Arid Land Research and Management, 15:23–39, 2001
Copyright © 2001 Taylor & Francis
0890-3069/01 $12.00 + .00

# Summer Establishment of Sonoran Desert Species for Revegetation of Abandoned Farmland Using Line Source Sprinkler Irrigation

BRUCE A. ROUNDY

Department of Botany and Range Science
Brigham Young University
Provo, Utah, USA

HOSSEIN HEYDARI

University of Tehran
Tehran, Iran

CAROLYN WATSON
STEVEN E. SMITH

School of Renewable Natural Resources
University of Arizona
Tucson, Arizona, USA

BRUCE MUNDA
MARK PATER

United States Department of Agriculture
Natural Resources Conservation Service Plant Materials Center
Tucson, Arizona, USA

*A line source sprinkler was used to determine water requirements of adapted species for revegetation of abandoned farmlands in the Sonoran Desert of southern Arizona. Six grass and seven woody species were seeded on a fine-sandy soil initially at field capacity water content during the summers of 1992 and 1993 in Tucson, Arizona. The line source sprinkler created a greater difference in soil water availability between irrigated and unirrigated soils than within the irrigation gradient itself. Initial irrigation was followed by periods of summer rainfall in both years. Species emergence and establishment varied with amount and timing of irrigation and summer rainfall. After the initial 14 days of irrigation in 1992 and 11 days in 1993, soil water availability was intermittent in the surface soil but was consistently high at depths greater than 18 cm. Emergence was more sensitive to the irrigation gradient than was plant survival. Most species established successfully with at least 210 mm of irrigation plus precipitation. A possible strategy for establishing many of these species on abandoned farmland would be to fill the soil profile to field capacity by irrigating on consecutive days until emergence is observed. Direct seeding without irrigation or water concentration is not recommended due to the erratic and*

Received 21 April 2000; accepted 5 July 2000.
Address correspondence to Dr. Bruce A. Roundy, Department of Botany and Range Science, 401 WIDB, Brigham Young University, Provo, UT 84602, USA. E-mail: bruce_roundy@byu.edu

*limited nature of summer rainfall on abandoned farmland in the lower Sonoran Desert.*

**Keywords** revegetation, seedling emergence, survival, water requirements, drought tolerance, soil water availability

Since the early 1950s, over 400,000 ha of once-irrigated farmland have been abandoned in Arizona (Charney and Woodward 1990). Abandonment is the result of variability in costs of production and also in demand and returns for agricultural products over the years (Shapiro 1989). When Arizona's 1980 Groundwater Management Act restricted pumping in certain Active Management Areas, cities began purchasing farmlands for water sources (Gelt 1993). Future purchase of such so-called "water farms" has now been prohibited by the 1990 Groundwater Transportation Act, but large tracts of retired croplands used as water farms still lie abandoned. Problems with abandoned farmlands include wind erosion and hazardous dust storms that have resulted in highway fatalities, expense of controlling weeds such as Russian thistle, *Salsola iberica* Sennen & Pau, and loss of ecological and aesthetic value (Meitl, Hathaway, and Gregg 1983).

Much of the abandoned farmland in Arizona is in the south-central part of the state in the Santa Cruz Valley and along the Gila River between Phoenix and Yuma. These lands are characterized by fine-textured soils and annual rainfall often less than 250 mm (Jackson, McAuliffe, and Roundy 1991; Gelt 1993). Reinvasion of these lands from native shrubs such as creosotebush, *Larrea tridentata*, and desert saltbush, *Atriplex polycarpa* (Torrey) S. Wats., is limited by lack of dispersal vectors as well as aridity, salinity, poor soil physical conditions, and disruption of former natural drainage patterns (Allen and Jackson 1992; Jackson 1992). Some abandoned farmlands with comparatively coarser-textured soils and higher annual rainfall may be colonized by desert broom (*Baccharis* spp.) and burroweed, *Isocoma tenuisecta* Greene, while others remain bare or dominated by Russian thistle over 25 years after abandonment (Karpiscak 1980). These lands are classified by the U.S. Department of Agriculture, Soil Conservation Service (1981) as lower and upper Sonoran Desert Shrub, Phoenix Desert Shrub, and Chihuahuan Semidesert Grassland.

Revegetation of abandoned farmland without irrigation generally requires some form of water harvesting and concentration because sufficient rainfall to naturally establish desert perennials is infrequent (Bainbridge and Virginia 1990; Cox et al. 1982; Shanan et al 1970). The Natural Resource Conservation Service (Munda 1993) and Jackson and others (1991) have successfully established native shrubs between runoff areas and catchment berms near Redrock and Eloy, Arizona, respectively. Ripping to increase infiltration has also increased plant establishment on abandoned farmlands with compacted, fine-textured soils (Munda 1993).

Use of functioning irrigation systems to establish adapted plants during the first year after abandonment is a promising approach to revegetating abandoned farmlands in arid areas with erratic precipitation (Cox and Thacker 1992). However, establishment and persistence of irrigation-established plants is highly dependent on site conditions and drought tolerance of the seeded species. For example, Cox and Madrigal (1988) failed to establish forage grasses permanently on a silty clay loam soil at the San Xavier Indian Reservation, but Cox and Thacker (1992) succeeded in establishing grasses on sandy loam and clay loam soils in the Avra Valley in southeastern Arizona. In the latter study, plant establishment required sufficient irrigation to keep the soil surface moist until seedling roots were 5 to 15 cm long (four to six weeks of irrigation). To successfully establish, many warm-season grasses may require rather extended periods of available soil moisture at the soil surface to develop adventitious roots (Roundy et al. 1993, 1997). Establishment of woody species in the desert is also dependent on rapid root growth to stay below the soil drying front (Bainbridge and Virginia 1990; Jackson, McAuliffe, and Roundy 1991).

Transplants with deep roots grown in tall pots have survived well in the Sonoran-Mojave transition zone of southern California (Holden 1992). However, direct seeding is usually necessary to revegetate large-scale disturbances (Roundy 1999).

If existing irrigation systems can be used to revegetate farmlands the first year after abandonment, we need to identify adapted plant materials and their associated water requirements for establishment. The line source sprinkler system (LSS) produces a gradient in applied water that has been used mainly to determine crop production response to irrigation (Miller and Hang 1980). LSS has the advantage of providing a continuous gradient in irrigation from excess to no irrigation within a small area as distance increases from the line source (Hanks et al. 1976; Fernandez 1991). The objective of our research was to use LSS to determine potential for establishment of direct-seeded grasses, shrubs, and trees in the Sonoran Desert.

## Materials and Methods

The study site was at the Tucson Plant Materials Center of the Natural Resources Conservation Service. Elevation is 773 m and mean annual precipitation is 293 mm with 54% (159 mm) falling between July and October (Sellers, Hill, and Sanderson-Rae 1985). Soils are of the Anthony series, loamy fine-sand, mixed, calcareous, thermic family of Typic Torrifluvents.

We seeded six grasses and seven shrubs or trees considered adapted to Phoenix Desert Shrub climatic conditions (Jordan 1981) in 1992 and 1993 in July prior to the summer rainy season (Table 1). Laboratory germination tests were conducted to determine the pure live seed percentage of each seed lot and seeds of woody species that did not imbibe water were scarified by hand with sand paper and retested. Grasses, shrubs, and trees were seeded at rates of 66, 33, and 16 pure live seeds per m of row, respectively, in rows 0.41 m apart using a no-till planter. Rows were seeded perpendicular and to a distance of 16.5 m on both sides of the line source sprinkler. The experimental design was a randomized complete block with treatments arranged as a split plot. Blocks were replicated six times, with three blocks on each side of the LSS. Species were whole plots and irrigation levels were subplots. The soil was preirrigated in both years prior to sowing to fill the soil profile to field capacity to a depth of 1 m and to create similar antecedent soil moisture conditions throughout the field. An extra sacrifice row of each species was seeded next to each row in two of the six total replications for root measurements of selected shrubs and trees.

