

Improved establishment and development of three cactus species inoculated with *Azospirillum brasilense* transplanted into disturbed urban desert soil

Yoav Bashan, Adriana Rojas, and M. Esther Puente

Abstract. Survival and development of cactus transplants in urban, disturbed areas of the desert near La Paz, Baja California Sur, Mexico, was monitored. Young plants of three species of pachycereid cacti (*Pachycereus pringlei*, *Stenocereus thurberi*, and *Lophocereus schottii*) inoculated with the plant growth promoting bacterium *Azospirillum brasilense* in an eroded area (a dirt road) had a high survival rate and developed more rapidly compared with uninoculated control plants during a 3.5-year period after transplantation. Soil erosion in the inoculated experimental area diminished. Small, but significant soil accumulated in association with the growth of cactus roots into the wind-deposited dust. One demonstrated mechanism for stabilizing dust was by the upward growth of small roots during the rainy season into the deposited dust. *Azospirillum brasilense* survived well in the rhizospheres of these cacti for 2 years, but not in root-free soil. This study demonstrated the feasibility of using bacterial inoculation of cacti to enhance their establishment in disturbed areas, with the potential to stabilize soil.

Key words: *Azospirillum*, beneficial bacteria, cactus, plant inoculation, plant growth promoting bacteria, PGPR, soil erosion, soil reclamation.

Resume : Nous avons mesuré la survie et la croissance de cactus transplantés dans des zones urbaines altérées du désert à proximité de La Paz, Baja California Sur, Mexico. Des jeunes plants de trois espèces de cactus (*Pachycereus pringlei*, *Stenocereus thurberi* et *Lophocereus schottii*) inoculés avec une bactérie favorisant la croissance, *Azospirillum brasilense*, et transplantés dans une zone dénudée (chemin de terre) ont montré un taux élevé de survie et ils se sont développés plus rapidement que des plants-temoins non-inoculés et ce sur une période de 3.5 ans suivant la transplantation. L'érosion du sol a diminué dans la zone expérimentale. On a noté une accumulation faible mais significative de terre reliée à la pousse des racines des cactus dans la poussière déposée par le vent. Un des mécanismes de stabilisation a été l'augmentation de croissance des petites racines durant la saison des pluies dans la poussière accumulée. *Azospirillum brasilense* a bien survécu dans la rhizosphère de ces cactus pendant deux ans mais pas dans un sol exempt de racines. Cette étude confirme qu'une inoculation avec un promoteur bactérien favorise l'implantation des cactus dans des zones urbaines altérées et aide à la stabilisation du sol.

Mots clés : *Azospirillum*, bactéries utiles, cactus, inoculation des plantes, bactéries favorisant la croissance des plantes, PGPR, regeneration du sol.

[Traduit par la Rédaction]

Introduction

When naturally vegetated deserts are cleared to produce marginal agricultural land that is later abandoned (a process often called "desertification"), or to, build urban neighborhoods lacking paved roads, nothing remains to hold the topsoil against wind-caused erosion. The result is severe soil erosion and subsequent dust

pollution. The latter, only indirectly but significantly, increases chronic respiratory illnesses (Ortega-Rubio et al. 1998; Servin and Tejas 1991; Strannegaard and Strannegaard 1990; Subsecretaria de Coordinación 1992). This phenomenon has been increasing throughout the developing world (Ellis and Turnley 1990; Kelkar and Kamath 1982; Kostyuchenko 1984; Pewe 1981). In North America, it is predominant in the semiarid areas of northern Mexico (Anonymous 1994; Grover and Musick 1990). Prevention of soil erosion and dust pollution in urban, low income, desert communities in Baja California Sur and in northwest Mexico is difficult for various reasons. (i) Local municipalities are poor and can afford to pave only some roads, thus the unpaved roads yield heavy dust pollution caused by auto and truck traffic and strong desert winds (Gobierno del Estado 1992). In the city of La Paz, for example, 43% of the total 450 km of

Received December 15, 1999. Revision received March 22, 1999. Accepted March 23, 1999.

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streets are unpaved (Plan Municipal de Desarrollo 1993-1996, 1993), (ii) deforestation of the tropical dry forest in northwestern Mexico (Arriaga et al. 1993) is considered to be necessary for the survival of small communal agricultural communities (Ejidos) having large land holdings, (iii) overgrazing by free-roaming cattle and goats is widespread and traditional (Martinez-Balboa 1981), (iv) fresh water is scarce and cannot be used to irrigate noncrop plants that might hold the topsoil, or is used for priority tourist projects, (v) state governments and municipalities lack financial resources to enforce existing laws against commercial wood cutting, and (vi) desert trees, which ordinarily prevent erosion (such as mesquite and ironwood that form the tropical dry forest in southern Baja California (Arriaga et al. 1993)), are valued for charcoal (Nabhan 1992).

It has been mistakenly assumed that these deforested abandoned agricultural lands will revert to their original state on their own. Whereas this may be true for the forests in temperate areas where land no longer cultivated recovers gradually with annual and perennial weeds to be gradually replaced by longer-lived woody species (Horn 1974; Tilman 1986), this is not true for semiarid and arid zones. In semiarid eastern Colorado, there is limited reestablishment of native perennial grasses on fields that had been cultivated 40 years earlier (Reichardt 1982). In the Sonoran desert, reestablishment of formerly dominant saltbush is very limited. In some fields, virtually no plant cover exists 35 years after abandonment (Jackson et al. 1991). Abandoned fields in northwestern Mexico quickly become a barren landscape with few, if any, annual plants (Anonymous 1994). These areas cannot reforest naturally with their natural cacti, because the nurse trees (where cactus are primarily growing under their canopy) which are essential for the establishment of cactus seedlings (Franco and Nobel 1989; McAuliffe 1984) have been removed. As a consequence of desertification, during the windy seasons of spring and summer in northwestern Mexico, large clouds of dust are created. For several days at a time, typical strong summer winds can reduce the visibility in neighboring urban areas to less than 50 m. The view of the city of La Paz from a distance is obscured almost daily by a blanket of dust and smog caused by vehicle traffic (Bashan et al. 1992; Ortega-Rubio et al. 1998) with levels surpassing the U.S. Environmental Protection Agency and the Mexican standards for air quality (Ortega-Rubio et al. 1998).

