control plots. The control plots averaged 0.09% total soil nitrogen (standard error of ± 0.004%), while the lopped-and-scattered plots averaged 0.11% (standard error of ± 0.005%), a 22% increase. The reason for this increase is unclear. It may be that the lopp-and-scatter material contained more leaf litter and this leaf litter decomposed at a faster rate than the woody material; thereby, resulting in the nutrients being more readily incorporated into the soil with this treatment. A significant difference was found between the soil pH levels on the commercial compost plots and the control plots, and between the chip mulched plots and the control plots. Both the commercial compost and the chip mulched plots had an average pH of 6.0 (standard error of ± 0.05 and ± 0.06, respectively), while the control plots had an average pH of 5.8 (standard error of ± 0.05). Interestingly, the control plots had higher levels of plant available phosphorus, with an average of 11.4 ppm (standard error of ± 0.6 ppm), than observed on the chip mulched and the commercial compost plots that had an average of

7.4 ppm and 8.6 ppm (standard error of ± 0.5 ppm), respectively. In addition, the lopped-and-scattered plots had higher levels of plant available phosphorus that the chip mulched plots, as they averaged 10.4 ppm (standard error of ± 0.7 ppm).

A noteworthy observation is that the lopped-and-scattered treatment also had the lowest average soil pH of all the treatments. A negative correlation was observed between the average soil pH levels and the average plant available phosphorus. It would appear that the mulching treatments resulted in increased levels of soil pH, which subsequently influenced the availability of phosphorus within the soil. As soil pH increases, conditions become more favorable for fixation reactions to occur that convert soluble phosphorus to insoluble phosphorus (Stevenson 1986). The effects of the mulching treatments on soil pH and plant available phosphorus could potentially have a negative long-term effect on herbaceous production, as available phosphorus is often a limiting factor in arid and semi-arid environments and is an essential element for plant development and growth (Day and Ludecke 1993). It is unclear why the treatments influenced the soil pH in the manner that they did.

Interaction Effects

The significance of interaction effects between the overstory and mulching treatments was evaluated for total organic carbon, total soil nitrogen, nitrate, total soil phosphorus, plant available phosphorus and pH. Significant interaction between treatments did occur for pH, however, all other interactions were insignificant. The interaction effect for soil pH was mainly a result of the variability caused by the effects of the mulching treatments.

Annual Variability in Soil Properties

A significant amount of variability occurred between the annual measurements of soil properties (Table 5). The percent of total organic carbon found in the soil significantly increased with each year from the base year of 1996, with a dramatic 99% increase in 1999. The total nitrogen present in the soil experienced no significant changes from 1996 to 1997. A significant increase was observed in 1998 in comparison to 1996 and, similar to organic carbon, an appreciable increase of 56% in total soil nitrogen was observed in 1999 (Figure 7). The soil nitrate content increased in all years following the base year of 1995. The greatest increase from 1995 occurred in 1996 and 1999, with an almost 20-fold and 27-fold increase, respectively. Soil pH levels increased following 1995, with significant increases in 1996 and 1999.

A high degree of variability between years was observed in the levels of total phosphorus in the soil (Figure 8). There was no difference in total phosphorus levels between 1995 and 1996; however, a decline was observed in 1997, with a 61% decrease in total phosphorus levels. This decline was followed by a 2.5-fold increase in 1998 and an additional 36% increase in 1999. The plant available phosphorus was also variable from year to year (Figure 8). A 20% increase was observed in plant available phosphorus from 1995 to 1996, followed by a 36% decrease in 1997. However, the levels of plant available phosphorus persisted at significantly lower levels than 1996 for 1998 and 1999. In addition, plant available phosphorus was at its lowest in 1999, with a 38% decrease in levels compared to 1998. As a general observation, all soil properties except

Table 5. Average annual levels of soil properties from 1995 to 1999.