The LSS had nine sprinklers 6 m apart on 1.6 m high risers with each sprinkler producing an overall wetted radius of 13.5 m. Irrigation water was applied daily for at least 10 days after sowing to maintain available moisture in the upper 3 cm of soil nearest the line source. Applied water was measured in catch cans after every irrigation and plant density was counted in one or two subsamples, 1 m long within the seeded rows, every one to three weeks until November at distances of 1.5, 4.5, 6, 7.5, 10.5, 13.5, and 16.5 m from the line source. Soil matric potential (MPa) was measured every minute and hourly averages recorded using gypsum cells connected to Campbell Scientific, Inc. CR-10 electronic microloggers. Two gypsum cells were placed at depths of 1–3, 8–10, and 18–20 cm, while one cell was placed at depths of 38–40 and 58–60 cm in each of three blocks at distances of 1.5, 6, 10.5, and 16.5 m from the line source.

Plant height was measured every one to two weeks on the same five plants of four woody species (jojoba—*Simmondsia chinesis*; cat claw acacia—*Acacia greggii*; velvet mesquite—*Prosopis juliflora* var. *velutina*; and blue palo verde—*Cercidium floridum*) at distances of 1.5, 7.5, and 13.5 m from the line source. Tap root length of excavated plants was measured at the same distances and for the same species as plant height.

**TABLE 1** Grasses, shrubs, and trees direct-seeded in a line source sprinkler irrigation experiment at Tucson, Arizona, in the summers of 1992 and 1993

| Common name | Family, tribe, or subfamily | Species |
|---|---|---|
| **Grasses** | | |
| Purple threeawn [a] | Agrostideae | *Aristida purpurea* Nutt. |
| Cane bluestem | Andropogoneae | *Bothriochloa barbinodes* (Lag.) Herter |
| Spike dropseed | Agrostideae | *Sporobolus contractus* Hitchc. |
| Galleta | Zoysieae | *Hilaria jamesii* (Torr.) Benth. |
| Arizona cottontop | Paniceae | *Digitaria californica* (Benth.) Henr. |
| Lehmann lovegrass | Festuceae | *Eragrostis lehmanniana* Nees |
| **Shrubs** | | |
| Creosotebush | Zygophyllaceae | *Larrea tridentata* (DC.) Cov. |
| Triangleleaf bursage | Ambrosieae | *Ambrosia deltoidea* (Torrey) Payne |
| Jojoba | Buxaceae | *Simmondsia chinensis* (Link) Schn. |
| Cat claw acacia | Mimosoideae | *Acacia greggii* A. Gray |
| **Trees** | | |
| Ironwood | Papilionoideae | *Olneya testota* A. Gray |
| Velvet mesquite | Mimosoideae | *Prosopis juliflora* (Swartz) DC. var. *velutina* (Wooton) Sarg. |
| Paloverde | Caesalpinoideae | *Cercidium floridum* Bentham |

[a] Seeded in 1992 only.

Significance of block and species effects on plant density, tap root lengths, and shoot height was determined by univariate analysis of variance. Irrigation treatments using LSS are not randomized (Hanks et al. 1980). Repeated measures multiple analysis of variance was used to determine significance of irrigation and irrigation × species interactions for plant density (Potvin and Lechowicz 1990; Fernandez 1991; Kuehl 1994). Significance of Mauchly's criterion and failure to meet appropriate Huynh-Feldt conditions precluded use of univariate tests and dictated the use of multiple analysis of variance for these tests (Potvin and Lechowicz 1990). Profile transformation in the repeated measures analysis of variance was used to compare plant density at one irrigation level with the adjacent and next lower irrigation level (Fernandez 1991). Grasses and woody species were analyzed separately and a separate analysis was conducted for each sampling date.

## Results

### *Irrigation, Water Availability, and Overall Plant Response*

Natural precipitation after sowing for July and August totaled 76.2 and 68.1 mm in 1992 and 1993, respectively (Figure 1). Total irrigation plus precipitation for July and August after sowing ranged from 356.7 to 106.9 mm in 1992 and 285.2 to 106.6 mm in 1993 from 1.5 to 13.5 m from the line source. Potential evapotranspiration calculated from the Arizona Meterological Network (2000) weather station for Tucson using a modification of the Penman equation for July and August totaled 414 mm in 1992 and 412 mm in 1993. Potential evapotranspiration from the start of irrigation to the end of August was 304 mm for 1992 and 255 mm for 1993. Potential evapotranspiration during the irrigation period was 53 mm greater in 1992 and 30 mm greater in 1993 than the total rain plus irrigation at 1.5 m from the line source (Figure 1). From the start of irrigation to the end of August, air temperatures averaged 29.1°C in 1992 and 29.9°C in 1993, while relative humidity averaged 48% in 1992 and 36% in 1993. For both years, irrigation was applied frequently right after sowing in July, while natural precipitation was most frequent in August (Figure 2). This pattern of water inputs, as well as the initially wet soil profile, mainly resulted in measured differences in soil water availability between irrigated and unirrigated soils, rather than differences among irrigation levels (Figure 3). Soil water at the 1–3 cm depth from 1.5 to 10.5 m from the line source was highly available through mid August, while unirrigated soils were dry at that depth until natural precipitation fell in early August. At 8–10 cm, soil water potential on unirrigated soils declined prior to the initiation of summer rains in 1992 and 1993, and after cessation of rainfall in mid August in 1993. Soil water was available below a depth of 18 cm through July and August for both irrigated and unirrigated soils. Block and block × irrigation effects on plant density were generally not significant, except for some sample dates (Table 2). Significant block effects on grass density and block × irrigation effects on shrub density for the earlier sampling dates in 1992 may have been associated with uneven water applications. Although irrigation was conducted at night to minimize wind drift, some drift was unavoidable. Uneven application of water was also associated with imperfect leveling of the field, but there was no surface crusting and little runoff or run-on was observed. Applied water varied most at the greatest distance from the line source (Figure 1). Water applications were more variable in 1992 than 1993. Coefficients of variation for individual days of irrigation at different distances from the line source in 1992 averaged 9.4% at 1.5 m, 8.8% at 4.5 m, 11.4% at 7.5 m, 27.3% at 10.5 m, and 108.6% at 13.5 m. In 1993 they averaged 3.2% at 1.5 m, 1.8% at 4.5 m, 1.3% at 7.5 m, 2.2% at 10.5 m, and 3.4% at 13.5 m. Variation can be reduced by irrigating only during windless times. Overall, the line source sprinkler produced a gradient in water