Desert plants, especially cacti, are excellent topsoil stabilizers (Gibson and Nobel 1986). These plants could be used to prevent soil erosion, and reduce dust in urban areas except for the low establishment rate and subsequent slow development of cacti when transferred from natural habitats or from a nursery to eroded urban soil. Cacti may, however, benefit from a beneficial microbial population on planting and immediately thereafter, as is common in temperate reforestation practices (Chanway and Holl 1992). Cardon cactus (*Pachycereus pringlei*), for example, reacted positively to artificial inoculation with one species of plant growth promoting bacterium, *Azospirillum brasilense*, as do other plants (Bashan and Holguin 1997a). Seed germination may increase, and survival and growth rates may improve (Puente and Bashan 1993; A. Carrillo 1998, unpublished data). All cactus species in Baja California that have been

studied so far, including the species used in this study, were Vesicular-arbuscular mycorrhizal (VAM) (Rose 1981). It is unknown, however, if and how VAM fungi aid cactus establishment and growth.

The aims of this study were to (i) determine whether two strains of *A. brasilense* could improve the establishment and growth of three large cactus species in an eroded urban location, (ii) demonstrate, under semiarid conditions, the feasibility of urban revegetation with cactus, and (iii) measure the effect of cactus revegetation on urban soil erosion and soil reclamation.

Materials and methods

Site location

The experiment was done on a 20-m-wide dirt road (street no. 1 approximately 150 m from the western beach of Bahía de La Paz) in the residential neighborhood of El Comitan, 17 km northwest of La Paz, Baja California Sur, Mexico (24°10'N; 110°20'W). The road was constructed in 1973 and has been used daily by sparse auto traffic. The road has a minimal downhill slope, facilitating drainage during infrequent storm periods. The two sides of the road, which is about 14 m wide, were blocked from traffic in 1993 to conduct the experiment leaving a 6-m space between the experimental plots for local traffic. The transplants were planted directly on the road surface after soil preparation described later. The site has no buildings on one side and a single mobile home, over 20 m away, on the other side. Apart from domestic aerial electrical wires, no utility cables or tunnels were present at the site.

Determination of soil characteristics

Soil characteristics were measured using standard techniques: total nitrogen content by automatic micro-Kjeldahl after digestion (digestion system 12.1009, and Kjeltec auto 1030 analyzer, Tecator, Höganäs, Sweden), phosphorus, organic matter, and soil and water salinity according to Chapman and Pratt (1984), calcium and potassium by atomic absorption (Buck scientific atomic absorption spectrophotometer model 200A, East Norwalk, Conn.). Soil texture was determined according to Gee and Bauder (1986).

Collection of young cacti for transplant

Young cactus plants (approximately 3-4 years old; 10-20 cm in height) of the two columnar cacti, the giant cardon (*Pachycereus pringlei* Britton and Rose), and Pitaya dulce (*Stenocereus thurberi* (Engelman) Buxbaum), and the branched Garambullo cactus (*Lophocereus schottii* (Engelman) Britton and Rose), growing under several nurse mesquite trees (*Prosopis articulata*) were collected in November 1993 (the dry season in Baja California Sur) from an adjacent undisturbed site. Plants were collected during the cool, late-afternoon hours with a large spade (with little sandy soil adhering to their roots) and transferred to a ventilated, open palmthatched but for 4 weeks for natural repair of root damage. Additionally, complete branches of *S. thurberi* were excised from an adult plant, using a single cut, to regenerate plants from the cuttings, and similarly treated. This procedure is a common treatment used to avoid rotting of cactus after transplanting. Cacti are seldom affected by the omission of irrigation during the dry season, so vegetative parts and whole plants can be stored out of the soil for long periods.

Bacterial strains and growth conditions

The cacti were inoculated with the *Azospirillum* strains, *A. brasilense* Cd (DSM 7030, Braunschweig, Germany) and Sp-245 (donated by J. Döbereiner, EMBRAPA, Rio de Janeiro, Brazil).

Azospirillum strains were grown on N-free OAB medium (Bashan et al. 1993) for 16 h at 30 ± 1°C at 200 rpm. Bacteria were harvested by centrifugation (7000 x g, 10 min), washed twice in potassium phosphate buffer (pH 7.0, 0.06 M) supplemented with 0.15 M NaCl (PBS), and once in saline tap water (4633 µmhos/cm² containing no detectable N-P-K) obtained from a well in the experimental site, and were prepared for inoculation at a concentration of 8 x 10⁶ CFU/mL (Bashan 1986) in this saline tap water. Equal volumes of each bacterial strain were mixed into one solution before inoculation. Periodical attempts to isolate arid *Azospirillum* sp. from various sites in the experimental general area during the last decade failed. It appears that the El Comitan area does not have a local *Azospirillum* population (M.E. Puente, unpublished data).