Year	Total Organic Carbon	Total Nitrogen	Nitrate	Total Phosphorus	Plant Available Phosphorus	pH	C:N	P:PO
	%		ppm					
1995	0.83	0.09	14.7	229.7	10.9	5.7	9:1	21:1
1996	0.71	0.08	102.0	225.1	13.0	6.1	9:1	17:1
1997	1.0	0.09	55.6	87.6	8.3	5.9	11:1	11:1
1998	0.94	0.09	60.5	294.6	9.4	5.9	10:1	31:1
1999	1.9	0.15	139.0	401.6	5.8	6.0	13:1	69:1

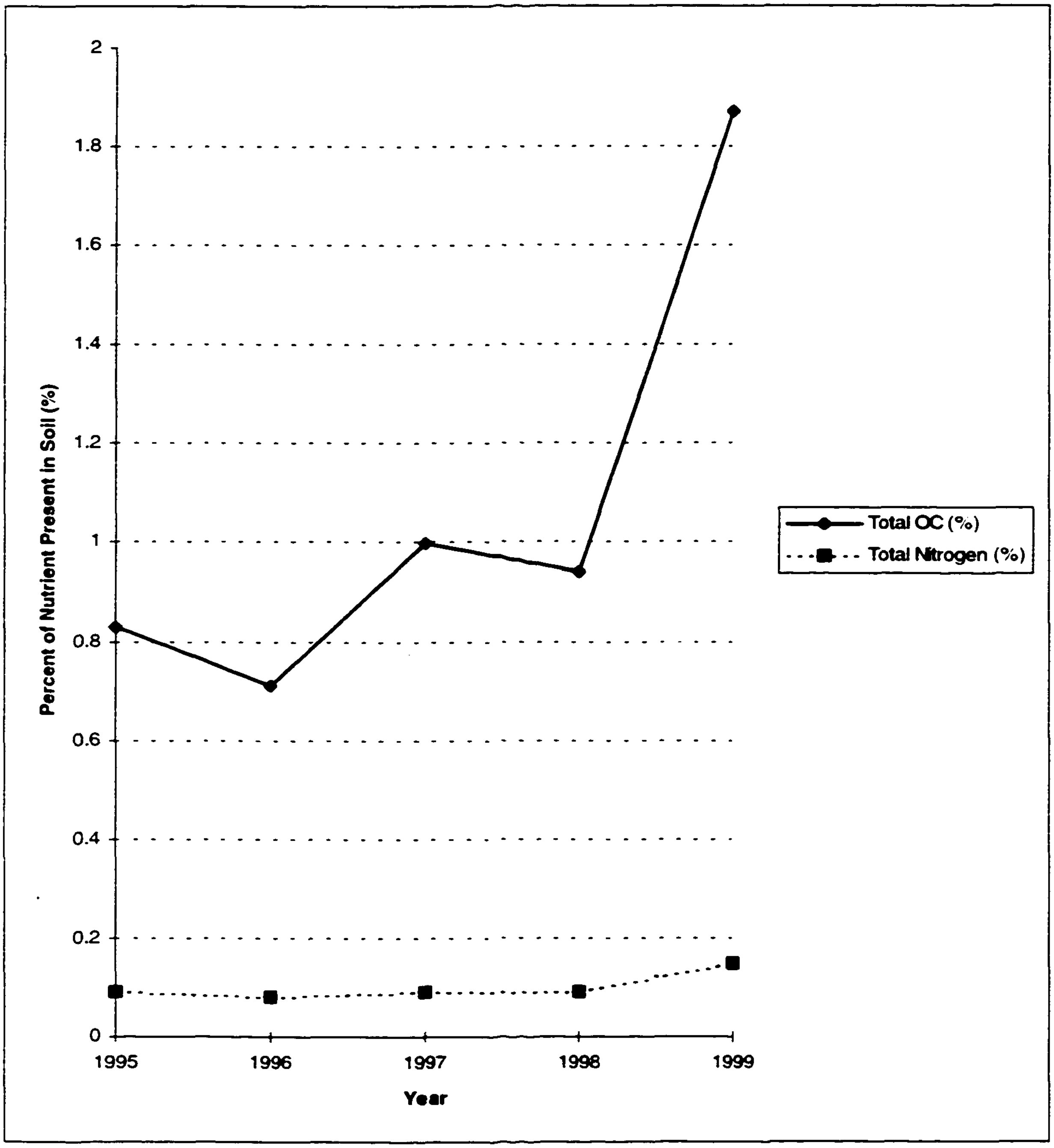

Figure 7. Average annual levels of organic carbon and total nitrogen in the soil.