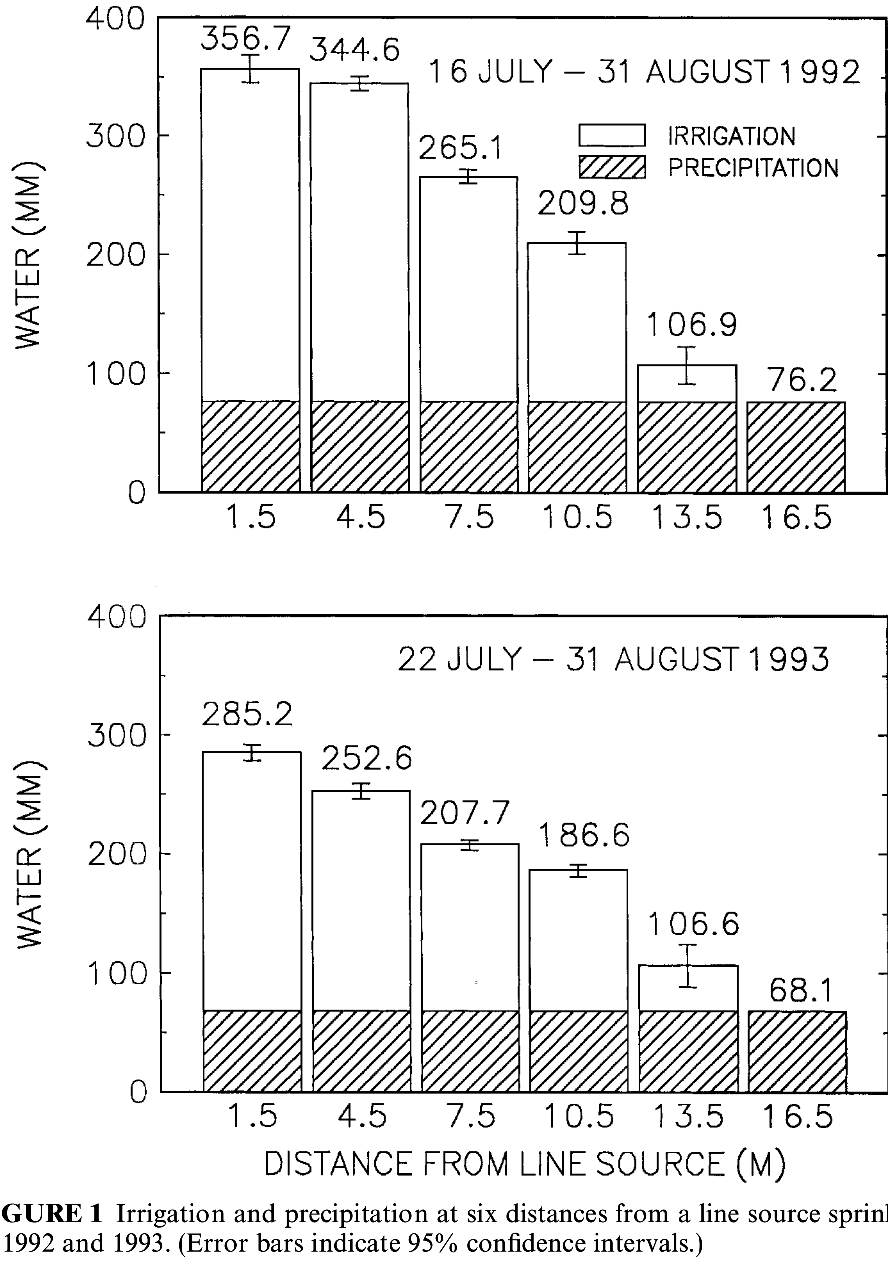


**FIGURE 1** Irrigation and precipitation at six distances from a line source sprinkler in 1992 and 1993. (Error bars indicate 95% confidence intervals.)

applied that resulted in differences in plant establishment, but the greatest difference in water availability and plant establishment was between irrigated and unirrigated soils.

Species, irrigation, and the species × irrigation effects on plant density were significant ($p < 0.05$) for most sample dates for grasses and woody species (Table 2). Bursage, *Ambrosia deltoidea*, had limited emergence and was not included in the analysis. Profile contrasts indicated that, in general, density of both grasses and woody plants varied mainly among the lower levels of irrigation and nonirrigated areas, rather than among the higher levels of irrigation. Species interactions with plant density differences associated with different irrigation levels were also mostly significant ($p < 0.05$) under less or no irrigation, than under higher irrigation.

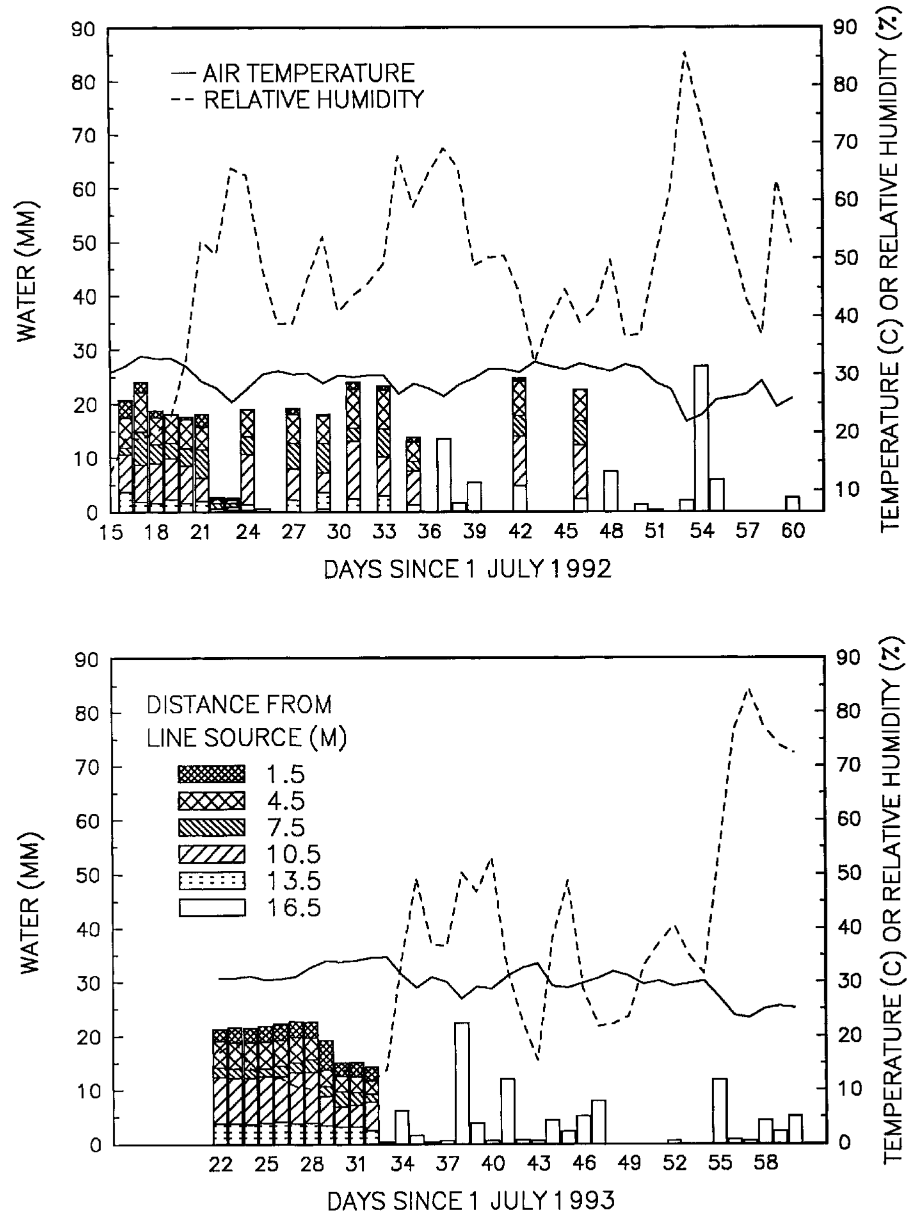


**FIGURE 2** Average daily air temperature, relative humidity, and date and amount of summer rainfall and irrigation from a line source sprinkler during the summers of 1992 and 1993 at Tucson, Arizona. (Stacked bars represent the amount of irrigation water applied at the indicated distance from a line source sprinkler. Open bars indicate amount of rainfall.)