Soil preparation before planting

After over 20 years of constant use, it was difficult to dig planting holes into the hard surface of the dirt road. Soil compactness was 84% in comparison with natural cactus-forest soil of 70%, where local basalt rock equals 100% (Fig. 3A). The soil was therefore tilled with a heavy-duty rotary plow to a depth of 35 cm. Although the compactness of the newly mixed soil remained high (79.5%), the cultivation allowed planting. Cacti were transplanted, after inoculation with *Azospirillum* spp., in holes 10-15 cm deep.

Inoculation and transplanting

Cactus roots or branches were immersed for 24 h in 15-L buckets containing bacterial liquid inoculant. Noninoculated control cacti were immersed in tap water. All plants were planted on December 15, 1993, with a distance of 60 cm between plants. Immediately after planting, each plant (both inoculated and noninoculated) received 10 L of tap water (also used for the inoculant) using a standard agricultural drip-irrigation system operating at a rate of 4 L/h to provide favorable moist conditions for the inoculated bacteria. Irrigation immediately after inoculation is a common procedure in *Azospirillum* inoculation with crop plants (Sang et al. 1986). Inoculation was repeated three times per year for the first 2 years as follows. First, each plant was irrigated with 2 L of tap water to moisten the otherwise dry soil. Next, inoculation was done by manually irrigating each plant with 100 mL bacterial suspension (8 x 10⁶ CFU/mL per strain) near the plant and in the moistened area. Immediately afterwards, plants were given another 2 L of tap water, again through the irrigation system. Noninoculated transplants received tap water only at the time of inoculation. Wild plants not removed from under their nurse tree received no irrigation. Heat-killed bacteria were not used as controls, because dead *Azospirillum* has no growth-promoting effects on carbon cacti (Puente and Bashan 1993), and irrigated controls were excluded, since this procedure is not realistic for cactus revegetation under arid conditions.

Maintenance of the experiment

In all plots, weeds were cleared twice a year, after the July-September rainy season and in January, and the irrigation system was cleaned of salt deposits and debris before every inoculation period. No fertilization was given. No annual weeds were grown under the mesquite nurse trees.

Measurements of cactus biovolume

Periodically, all the cacti were measured. The volume of a plant was considered a true representation of the plant size, because all varied in height, thickness, and number of branches. Since it was not possible to uproot the plants for accurate laboratory volume determinations, an indirect measurement of volume was developed. Because of the characteristic cross-section of cactus plants (spine-bearing tubercles arranged in vertical ribs which differ between the species), the volume of each plant was calculated from measure-

ments taken from the outside diameters of each plant. These were the diameters between opposite ribs and diameters between opposing tubercles (both measured at the same place on the plant) and the height of the plant. If the diameter varied along the plant's vertical axis (especially in larger columnar cacti at the end of the experiment) more measurements were taken. In the branched cactus, *L. schottii*, every branch was measured separately. Volume (CM) was calculated using the following formulae developed for that purpose:

For <i>S. thurberi</i>	$V = \Sigma_3^1 [\pi\alpha_1^2 + 7.5\pi(\alpha_2 - \alpha_1)^2]h$
For <i>P. pringlei</i>	$V = [\pi\alpha_1^2 + 6.5\pi(\alpha_2 - \alpha_1)^2]h$
For <i>L. schottii</i>	$V = \Sigma_n^1 [\pi\alpha_1^2 + 4(\alpha_2 - \alpha_1)^2]h$

Where V is the plant volume; α_1 , the radius measured between opposing ribs; α_2 , the radius measured between opposing tubercles; h, the height of the entire plant or length of a branch; and n, the number of branches.

To confirm the volume calculations, three young plants of each species were uprooted, measured, and their volume was calculated. Then the true volume was determined by submerging the plant in a large beaker and measuring water displacement. The calculated average volume of three *P. pringlei* plants was 317 ± 21 cm³, and their true volume was 326 ± 17 cm³. For *S. thurberi*, the calculated volume was 567 ± 38 cm³, and the true volume was 547 ± 16 cm³. For *L. schottii*, the calculated volume was 412 ± 18 cm³, and the true volume was 426 ± 33 cm³. Therefore, we consider our calculated volume method a functional method for determining cactus volume.

The percentage of rate of growth per month (R) was calculated by the following formula:

$$R = \frac{(V_n - V_0)}{n} \times 100$$

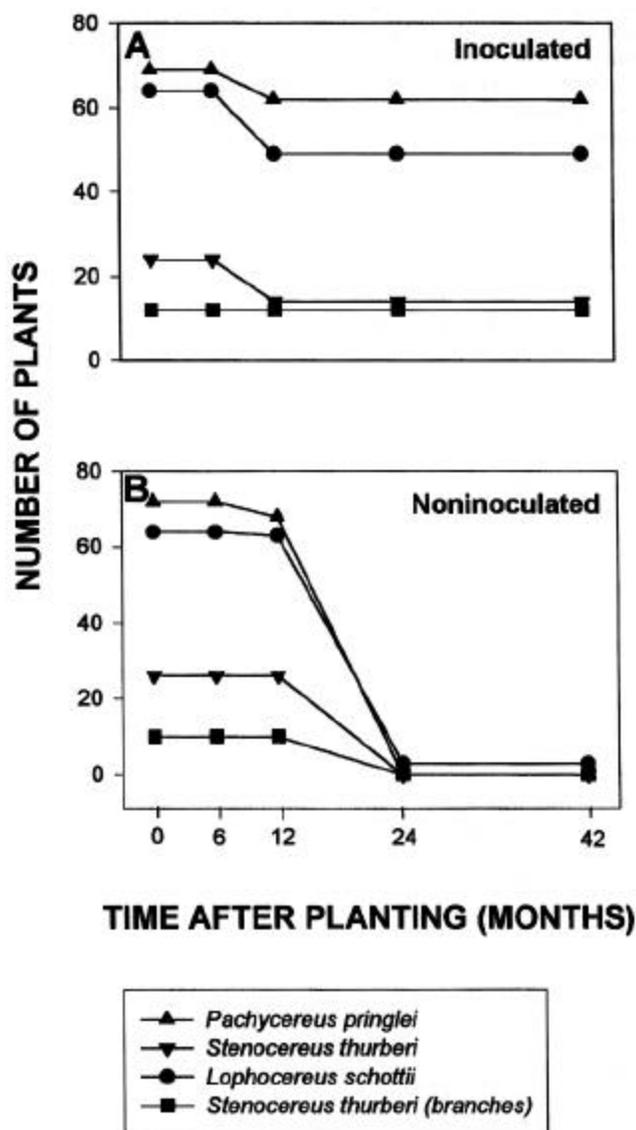
Where V₀ is the volume of the plant at the previous determination or at inoculation time; V_n, the volume of the plant at the end of the period when measured; and n, the number of months passed since the previous determination.