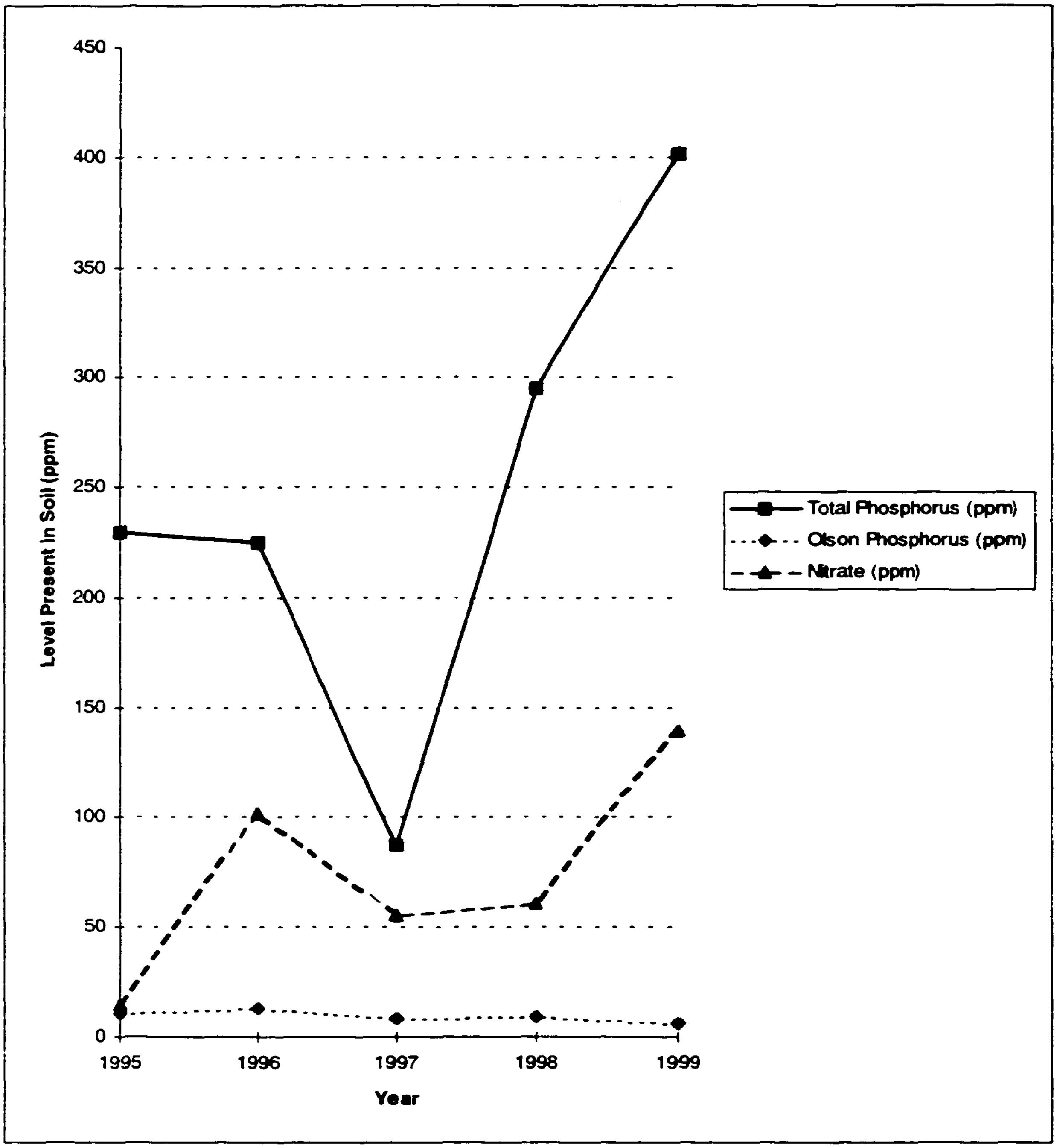

Figure 8. Average annual levels of total phosphorus, plant available phosphorus and nitrate in the soil.

pH and plant available phosphorus experienced a considerable increase in 1999. It was also observed that the average C:N ratio and the average P:PO_4 ratio steadily increased over the study period, with the most dramatic increase in 1999. The C:N ratio significantly increased in 1996 and 1998, and the P:PO_4 ratio increased in 1998 and 1999. The explanation for the annual variability that occurred with the soil properties is undetermined. Nutrient cycling in semi-arid environments is variable and a function of the type of organic matter, time, soil temperature, soil moisture, and relative abundance of carbon and nitrogen (Black 1968).

MANAGEMENT IMPLICATIONS

The application of the information obtained from this study is governed by the objectives of the manager. Both of the overstory treatments represented in this study significantly increased annual herbaceous production by over 20%. The treatment of complete removal of mesquite overstory with no removal of regrowth had the greatest affect on herbaceous production, especially in years of average or above average precipitation. This treatment required relatively little cost and energy input in comparison to other forms of mesquite control and produced significant increases in herbage production over the five-year term of this study. This treatment would be most effective in areas that have an understory of predominantly native herbaceous species.

The overstory treatments had no effect on Lehmann lovegrass production, but were found to significantly increase production of native herbaceous species. Previous studies conducted in southern Arizona concluded that mesquite control resulted in an increase in production of both Lehmann lovegrass and native species (Kincaid et al. 1959; Cable and Tschirley 1961; Cable 1976; Martin and Morton 1993). The level of annual precipitation may explain the discrepancy between these studies and the study represented here. The locations of the previous studies received more annual precipitation than the study site represented here. Therefore, the results from this study indicate that in areas that have predominantly Lehmann lovegrass