*Grasses*

In 1992 and 1993, most grass species sown within 10.5 m of the line source reached maximum density two weeks after the first irrigation and stayed near that density into September (Figures 4 and 5). In general, most grasses established well at a

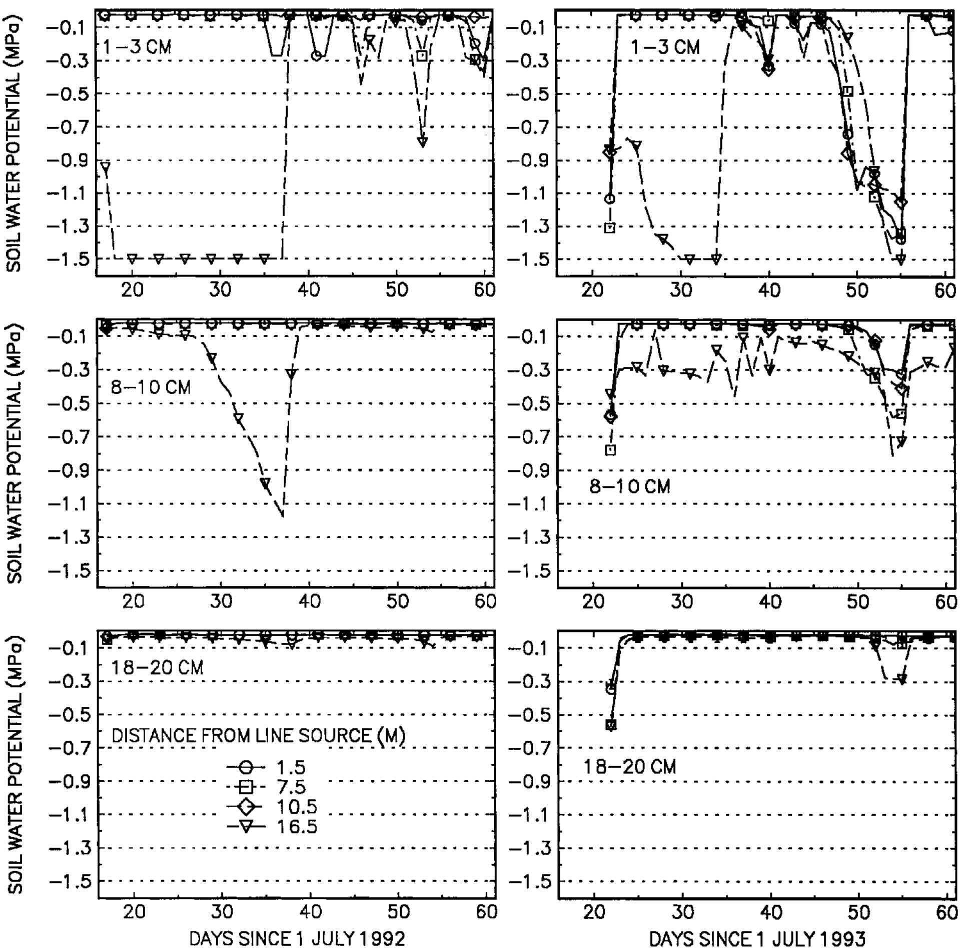


**FIGURE 3** Soil water potential at four distances from a line source sprinkler for five soil depths during the summers of 1992 and 1993 at Tucson, Arizona.

distance of 10.5 m or closer to the line source. This is equivalent to irrigation plus precipitation of 210 mm in 1992 and 187 mm in 1993 (Figures 1 and 2). Purple threeawn—*Aristida purpurea* Lehmann lovegrass—*Eragrostis lehmanniana*, cane beardgrass—*Bothriochloa barbinodes*, and spike dropseed—*Sporobolus contractus*, all had acceptable establishment (> 5 plants/m of row) under natural rainfall in 1992 (76 mm), while no grasses established acceptably under natural rainfall in 1993 (68 mm).

The total amount and pattern of rainfall and the associated periods of available water may have affected establishment. Initial periods of available water at the 1–3 cm depth (wet, soil matric potential $> -1.5$ MPa) and unavailable water (dry, $< -1.5$ MPa) for 1992 were 28 days wet, 10 days dry, and 5 days wet, and for 1993 were 19 days wet, 2 days dry, 18 days wet (Figure 4). Soil water sensors were 2 cm in diameter and had to be buried at least 1 cm below the soil surface. The soil water potential at a 1–3 cm depth as measured by the sensors was probably higher than that of grass seeds buried at 0.5–1 cm. This may be the reason that measured surface soil water potential does not explain the decline in grass seedling density with decreasing irrigation, especially in 1992 (Figures 4 and 5).

Final counts of grass density were similar to maximum emergence counts, showing a high first-season survival rate. Some species of warm-season grasses

**TABLE 2** Significance of irrigation and interactions of irrigation with block and species from repeated measures multiple analysis of variance and significance of block and species from analysis of variance of grass and shrub density for a line-source sprinkler experiment in Tucson, Arizona

| Vegetation | Year of seeding | Day since first irrigation | Species (S) | Irrigation (I) | Block (B) | S*I | B*I |
|---|---|---|---|---|---|---|---|
| **Grasses** | 1992 | | | | | | |
| | | 7 | ** [a] | ** | * | * | * |
| | | 14 | ** | ** | ** | ** | N |
| | | 22 | ** | ** | * | * | N |
| | | 37 | ** | ** | * | * | * |
| | | 43 | ** | ** | * | * | * |
| | | 66 | ** | ** | * | * | ** |
| | | 85 | ** | ** | * | * | * |
| **Grasses** | 1993 | | | | | | |
| | | 8 | ** | ** | N | ** | N |
| | | 15 | ** | ** | N | ** | N |
| | | 22 | ** | ** | N | ** | N |
| | | 32 | ** | ** | N | ** | N |
| | | 43 | ** | ** | ** | * | N |
| **Shrubs or trees** | 1992 | | | | | | |
| | | 7 | ** | ** | N | ** | ** |
| | | 14 | ** | ** | * | ** | ** |
| | | 22 | ** | ** | N | ** | ** |
| | | 37 | ** | ** | N | ** | * |
| | | 43 | ** | ** | N | ** | N |
| | | 66 | ** | ** | N | * | N |
| | | 85 | ** | ** | N | N | N |
| **Shrubs or trees** | 1993 | | | | | | |
| | | 8 | ** | ** | N | ** | N |
| | | 15 | ** | ** | N | N | N |
| | | 22 | ** | ** | N | N | * |
| | | 32 | ** | ** | N | ** | * |
| | | 43 | ** | ** | N | ** | N |

[a]N, *, and ** = not significant at $P > 0.05$ and significant at $P \leq 0.05$ and $\leq 0.01$, respectively.