Measurement of soil erosion and rainfall

Soil erosion at the experimental site was determined as follows. The level of the soil surface was marked on five iron bars driven into the soil to a depth of 80 cm. The level of the remaining dirt road and that of the experimental site beside that road were similar at the beginning of the experiment. The depth of soil erosion (soil level relative to the original level) of the road (40 x 6 m) adjacent to the experiment (and used throughout the period) was measured either by using a commercial mason's level and threads or by a laser beam fixed horizontally at the original soil level. The depth of soil erosion was taken from these two horizontal level markers. Since soil erosion was unequal along the road, measurements were taken over four unequal segments (8, 12, 10, 10 m in length, but each having a similar erosion profile) alongside the experimental area. Soil loss in the four road segments was calculated using a basic triangle prism formula, because it characterized the erosion profile:

$$V = \Sigma_4^1 \left(\frac{W \times D}{2} \right) L$$

Fig. 1. Survival during 3.5 years after transplanting of inoculated (A) and noninoculated (B) with *Azospirillum* strains of three cactus species.



Where W is width of the road (600 cm); L, the length of the eroded section (cm); D, the depth or erosion (cm^{-1}); and V, the volume (m^3) of soil loss.

Results were calculated as cubic metres of soil loss per hectare. Soil erosion and soil accumulation in the revegetated area was measured similarly.

Rainfall was measured at the meteorological station of the Center for Biological Research of the Northwest located 150 m NW of the experimental field. Calculation of the estimated water received by each plant was based on the assumption that each plant had 1.44 m^2 of soil surface to receive rainfall and irrigation, but the same space might be shared with at least the eight neighboring plants.

Bacterial counts

Bacteria were counted by the liquid enrichment technique (Bashan et al. 1991), using a count-plate method on BLCR medium (Bashan et al. 1993), on both roots and nearby soil from samples taken by a small spade or for soil core samples described later.

Each count was made 2 months after each inoculation. Since the method does not differentiate between colonies originating from single cells or bacterial aggregates adhered to roots or soil particles, bacterial numbers recorded are probably lower than actual.

Root distribution in the upper layer of the experimental plot

Ten core samples were taken from the inoculated area by the transparent Plexiglas test tube sampler of Bashan and Wolowelsky (1987). After retrieving the test tubes and cleaning their outer surfaces, the locations of roots were marked on the Plexiglas after staining with 5 mL 0.01% toluidine blue (Böhm 1979) added directly to the soil core. Later, total root pieces were counted after sieving the tube content through a 1-mm mesh net. The soil surface roots were quantified after sieving separately the top 1 cm of the soil core samples. This technique does not differentiate between the roots of each cactus species. Every root segment (marked on the Plexiglas tube) is presented schematically, because in black and white photography it is difficult to differentiate between soil particles and lightly stained roots. Samples were taken twice a year; once in October (after the summer rainy season) and once in June (the end of the dry season), starting 1 year after planting. From noninoculated plants, only one sample was taken after 1 year, because the plants did not survive longer (see Results).

Experimental design and statistical analysis

The experiment had a random-block design in 15 blocks. Each block consisted of inoculated and noninoculated treatments. Each treatment contained 616 plants (randomly chosen) of the three cactus species. The experiment was done on two road parcels of $45 \times 7 \text{ m}$ each. Both parcels had identical soil characteristics and were located 6 m apart. The experiment had a total of 330 cactus plants. Because the three cactus species grow in a community in nature, to mimic that, each treatment contained plants of the three species. Each plant species in each treatment and in each block was compared with its own kind, for example, inoculated *P. pringlei* plants were compared with noninoculated *P. pringlei* plants, and this was repeated in the 15 blocks. Bacterial counts were done in five replicates, where one isolation from one soil sample served as a replicate. Soil and water analyses were done in triplicate from inoculated and noninoculated plots and from the road itself, and soil core sampling was done in five replicates. Results were analyzed by one-way analysis of variance (ANOVA) at $P \leq 0.05$. Standard error accompanied all soil analyses, and Student's t-tests were made to determine root distribution profiles in soil. Data in percentage were transformed to arcsin before analysis.