understory and receive 380 mm of annual precipitation or less, an overstory treatment of top removal of mesquite may not increase annual herbage production enough to justify such a treatment if the objective of the treatment is solely to increase production. However, in situations where the management objective is to increase the production of native herbaceous species and allow them to compete more effectively with Lehmann lovegrass, a treatment of top removal of mesquite may be quite effective. Lehmann lovegrass occupies a superior competitive role and has been observed to displace native herbaceous species (Kincaid et al. 1959). A treatment of top removal of mesquite will increase native herbaceous species and allow them to persist and compete more effectively with Lehmann lovegrass.

The mulching treatments represented in this study were found to be ineffective in increasing herbaceous production. The amounts of mulch applied to the treated plots were insufficient to alter the evaporation rates adequately to significantly affect the level of soil moisture available to herbaceous plants. However, these treatments may have had an impact on herbage production if the amounts of mulch applied to the soil surfaces were of a sufficient level to influence the evaporation rates. Determining the most efficient level of mulch can be difficult to determine. Insufficient rates of mulch will not successfully influence evaporation rates enough to increase available soil moisture and excessive mulch can result in an increase in soil temperatures, which can increase evaporation (Lemon 1956). A small scale study, with varying levels of mulch and consistent monitoring of soil moisture and soil temperature may be required to determine the most effective levels of mulch to apply. Additional monitoring of soil chemical properties would also be required. The results of this study indicate that the treatments of chip mulch and commercial compost significantly increased soil pH, which resulted in a reduction of plant available phosphorus. The effect did not influence herbaceous production; however, because phosphorus can be a limiting factor in semi-arid environments, increased levels of mulch may reduce plant available phosphorus to a degree that will negatively affect plant growth.