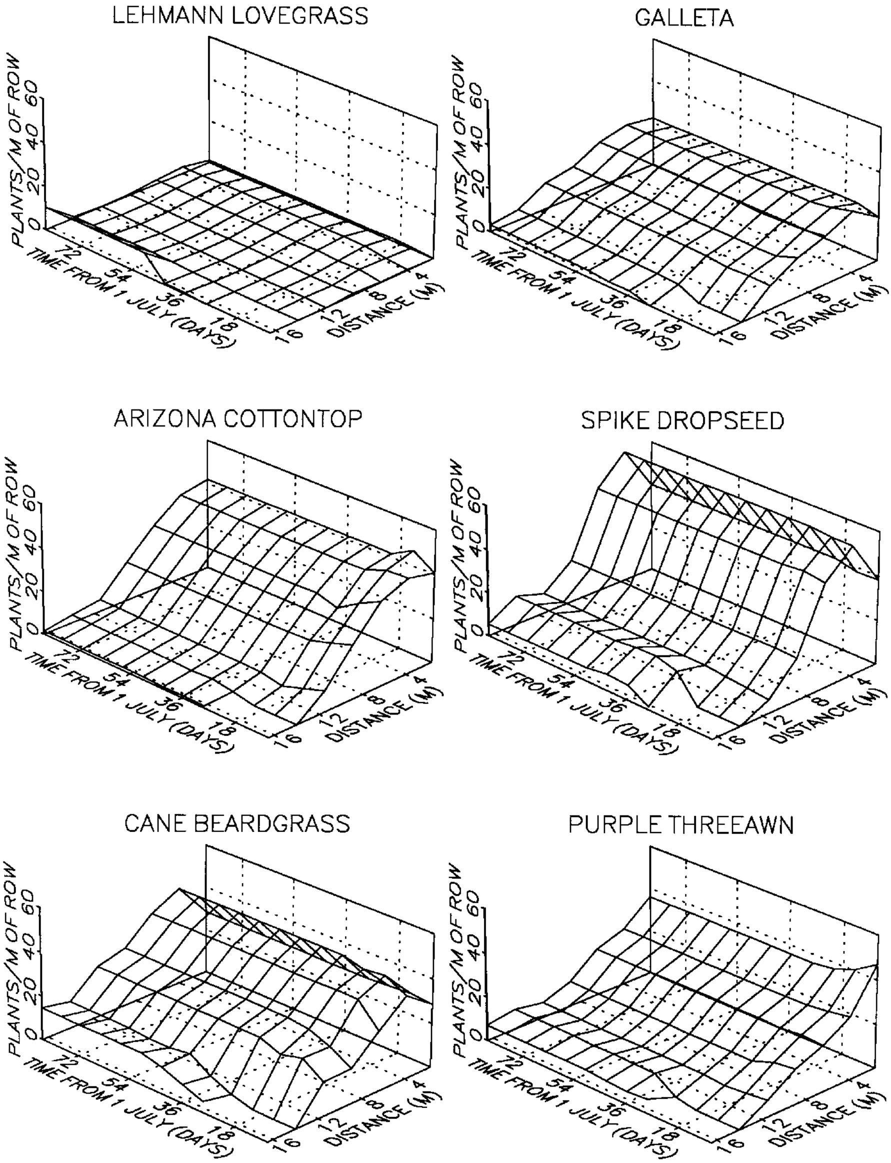


**FIGURE 4** Plants per m of row of six grasses sampled at seven distances from a line source sprinkler on 12 dates in summer 1992 at Tucson, Arizona.

require two weeks of available water to initiate adventitious roots which arise near the soil surface (Roundy et al. 1993). These grasses are susceptible to post-germination dry periods and may have high mortality if rainfall or irrigation sufficient to germinate seeds is followed by 1–2 weeks of drying (Roundy, Abbott, and Livingston 1997). In this study, germination and seedling emergence of grasses were much more sensitive to the irrigation gradient and differences between irrigation and rainfall than was seedling survival. The consistency of initial irrigation and natural rainfall, as well as the initially wet subsurface soil in this study, combined to allow survival of seedlings once they emerged.

The grass species differed in their sensitivity to irrigation and rainfall. Although Arizona cottontop—*Digitaria californica*, had the highest density of any of the

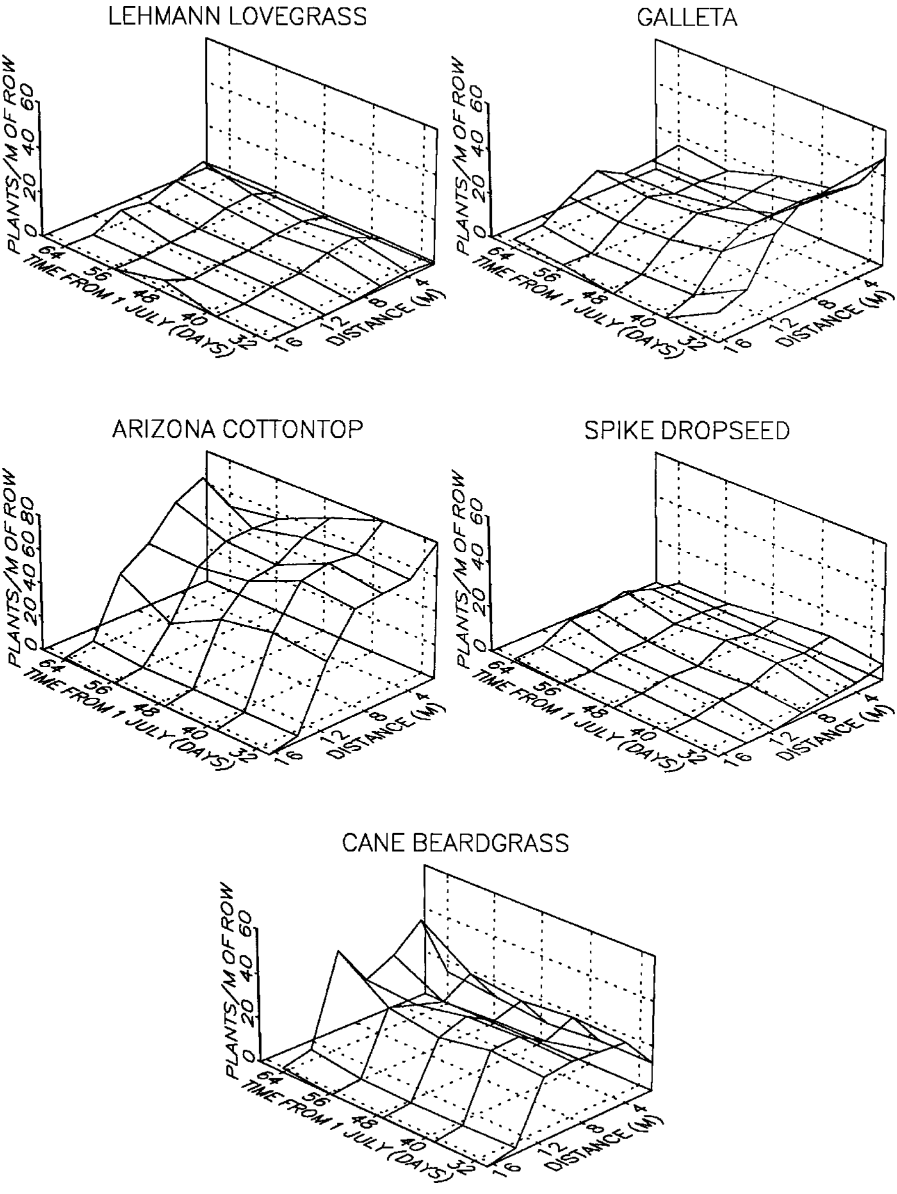


**FIGURE 5** Plants per m of row for six grasses sampled at seven distances from a line source sprinkler on five dates in summer 1993 at Tucson, Arizona.

grasses under irrigation, it had limited establishment with no irrigation (Figures 4 and 5). Spike dropseed had much higher emergence in 1992 than 1993. Lehmann lovegrass exhibited a late germination pattern, with limited emergence from irrigation but acceptable establishment from summer rains under no irrigation in 1992 (Figure 4). This species also emerged later than the other grasses in 1993, but established better with irrigation than with rainfall alone in that year (Figure 5). Although Lehmann lovegrass has a reputation for much more dependable establishment than native grasses in rangeland seedings (Roundy and Biedenbender 1995; Roundy et al. 1996), it did not establish as well as the native grasses in this study.