Results

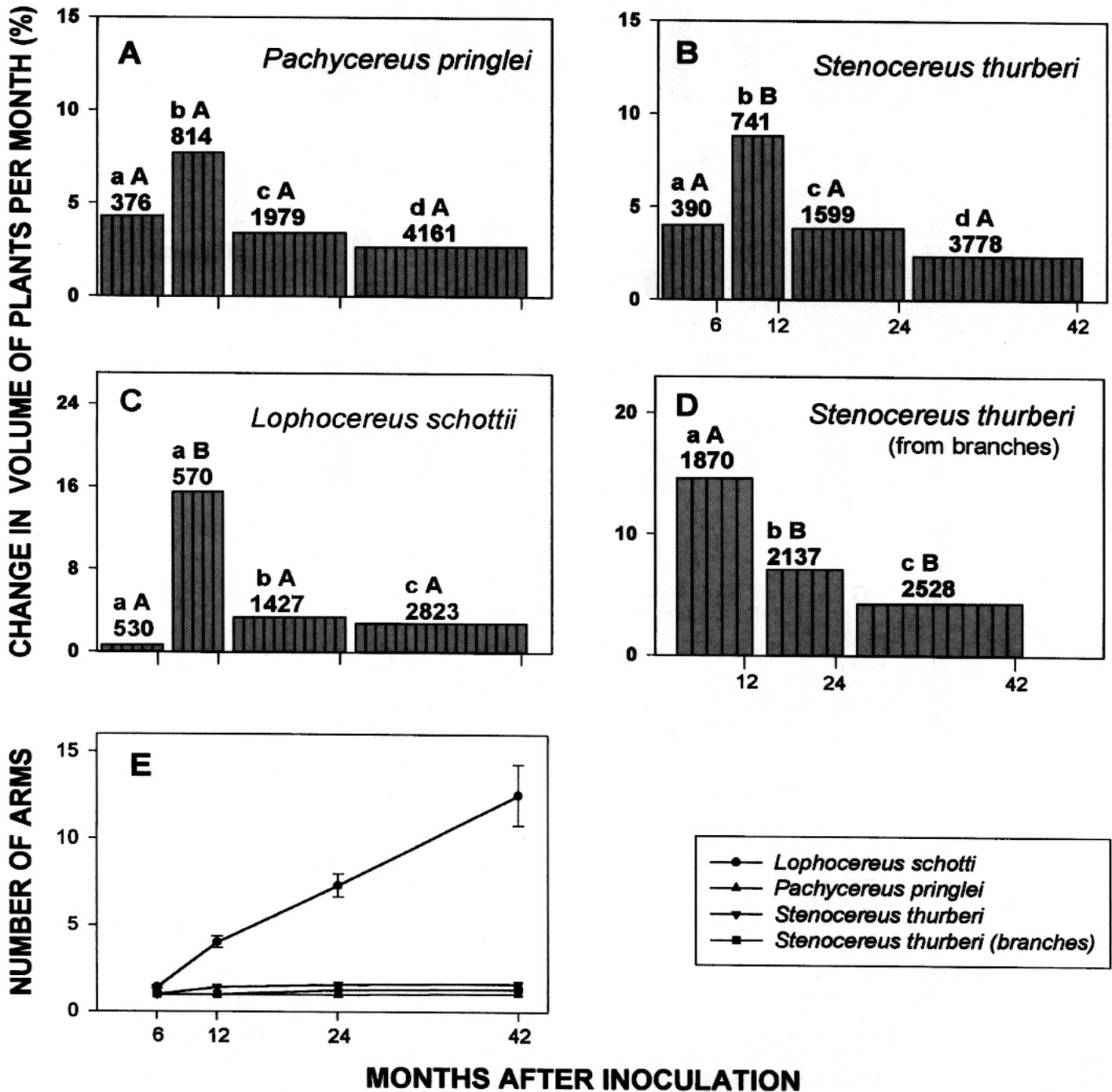
Survival of cacti

Cacti in the noninoculated plots survived for 6 months and then started to die. Two years after planting, only three specimens of *L. schottii* survived out of 63 original plants. On the inoculated plot, some initial mortality occurred during the first 12 months. Later, the population stabilized and remained constant for the duration, 3.5 years, of the experiment (Fig. 1). The average survival rate of all inoculated three cactus species after 3.5 years was 76%. The survival of noninoculated plants was <2%.

Development of inoculated cactus plants in transplanting areas

Although an attempt was made to choose wild plants of similar size, the heterogeneity of the wild-plant population caused