SUMMARY

Overstory Treatments

Both of the overstory treatments resulted in an increase of over 20% in total annual herbaceous production from 1995 to 1999. Analyses of year-to-year production revealed that the overstory treatments resulted in increased herbaceous production from 1997 to 1999. This increase in herbaceous production is probably due to the relative increase in annual precipitation during these years.

An evaluation of the response of spring versus fall herbaceous production revealed that the overstory treatments had no effect on spring production. The lack of treatment effects on spring herbaceous production is most likely due to the 48% below average precipitation that occurred during this season. The overstory treatment of complete removal of mesquite overstory with no removal of regrowth did result in higher fall herbaceous production. This treatment resulted in a 23% increase in fall herbaceous production. The treatment effect on fall herbaceous production may be due to the reduced water requirements of mesquite during the summer and fall in comparison to the spring, and the majority of herbaceous growth occurs in the summer and fall months.

The overstory treatments were also found to increase production of native herbaceous species; however, they had no effect on Lehmann lovegrass. The overstory treatment of complete removal of mesquite overstory with no removal of regrowth increased total annual production of native herbaceous species by 79%. In addition, this treatment resulted in a 2-fold increase in fall production of native species over the other two treatments. It would appear that Lehmann lovegrass was not in direct competition with mesquite trees for resources, while native species were. In summary, the overstory treatment of complete removal of mesquite overstory with no removal of regrowth had the greatest impact on fall production of native herbaceous species during years of relatively high precipitation, at times increasing production by almost 2-fold.

The effects of overstory treatments on total organic carbon, total nitrogen, nitrate, total phosphorus, plant available phosphorus and pH in the soil were evaluated, and the treatments were found to have no effect on any of these properties. Given the relatively slow rate of nutrient cycling in semi-arid environments, it could be that the term of the study was not of adequate length to reflect any treatment effect.

Mulching Treatments

The mulching treatments had no effect on total annual, spring or fall production of herbaceous species. These treatments also did not affect the production of Lehmann lovegrass, native herbaceous species, perennial species or annual species. This is probably due to the below average precipitation during the study period, and inadequate levels of mulch to alter the constant rate stage of evaporation.

The mulching treatments had no effect on total organic carbon, nitrate or total phosphorus. However, the treatments did affect total nitrogen, pH and plant available phosphorus. The total soil nitrogen was 22% higher on the plots that received the lopped-and-scattered treatment than the control plots. The reason for this increase is undetermined. Soil pH was higher on commercial compost plots and chip mulched plots in comparison to the control plots. Interestingly, the control plots had considerably higher levels of plant available phosphorus than the chip mulched plots and the commercial compost plots. A negative correlation was observed between the soil pH and the plant available phosphorus levels. This finding suggests that the chip mulch and commercial compost treatments increased soil pH and, subsequently, influenced the availability of phosphorus within the soil. This could potentially have negative long-term effects on herbaceous production because phosphorus is often a limiting factor for plant growth in arid and semi-arid environments.

Interaction effects between overstory and mulching treatments were evaluated for herbaceous production and soil properties. Possible interactions between treatments were evaluated for total annual, spring and fall herbaceous production. A significant interaction effect did occur for total annual herbaceous production, and this is predominantly a result of the overstory treatments. In addition, possible interactions between treatments were evaluated for total organic carbon, total soil nitrogen, nitrate, total soil phosphorus, plant available phosphorus and pH. A significant interaction did occur for soil pH and this was mainly attributed to the effects of the mulching treatments.

Annual Variability of Herbaceous Production and Soil Properties

Herbaceous production was variable between the years of the study and this variability was correlated to the annual precipitation. Total annual herbaceous production, Lehmann lovegrass production and production of perennial herbaceous species were all correlated to the annual precipitation. In addition, the annual variation of soil properties such as soil pH, total soil nitrogen, total organic carbon and nitrate were correlated to total herbaceous production.