All of the native grasses showed good potential to establish under irrigation for these soils, soil moisture conditions, and climate. All of the grasses except galleta are known to have the $C_4$ photosynthetic pathway (Waller and Lewis 1979). Cane beardgrass required the least water for high and moderate establishment, and had low establishment only with the least amount of precipitation (Table 3). Purple threeawn and spike dropseed had moderate establishment with only 76 mm of precipitation. While most of the grasses had moderate establishment with 76–210 mm of irrigation or rainfall, consistent establishment would probably require at least 200 mm (Table 3). Success would be maximized by sowing prior to summer rains in July, then subsequently irrigating daily for 1–2 weeks to keep the soil wet until seedlings emerge. The 200 mm would wet the sandy soil in this study to approximately 30–40 cm deep which should be sufficient to encourage sustained root growth. If initial irrigation and emergence were not followed by summer rains, additional irrigation would help adventitious roots develop and ensure first-season establishment. Successful establishment of these grasses on sites with finer-textured soils would probably require more irrigation and rainfall due to lower infiltration rates and slower emergence and root growth.

### *Shrubs and Trees*

Profile analyses indicated that differences in woody plant densities generally occurred at distances between 7.5 and 16.5 m from the line source. All species emerged within a week of initial irrigation except for jojoba which emerged about two weeks after the other species (Figures 6 and 7). In 1992, all species except creosotebush had good emergence (> 10 plants per m of row) at a distance of 10.5 m or closer from the line source (Figure 6). Irrigation plus precipitation at these distances was greater than or equal to 210 mm (Figure 1). Most species had lower seedling densities in 1993 than 1992, and in that year seedling densities were also highest within 10.5 m of the line source, equaling 187 mm or more of irrigation plus precipitation (Figures 1, 6, and 7). Seedling survival of woody species was generally higher

**TABLE 3** Water (mm, irrigation plus precipitation) that resulted in high, moderate, and low establishment (≥ 15, 5–14, 0–4 plants per m of row, respectively), of grasses and woody species seeded on a loamy, fine-sand soil in the summers of 1992–1993 at Tucson, Arizona (differences in water amounts and ranges for a category reflect differences and ranges for the two years)

| | High (mm) | Moderate (mm) | Low [a] (mm) |
|---|---|---|---|
| **Grasses** | | | |
| Purple threeawn | 265 | 76 | — |
| Cane beardgrass | 187–210 | 76–107 | 68 |
| Arizona cottontop | 107–265 | 68–210 | 107 |
| Lehmann lovegrass | — | 76–187 | — |
| Galleta | 208–265 | 107 | 68–76 |
| Spike dropseed | 265 | 76–187 | 107 |
| **Shrubs and trees** | | | |
| Cat claw acacia | — | 187–210 | 107 |
| Blue palo verde | — | 68–107 | 76 |
| Creosotebush | — | 187–345 | 107–265 |
| Ironwood | — | 210 | 107 |
| Mesquite | — | 76–107 | 68 |
| Jojoba | 345 | 187–210 | 76–107 |

[a] Low = plant establishment was not significantly different from zero at the amounts of water indicated.

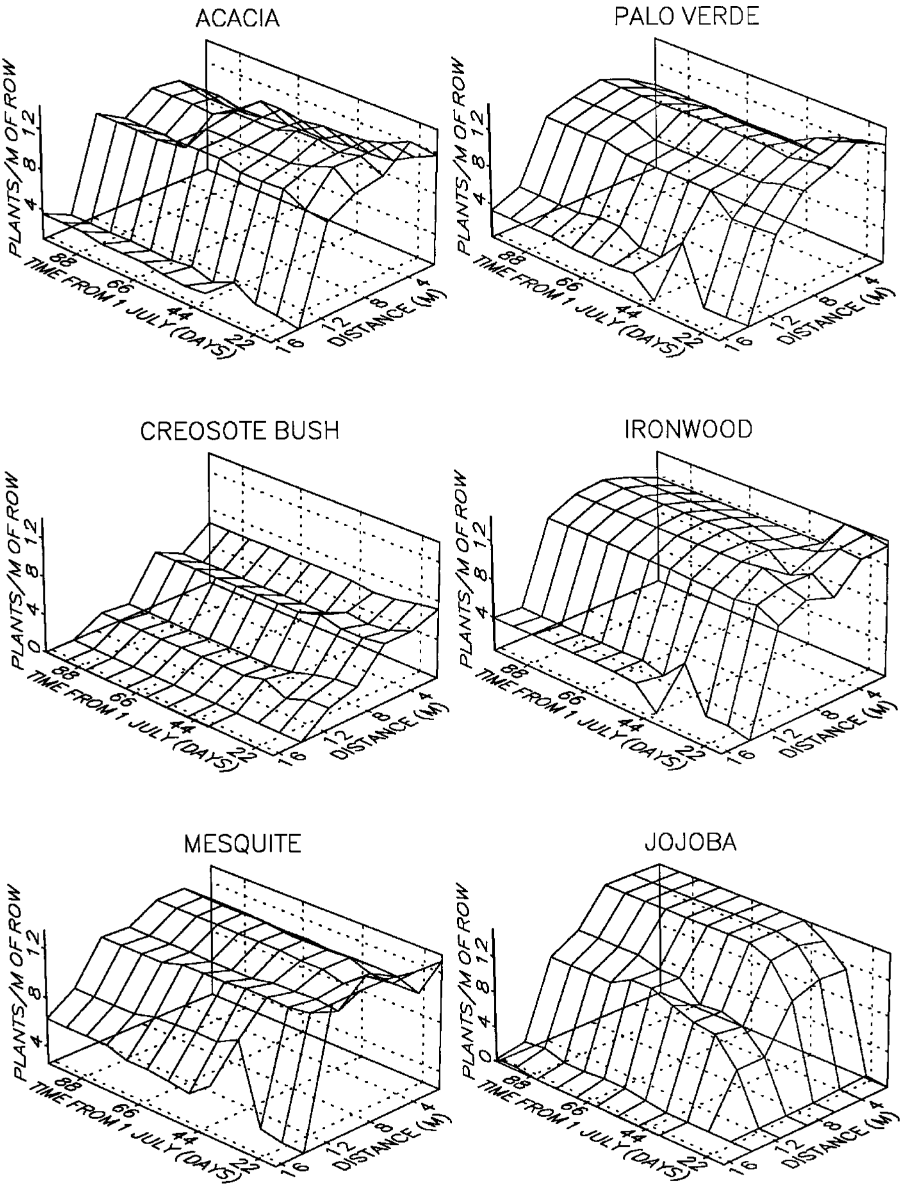


**FIGURE 6** Plants per m of row for six woody species sampled at seven distances from a line source sprinkler on 12 dates in summer 1992 at Tucson, Arizona.

in 1992 (> 90%) than in 1993 (about 50–60%). There were 14 major irrigations in 1992 and 11 in 1993 (Figure 2), and even the surface of irrigated soils dried out sooner in 1993 than 1992 (Figure 3). This may have affected the seedling survival of woody species in 1993, but grasses during the same time period had limited mortality.