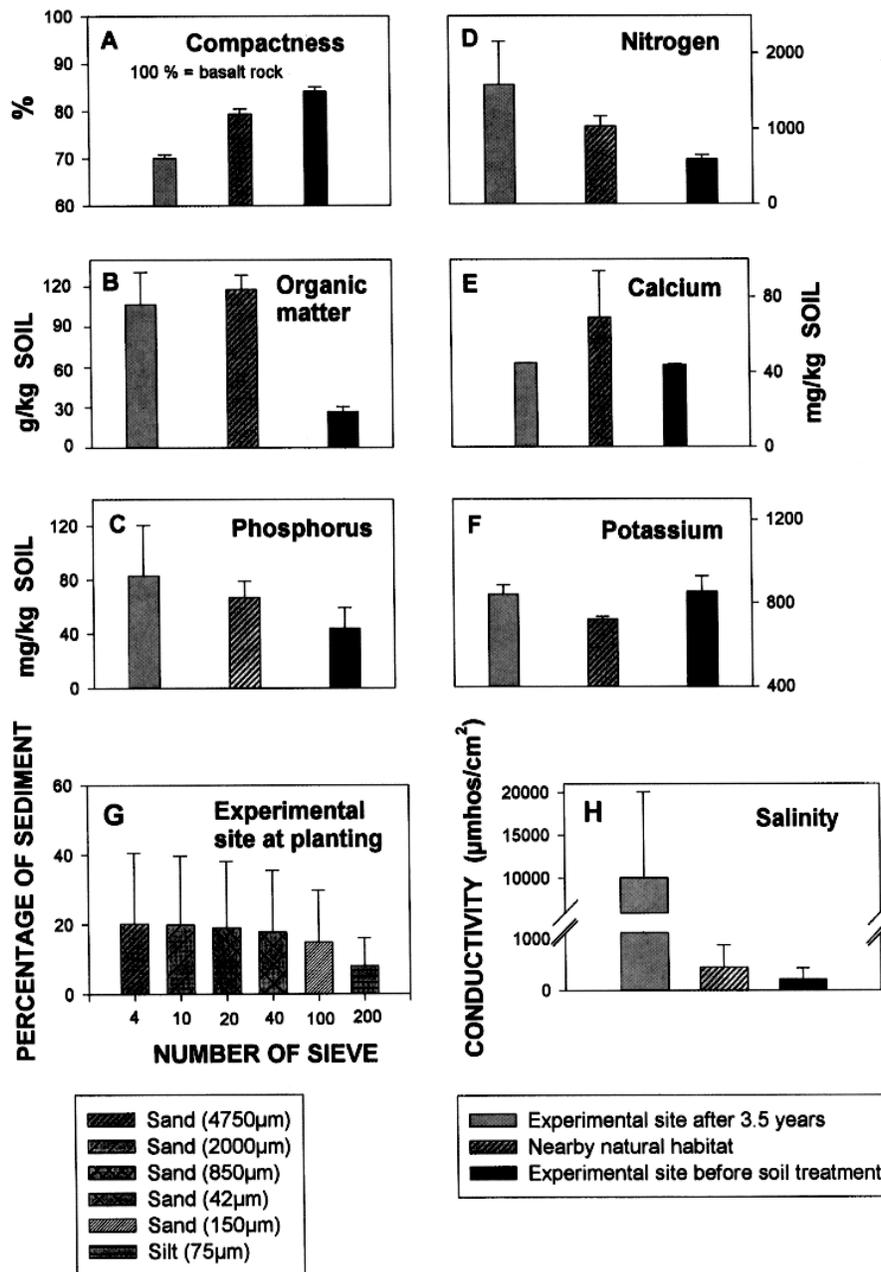
Fig. 2. Development of cactus plants after inoculation with *A. brasilense* (A-D), and the number of side arms developed by each cactus species (E). A group of columns denoted by a different uppercase letter, within each subfigure, represent significant statistical differences related to the rate of growth per month. A group of columns denoted by a different lowercase letter, in each subfigure, differ significantly in relation with the plant size. All analyses were done by ANOVA. Numbers above the set of columns represent the actual average volume of these plants at sampling (cm³). Bars (Fig. 2E) represent SE.



variability between the plants and differential development. Some remained small throughout the experiment, whereas others grew into large plants (>1 m height for *P. pringlei* and 1.5 m for *S. thurberi* and >35 branches on *L. schottii* cacti). Therefore, the volume-increase rate of particular plants was evaluated (Fig. 2).

Because volume increase does not necessarily mean a taller plant, small differences in the diameter of the plant might result in a large increase in volume. All inoculated cactus species had a similar growth pattern represented by plant volume. The most marked

Fig. 3. Characterization of the disturbed soil used for cactus revegetation before planting and after 3.5 years of cactus cultivation. Bars represent SE.



effect on plant volume was between 6 and 12 months after the first inoculation (Figs. 2A-2D), after which the growth rate declined. The increases in volume of *L. schottii* were mainly caused by the production of many side branches, which were absent in *S. thurberi* and *P. pringlei* (Fig. 2E).

Soil characteristics before and after revegetation with cacti

Because the experimental site served as a public dirt road for about 20 years, no vegetation was found. A comparison

of soil characteristics was made between the conditions before planting and after 3.5 years of cactus revegetation and with nearby undisturbed cactus-forest soil. The most significant soil feature was the road compactness. The road was 14% more compact than undisturbed soil and 5% more compact than the experimental area after mechanical breaking and cactus cultivation (Fig. 3A). The initial low organic-matter content of the road (30 g/kg soil) increased significantly, reaching the level of organic matter content in the natural habitat (110 g/kg soil) as a result of cactus cultiva-

Fig. 4. Distribution of small roots in the uppermost 5 cm of topsoil of the experimental site in rainy and dry seasons 2.5 years after transplanting. This is a schematic representation in which each dot represents one detected piece of root in that location. Numbers represent the average number of root pieces detected in the uppermost 1 cm of soil 1 over a period of 2.5 years. Numbers denoted by different letters and related to rainy and dry season of each cactus species are significantly different in Student's *t*-test at $P \leq 0.05$.