Total organic carbon, total soil nitrogen, nitrate, total soil phosphorus, plant available phosphorus, soil pH, C:N and P:PO_4 were variable over the term of the study. As a general observation, all soil properties, except soil pH and plant available phosphorus, experienced considerable increases in 1999. This observation could be due to the increased precipitation in 1998 and 1999 or the nutrient cycling rate. Soil properties and nutrient cycling are dependent on a variety of factors including the type of organic matter in the soil, time, soil temperature, soil moisture, and the relative abundance of carbon and nitrogen.

APPENDIX A
Analysis of Variance Tables for Herbaceous Production

Table A-1. Analysis of variance for total annual herbaceous production and the overstory treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	2	6283148	3141574	3.31
Samples within treatments	297	282244005	950317	
Total	299	288527153	964974	

Table A-2. Analysis of variance for total annual herbaceous production and the mulching treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	3	2928749	976250	1.01
Samples within treatments	296	285598404	964859	
Total	299	288527153	964974	

Table A-3. Analysis of variance for total annual herbaceous production and between the years 1995 to 1999.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	4	156389281	39097320	87.29
Samples within treatments	295	132137872	447925	
Total	299	288527153	964973.8	

Table A-4. Analysis of variance for fall herbaceous production and the overstory treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	2	2552714	1276357	2.54
Samples within treatments	297	149481091	503303	
Total	299	152033805	508474	

Table A-5. Analysis of variance for fall herbaceous production and the mulching treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	3	870284	290095	0.57
Samples within treatments	296	151163521	510688	
Total	299	152033805	508474	

Table A-6. Analysis of variance for fall herbaceous production and between the years 1995 to 1999.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	4	71762379	17940595	65.93
Samples within treatments	295	80271426	272106.5	
Total	299	152033805	508474.6	

Table A-7. Analysis of variance for spring herbaceous production and the overstory treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	2	850443	425221	1.93
Samples within treatments	297	65408419	220230	
Total	299	66258862	221602	

Table A-8. Analysis of variance for spring herbaceous production and the mulching treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	3	645654	215218	0.97
Samples within treatments	296	65613208	221666	
Total	299	66258862	221602	

Table A-9. Analysis of variance for spring herbaceous production and between the years 1995 to 1999.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	4	38395438	9598859	101.63
Samples within treatments	295	27863424	94452	
Total	299	66258862	221602	

Table A-10. Analysis of variance for annual production of Lehmann lovegrass and the overstory treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	2	2558360	1279180	1.51
Samples within treatments	297	252375591	849749	
Total	299	254933951	852622	

Table A-11. Analysis of variance for annual production of Lehmann lovegrass and the mulching treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	3	2814898	938299	1.10
Samples within treatments	296	252119053	851754	
Total	299	254933951	852622	

Table A-12. Analysis of variance for annual production of Lehmann lovegrass and between the years 1995 to 1999.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	4	135859789	33964947	84.15
Samples within treatments	295	119074162	403641	
Total	299	254933951	852622	

Table A-13. Analysis of variance for annual production of native herbaceous species and the overstory treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	2	517389	258694	2.60
Samples within treatments	297	29551622	99500	
Total	299	30069011	100565	

Table A-14. Analysis of variance for annual production of native herbaceous species and the mulching treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	3	138461	46154	0.46
Samples within treatments	296	29930549	101117	
Total	299	30069011	100565	

Table A-15. Analysis of variance for annual production of native herbaceous species and between the years of 1995 to 1999.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	4	4061323	1015331	11.52
Samples within treatments	295	26007687	88162	
Total	299	30069011	100565	

Table A-16. Analysis of variance for annual production of perennial herbaceous species and the overstory treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	2	4578166	2289083	2.45
Samples within treatments	297	277741920	935158	
Total	299	282320086	944214	