In general, mesquite and palo verde required the least irrigation and precipitation (about 107 mm) for consistently successful establishment (> 5 plants per m of row, Table 3). Cat claw acacia had greater establishment in 1992 than 1993 (Figures 6 and 7). Creosotebush required more irrigation plus precipitation to establish successfully than did any of the other woody species (Table 3). All species but creosotebush had some establishment with no irrigation on both years, although

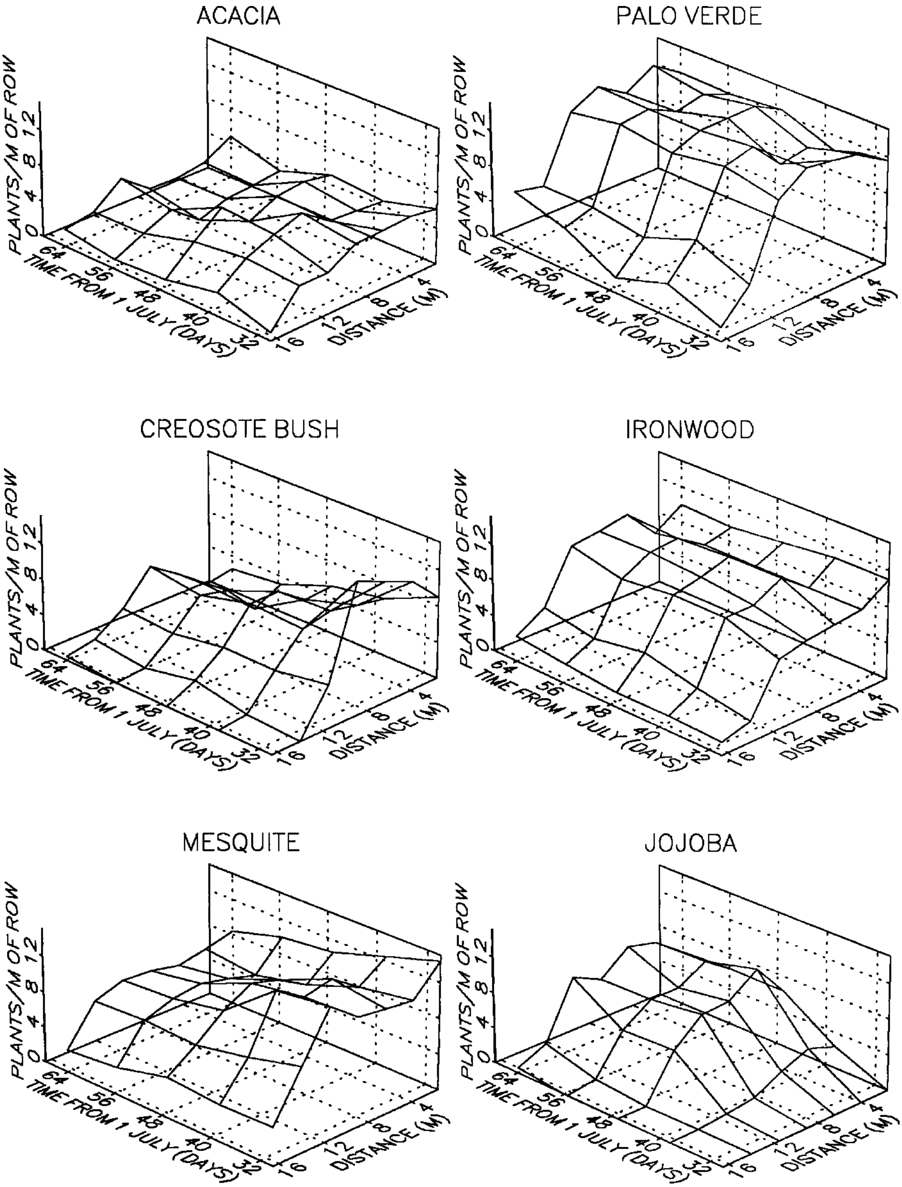


**FIGURE 7** Plants per m of row for six woody species sampled at seven distances from a line source sprinkler on five dates in summer 1993 at Tucson, Arizona.

jojoba's establishment was only 0.6 plants/m of row under natural rainfall in 1993 (Figures 6 and 7). As with the grasses tested, 200 mm of irrigation plus precipitation should be sufficient to establish most of these species under similar conditions (Table 3). To bring the upper 60 cm of this soil to field capacity water content would require 300–500 mm of irrigation plus precipitation, depending on evaporation.

Tap root depths of acacia, mesquite, and palo verde were greater than 50 cm deep by October of 1992 and November of 1993, while those of jojoba were less than 35 cm deep. Tap root depths for mesquite and acacia increased with distance from the line source, while those of palo verde and jojoba decreased. For example, tap root depths in November 1993 were 65 and 75 cm deep for acacia at 1.5 m and 13.5 m from the line source, those for mesquite were 85 and 113 cm, those for jojoba were 48 and 31 cm, and those for palo verde were 84 and 65 cm. Irrigation of 200–300 mm, in addition to natural precipitation should allow these species to germinate, while filling up the soil profile sufficiently to permit sustained root growth and survival.

Although some of these woody species established with 107 mm of irrigation plus precipitation, shoot growth was much greater for acacia, mesquite, and palo verde when total water received was over 265 mm. Shoot heights in October 1992 for plants receiving at least 265 mm total water were 43.2 cm for acacia, 46.7 cm for mesquite, and 54 cm for palo verde. For plants receiving only 107 mm total water, heights were 15.5 cm for acacia, 18.3 cm for mesquite, and 34.7 cm for palo verde. Jojoba had much less shoot and tap root growth than the other woody species measured and is known for its slow growth (Roundy and Ruyle 1989), and also for susceptibility to drought at the seedling stage (Sherbrooke 1976). Jojoba seedlings in this study elongated tap roots faster than shoots. In early September (11 September 1992, 72 days after 1 July) tap roots were 20 cm deep, while main shoots were only about 5 cm tall. Jojoba shoot growth was not increased by increased irrigation. Shoot heights in October 1992 associated with total water received were 6.6 cm for 356.7 mm water, 7.1 cm for 265 mm water, and 7.5 cm for 107 mm water. Water applications to produce high shoot growth could also produce excessive densities for some woody plants in a semiarid environment. If such high levels of irrigation are used (> 265 mm), pure live seeding rates should be reduced.

## Discussion

The line source sprinkler was useful in determining water requirements for establishment of the herbaceous and woody species tested. Although a gradient in irrigation was created by the line source, it did not result in a significant measurable difference in soil water potential and availability within the irrigation gradient. In this study, the soil profile was initially at field capacity prior to sowing and before initiation of the line source irrigation. Using the line source on initially dry soils would create a greater gradient in soil water potential and availability.

Periods of irrigation, natural rainfall, and soil water availability at the 1–3 cm depth on the irrigated and unirrigated soils were associated with seedling emergence patterns. Most species emerged on irrigated soils within a week of irrigation and did not emerge on unirrigated soils until the onset of summer rainfall. Exceptions to the rapid emergence pattern were Lehmann lovegrass and jojoba, both of which had delayed emergence. Lehmann lovegrass emerged best after summer rainfall and established only on nonirrigated soils in 1992. This may indicate that irrigation was sufficient to germinate, but not to maintain high soil water availability at the extremely shallow depths of emergence for this species (Winkel, Roundy, and Blough 1991). On the other hand, jojoba was slow to emerge, but eventually established best when irrigated, indicating that it started to germinate with irrigation but had slow shoot growth. Lack of differences in surface soil water availability measurements under the irrigation gradient did not explain differences under the gradient in grass density. Availability of water to seeds may have varied with the irrigation gradient on a smaller spatial scale than the 1–3 cm depth measured by the moisture sensors. It has been difficult to measure the moisture microenvironment at the scale of small seeds (Call and Roundy 1991).