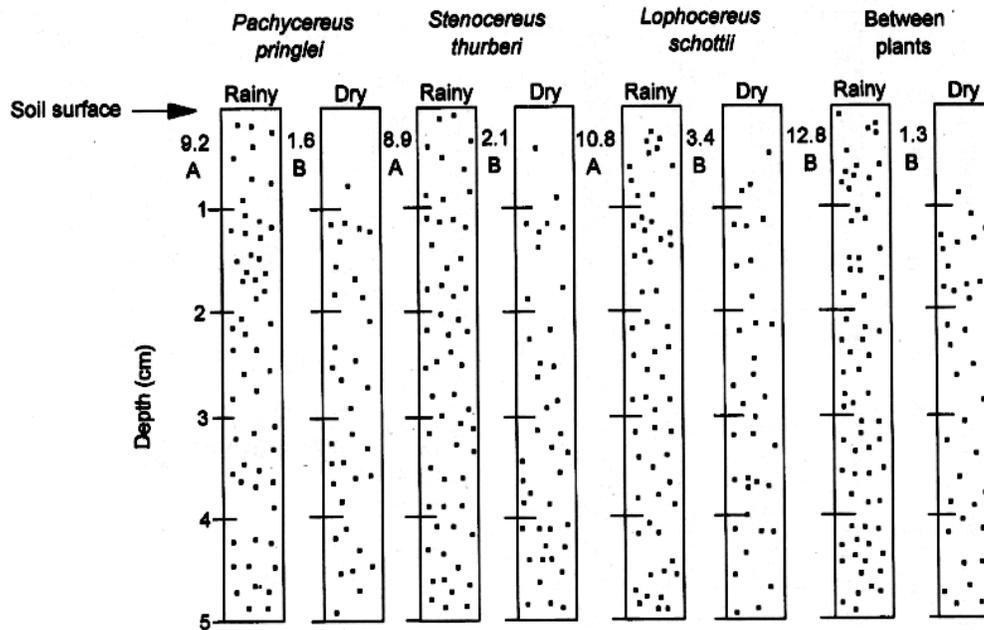


Table 1. Root distribution in the uppermost soil layer (10 cm) in the revegetated area.

Year of sampling location	No. of root pieces†					
	Dry season			Rainy season		
	1.00	2.00	3.5	1.00	2.00	3.5
Close to <i>Pachycereus pringlei</i> *	26aA†	31aAB	36aB	29aAB	38aB	42aB
Close to <i>Stenocereus thurberi</i>	24aA	34aB	38aB	34aB	37aB	43aB
Close to <i>Lophocereus schottii</i>	23aA	28aA	32aAB	26aA	35aB	41aB
Empty surface between plants	21aA	32aB	33aB	24aA	29aAB	38aB
Average root number	23.50	31.25	34.75	28.25	34.75	41.00

*Distance smaller than 20 cm from the plant.

†Numbers denoted with the same lowercase letter in each column do not differ significantly at $P \leq 0.05$. Numbers denoted with different uppercase letters in each row differ significantly at $P \leq 0.05$ by ANOVA.

tion (Fig. 3B). Similarly, the level of nitrogen increased (500-1500 mg/kg soil) (Fig. 3D). Cactus cultivation had no significant effect on the levels of phosphorus, calcium, potassium, or soil texture (Figs. 3C, 3E-3G.). Soil salinity in the experimental site was high during the entire experiment with values exceeding those in natural soils, probably from the limited irrigation with saline tap water given during inoculations (Fig. 3H).

Development of wild noninoculated cactus plants under nurse mesquite trees

Wild cactus plants growing under the mesquite nurse trees developed slowly, as is common for these plants when growing in an undisturbed habitat. Although their height steadily increased with time, the growth rate was nevertheless small: 45 cm/year for *P. pringlei*, 4.3 cm/year for *S. thurberi*, and 6.4 cm/year for *L. schottii*. The volumes of these wild plants increased steadily at a slow rate; approximately 3% per month for the two columnar cacti, and approximately 5% for the branched cactus.

Root distribution in the revegetation area before and after rain

The pattern of small root distribution in the upper soil surface (<10 cm) revealed that there are always more roots in the rainy seasons. Two years after planting, the root number was significantly higher than in the first year and then slowly increased with time (Table 1). However, the root spatial-distribution pattern differed greatly in the uppermost layer (<1 cm depth). In the dry season, this layer contained few roots, but after the rain, their number increased significantly (Fig. 4). A similar distribution pattern was observed when samples were taken close to any of the three cacti species or from the empty area between cacti plants (Fig. 4). No root presence in the uppermost soil layer was observed in noninoculated plants 1 year after transplanting.

Availability of water for the plants

Water was available from rainfall and the limited irrigation given at inoculation time (Fig. 5A). Figure 5 demonstrated that the extra irrigation any plant received at inoculation was small in

Fig. 5. Water availability in the experimental site: (A) total rainfall; (B) potential available water to the plants throughout the experiment from rainfall and irrigation; (C and D) potential available water to the plants on a monthly basis in 1994 and 1995 when the plants were irrigated.

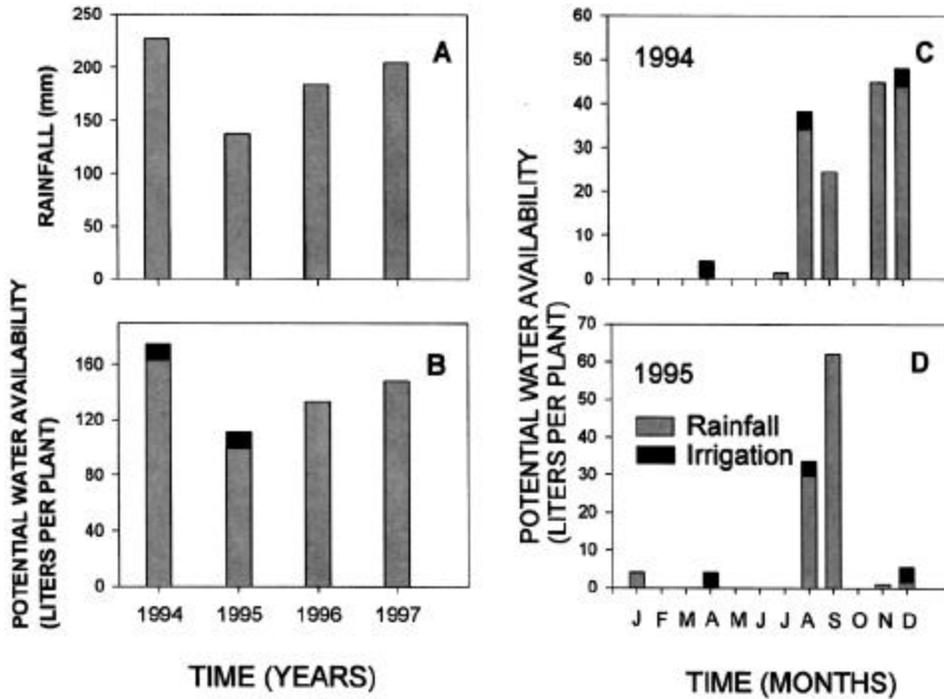
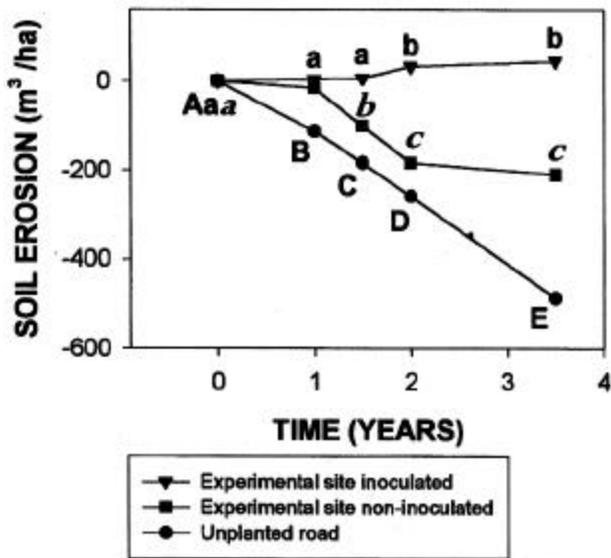