Table A-17. Analysis of variance for annual production of perennial herbaceous species and the mulching treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	3	2249041	749680	0.79
Samples within treatments	296	280071044	946186	
Total	299	282320086	944214	

Table A-18. Analysis of variance for annual production of perennial herbaceous species and between the years of 1995 to 1999.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	4	147581564	36895391	80.78
Samples within treatments	295	134738522	456740.8	
Total	299	282320086	944214.3	

Table A-19. Analysis of variance for annual production of annual herbaceous species and the overstory treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	2	65710.7	32855.4	2.21
Samples within treatments	297	4425374.6	14900.3	
Total	299	4491085.3	15020.4	

Table A-20. Analysis of variance for annual production of annual herbaceous species and the mulching treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	3	4014.6	1338.2	0.09
Samples within treatments	296	4487070.7	15159.0	
Total	299	4491085.3	15020.4	

Table A-21. Analysis of variance for annual production of annual herbaceous species and between the years of 1995 to 1999.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	4	1605219.0	401305	41.02
Samples within treatments	295	2885866.3	9783	
Total	299	4491085.3	15020	

APPENDIX B
Analysis of Variance Tables for Soil Properties

Table B-1. Analysis of variance for total soil organic carbon and the overstory treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	2	0.13	0.06	0.23
Samples within treatments	297	83.98	0.28	
Total	299	84.11	0.28	

Table B-2. Analysis of variance for total soil organic carbon and the mulching treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	3	1.48	0.49	1.77
Samples within treatments	296	82.63	0.28	
Total	299	84.11	0.28	

Table B-3. Analysis of variance for total soil organic carbon and between the years 1995 to 1999.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	4	50.58	12.65	111.26
Samples within treatments	295	33.53	0.11	
Total	299	84.11	0.28	

Table B-4. Analysis of variance for total soil nitrogen and the overstory treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	2	0.0038	0.0019	1.28
Samples within treatments	297	0.44	0.0015	
Total	299	0.45	0.0015	

Table B-5. Analysis of variance for total soil nitrogen and the mulching treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	3	0.0107	0.0036	2.44
Samples within treatments	296	0.4353	0.0015	
Total	299	0.4456	0.0015	

Table B-6. Analysis of variance for total soil nitrogen and between the years 1995 to 1999.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	4	0.1844	0.0461	51.99
Samples within treatments	295	0.2616	0.0009	
Total	299	0.4456	0.0015	

Table B-7. Analysis of variance for soil nitrate and the overstory treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	2	13221.6	6610.78	0.99
Samples within treatments	297	1969238.7	6675.39	
Total	299	1982460.3	6674.95	

Table B-8. Analysis of variance for soil nitrate and the mulching treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	3	26144.2	8714.74	1.31
Samples within treatments	296	1956316.1	6654.14	
Total	299	1982460.3	6674.95	

Table B-9. Analysis of variance for soil nitrate and between the years 1995 to 1999.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	4	533372.8	133343.2	27.15
Samples within treatments	295	1449087.5	4912.16	
Total	299	1982460.3	6674.95	

Table B-10. Analysis of variance for total soil phosphorus and the overstory treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	2	19380.5	9690.25	0.73
Samples within treatments	297	3977005.6	13390.59	
Total	299	3996386.1	13365.84	

Table B-11. Analysis of variance for total soil phosphorus and the mulching treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	3	22714.2	7571.4	0.56
Samples within treatments	296	3973672.0	13424.57	
Total	299	3996386.1	13365.84	

Table B-12. Analysis of variance for total soil phosphorus and between the years 1995 to 1999.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	4	2945588.2	736397.05	206.75
Samples within treatments	295	1050797.9	3562.03	
Total	299	3996386.1	13365.84	

Table B-13. Analysis of variance for Olson phosphorus and the overstory treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	2	12.5116	6.2558	0.28
Samples within treatments	297	6687.1136	22.5155	
Total	299	6699.6252	22.4068	