Although data from this experiment suggest that some species will establish with less water than others, the most important finding is that most of the species tested will establish with direct seeding and irrigation. A possible strategy for revegetating abandoned farmlands with similar soils and climatic conditions would be to irrigate daily for 1–2 weeks after sowing in July until seedlings emerge, applying a total of 200–300 mm of water. This should be sufficient to fill the soil profile enough to sustain seedling survival, especially with additional water from summer rainfall. Direct seeding of these species without supplemental irrigation is risky due to the erratic and limited nature of summer rainfall. From a practical standpoint, revegetation of these lands will be most successful if done right after abandonment, before the irrigation system falls into disrepair. For lands without an irrigation system, these plants show high potential for establishment if microcatchments (Edwards et al. 2000) or spot irrigation devices (Bainbridge and Virginia, 1990) can supply sufficient water for germination and root growth.

## References

Allen, E. B., and L. L. Jackson. 1992. The arid west: here the challenge is to reverse the downward spiral of desertification over vast areas. *Restoration and Management Notes* 10:56–59.

Arizona Meteorological Network. 2000. http://ag.arizona.edu/azmet

Bainbridge, D. A., and R. A. Virginia. 1990. Restoration of the Sonoran Desert of California. *Restoration and Management Notes* 8:3–14.

Call, C. A., and B. A. Roundy. 1991. Perspectives and processes in revegetation of arid and semiarid rangelands. *Journal of Range Management* 44:543–549.

Charney, A., and G. Woodward. 1990. Socioeconomic impacts of water farming on rural areas of origin in Arizona. *American Journal of Agricultural Economics* 72:1193–1199.

Cox, J. R., and R. M. Madrigal. 1988. Establishing perennial grasses on abandoned farmland in southeastern Arizona. *Applied Agricultural Research* 3:36–43.

Cox, J. R., and G. W. Thacker. 1992. *How to establish a permanent vegetation cover on farmland*. College of Agriculture, University of Arizona, Tucson, Arizona.

Cox, J. R., H. L. Morton, T. N. Johnson, G. L. Jordan, S. C. Martin, and L. C. Fierro. 1982. *Vegetation restoration in the Chihuahuan and Sonoran Deserts of North America*. U.S. Department of Agriculture, Agricultural Research Service Reviews and Manuals # 28. Tucson, Arizona.

Edwards, F. S., D. A. Bainbridge, T. A. Zink, and M. F. Allen. 2000. Rainfall catchments improve survival of container transplants at Mojave Desert site. *Ecological Restoration* 18:100–103.

Fernandez, G. C. J. 1991. Repeated measures analysis of line-source sprinkler experiments. *HortScience* 26:339–342.

Gelt, J. 1993. Abandoned farmland often is troubled land in need of restoration. *Arroyo* 7:7–8.

Hanks, R. J., D. V. Sisson, R. L. Hurst, and K. G. Hubbard. 1980. Statistical analysis of results from irrigation experiments using the line-source sprinkler system. *Soil Science Society of America Journal* 44:886–888.

Hanks, R. J., J. Keller, V. P. Rasmussen, and G. D. Wilson. 1976. Line source sprinkler for continuous-variable irrigation-crop production studies. *Soil Science Society of America Journal* 40:426–429.

Holden, M. 1992. The greening of a desert. *American Nurseryman* April 15, 1992:22–29.

Jackson, L. L. 1992. The role of ecological restoration in conservation biology. In *Conservation biology: The theory and practice of nature conservation, preservation, and management*, eds. S. K. Jain and P. L. Fiedler, pp. 433–451. Chapman and Hall, New York.

Jackson, L. L., J. R. McAuliffe, and B. A. Roundy. 1991. Desert restoration-revegetation trials on abandoned farmland in the Sonoran Desert lowlands. *Restoration and Management Notes* 9:71–80.

Jordan, G. L. 1981. *Range seeding and brush management on Arizona rangelands*. Cooperative Extension, University of Arizona, Tucson, Arizona.

Karpiscak, M. M. 1980. Secondary succession of abandoned field vegetation in southern Arizona. Ph. D. dissertation, University of Arizona, Tucson.

Kuehl, R. O. 1994. *Statistical principles of research design and analysis*. Duxbury Press, Belmont, California.

Meitl, J. M., P. L. Hathaway, and F. Gregg. 1983. *Alternative uses of Arizona lands retired from irrigated agriculture*. College of Agriculture, University of Arizona, Tucson, Arizona.

Miller, D. E., and A. N. Hang. 1980. Deficit, high frequency irrigation of sugar beets with the line-source technique. *Soil Science Society of America Journal* 44:1295–1298.

Munda, B. D. 1993. Revegetation projects at Redrock and Avra Valley, Arizona. In *Vegetation management of hot desert rangeland ecosystems*, ed. D. D. Young, pp. 255–260. University of Arizona, Tucson, Arizona.

Potvin, C., and M. J. Lechowicz. 1990. The statistical analysis of ecophysiological response curves obtained from experiments involving repeated measures. *Ecology* 71:1389–1400.

Roundy, B. A. 1999. Lessons from historical rangeland revegetation for today's restoration. In *Revegetation with native species, Proceedings, 1997 Society for Ecological Restoration annual meeting, 1997 November 12–15, Fort Lauderdale, FL., Proc. RMRS-P-8*. L. K. Holzworth and R. W. Brown, compilers, pp. 33–38. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, Utah.

Roundy, B. A., L. B. Abbott, C. Jones, S. H. Biedenbender, M. Livingston, and V. K. Winkel. 1996. Warm-season grass establishment in relation to summer rainfall patterns. In *Proceedings Fifth International Rangeland Congress, Vol. I*. ed. N. E. West, pp. 484–485. Society for Range Management, Denver, Colorado.

Roundy, B. A., L. B. Abbott, and M. Livingston. 1997. Surface soil water loss after summer rainfall in a semidesert grassland. *Arid Soil Research and Rehabilitation* 11:49–62.

Roundy, B. A., and S. H. Biedenbender. 1995. Revegetation in the desert grassland. In *The desert grassland*, eds. M. C. McClaran, and T. R. Van Devender, pp. 263–303. The University of Arizona Press, Tucson, Arizona.

Roundy, B. A., and G. B. Ruyle. 1989. Effects of herbivory on twig dynamics of a Sonoran Desert shrub *Simmondsia chinensis* (Link) Schn. *Journal of Applied Ecology* 26:701–710.

Roundy, B. A., V. K. Winkel, J. R. Cox, A. K. Dobrenz, and H. Tewolde. 1993. Sowing depth and soil water effects on seedling emergence and root morphology of three warm-season grasses. *Agronomy Journal* 85:975–982.

Sellers, W. D., R. H. Hill, and M. Sanderson-Rae. 1985. *Arizona climate*. Arizona Agricultural Experiment Station, University of Arizona, Tucson, Arizona.

Shanan, L., N. H. Tadmor, M. Evenari, and P. Reiniger. 1970. Microcatchments for improvement of desert range. *Agronomy Journal* 62:445–448.

Shapiro, E. A. 1989. Cotton in Arizona: A historical geography. M.S. thesis, University of Arizona, Tucson, AZ.

Sherbrooke, W. C. 1976. Differential acceptance of toxic jojoba seed (*Simmondsia chinensis*) by four Sonoran Desert heteromyid rodents. *Ecology* 57:596–602.

U.S. Department of Agriculture, Soil Conservation Service. 1981. *Land resource regions and major land resource areas of the United States*. Agriculture Handbook 296. U.S. Government Printing Office, Washington, D.C.

Waller, S. S., and J. K. Lewis. 1979. Occurrence of $C_3$ and $C_4$ photosynthetic pathways in North American grasses. *Journal of Range Management* 32:12–28.

Winkel, V. K., B. A. Roundy, and D. K. Blough. 1991. Effects of seedbed preparation and cattle trampling on burial of grass seeds. *Journal of Range Management* 44:171–175.