Table B-14. Analysis of variance for Olson phosphorus and the mulching treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	3	428.244	142.748	6.74
Samples within treatments	296	6271.38	21.187	
Total	299	6699.6252	22.4068	

Table B-15. Analysis of variance for Olson phosphorus and between the years of 1995 to 1999.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	4	811.49	202.87	10.16
Samples within treatments	295	5888.138	19.96	
Total	299	6699.625	22.4068	

Table B-16. Analysis of variance for soil pH and the overstory treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	2	0.5846	0.2923	1.32
Samples within treatments	297	65.766	0.2214	
Total	299	66.35	0.2219	

Table B-17. Analysis of variance for soil pH and the mulching treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	3	1.9489	0.6495	2.99
Samples within treatments	296	64.402	0.2178	
Total	299	66.35	0.2219	

Table B-18. Analysis of variance for soil pH and between the years of 1995 to 1999.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	4	4.427	1.107	5.27
Samples within treatments	295	61.923	0.21	
Total	299	66.35	0.2219	

Table B-19. Analysis of variance for microbial analysis and the overstory treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	2	0.059	0.03	1.88
Samples within treatments	297	4.854	0.016	
Total	299	4.913	0.164	

Table B-20. Analysis of variance for microbial analysis and the mulching treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	3	0.111	0.037	2.31
Samples within treatments	296	4.802	0.016	
Total	299	4.913	0.164	

APPENDIX C
Analysis of Variance Tables for Mesquite Overstory

Table C-1. Analysis of variance for mesquite volume and the mulching treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F
Among treatments	3	2.14	0.71	0.09
Samples within treatments	36	287.38	7.98	
Total	39	289.52	7.42	

APPENDIX D
Correlation Coefficient Analysis Tables

Table D-1. Results of correlation coefficient analysis to determine significance of correlation in soil properties with variation in soil pH.

Y Variable	R Value
Olson Phosphorus	0.24
Total Soil Nitrogen	NS
Total Soil Organic Carbon	NS
Total Soil Phosphorus	NS
Soil Nitrate	NS

Degree of Freedom = 298

Table D-2. Results of correlation coefficient analysis to determine significance of correlation in annual herbaceous production with variation in soil properties.

X Variable	R Value
Olson Phosphorus	NS
Total Soil Nitrogen	0.39
Total Soil Organic Carbon	0.45
Total Soil Phosphorus	0.49
Soil Nitrate	0.33
Soil pH	0.18

Degree of Freedom = 298

Table D-3. Results of correlation coefficient analysis to determine significance of correlation in average annual levels of soil properties with variation in annual precipitation.

Y Variable	R Value
Olson Phosphorus	NS
Total Soil Nitrogen	NS
Total Soil Organic Carbon	NS
Total Soil Phosphorus	NS
Soil Nitrate	NS
Soil pH	NS

Degree of Freedom = 3

Table D-4. Results of correlation coefficient analysis to determine significance of correlation in average annual herbaceous production with variation in annual precipitation.

Y Variable	R Value
Total Herbaceous Production	0.98
Production of Perennials	0.98
Production of Annuals	NS
Production of Lehmann Lovegrass	0.98
Production of Native Species	NS

Degree of Freedom = 3

Table D-4. Results of correlation coefficient analysis to determine significance of correlation in average spring herbaceous production with variation in annual spring precipitation.

Y Variable	R Value
Spring Herbaceous Production	NS
Spring Production of Perennials	NS
Spring Production of Annuals	NS
Spring Production of Lehmann Lovegrass	NS
Spring Production of Native Species	NS

Degree of Freedom = 3

Table D-5. Results of correlation coefficient analysis to determine significance of correlation in average fall herbaceous production with variation in annual fall precipitation.

Y Variable	R Value
Fall Herbaceous Production	NS
Fall Production of Perennials	NS
Fall Production of Annuals	NS
Fall Production of Lehmann Lovegrass	NS
Fall Production of Native Species	NS

Degree of Freedom = 3

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