Fig. 6. Soil erosion and soil reclamation in the experimental site. Data were collected from 2 parcels of 240 m² each and from the road transverse the experimental area and were converted to m³ lost soil/ha. Points followed by a different letter (capitals, italics, or lowercase letters) differ significantly at P ≤ 0.05 in ANOVA.



comparison with the overall amount of water that all the plants received either on a yearly (Fig. 5B) or monthly (Figs. 5C, 5D) basis.

Soil erosion

The road and the experimental area were eroded mainly by the strong daily winds and occasional summer hurricanes (especially

by hurricane "Faust" in late summer 1996, which passed directly over the area producing heavy rains and creating temporary streams in an otherwise dry landscape). The dirt road transverse the experimental site had an additional eroding factor; sparse vehicular traffic. The erosion was uneven along the road. It was more severe in the center probably because of water action. Figure 6 shows the road lost 0.049 m³ of soil/m² in 3.5 years (equivalent to 487.5 m³/ha). The inoculated cactus plantation accumulated 0.0046 m³ of soil/m² (equivalent to 45.8 m³/ha) during that period, probably from the nearby deteriorating road. The noninoculated cactus plantation (that ceased to exist after about 1.5 year) lost 0.021 m³ of soil/m² (equivalent to 209 m³/ha).

Survival of *Azospirillum* in soil and rhizosphere of cacti plants over a 2-year period

Both *Azospirillum* strains survived in very low numbers in root-free soil when samples were taken 1 month after inoculation. At a sampling 6 months later, they had disappeared. However, they survived well in the rhizosphere of the three cacti, albeit in low numbers, for 2 years (Table 2).

Discussion

Soil erosion, and subsequent dust blown by wind and vehicular traffic, characterizes urban areas in northwestern Mexico (Anonymous 1994). To reduce the health hazard from dust, soil stabilization is essential. We propose urban revegetation in semiarid zones with native species of large cacti inoculated with plant growth promoting bacteria as a feasible means to enhance plant establishment and development and therefore prevent soil erosion.

Table 2. Survival of *A. brasilense* Cd and Sp-245 in the bulk soil and in the rhizosphere soil of three cactus species.

Plant species and sampling time (months after inoculation)	Cd		Sp-245	
	Soil (CFU/g)	Rhizosphere (CFU/g)	Soil (CFU/g)	Rhizosphere (CFU/g)
<i>Pachycereus pringlei</i> 1	2.4±0.7×10 ³	5.4±0.3×10 ⁵	6.4±0.6×10 ³	4.7±0.4×10 ⁵
6	n.d.*	8.3±0.3×10 ⁴	n.d.	5.4±0.4×10 ⁴
12	n.d.	3.3±0.5×10 ³	n.d.	5.1±0.8×10 ³
24	n.d.	4.4±0.5×10 ²	n.d.	6.4±0.3×10 ³
<i>Stenocereus thurberi</i> 1	4.5±0.4×10 ³	6.6±0.2×10 ⁵	7.3±0.4×10 ²	5.9±0.5×10 ⁵
6	n.d.	2.7±0.6×10 ⁴	n.d.	5.6±0.4×10 ⁴
12	n.d.	3.9±0.7×10 ⁴	n.d.	9.2±0.7×10 ³
24	n.d.	2.3±0.5×10 ²	n.d.	8.3±0.4×10 ²
<i>Lophocereus schottii</i> 1	6.2±0.8×10 ²	7.3±0.6×10 ⁵	8.2±0.3×10 ²	8.7±0.3×10 ⁵
6	n.d.	6.4±0.7×10 ⁴	n.d.	4.9±0.2×10 ³
12	n.d.	7.1±0.2×10 ³	n.d.	7.4±0.4×10 ³
24	n.d.	17±0.3×10 ²	n.d.	6.7±0.5×10 ²

*n.d., Not detected.

We used three arborescent cacti as test species: *P. pringlei*, *S. thurberi*, and *L. schottii* because of several advantages these plant species have for urban revegetation. (i) They are robust, halotolerant, drought resistant, and well adapted to desert conditions (Roberts 1989). (ii) They have an extensive shallow root system capable of stabilizing large areas of topsoil (Gibson and Nobel 1986). (iii) After planting and establishment, the young plants need little maintenance or irrigation for their entire life span. (iv) They are long-lived and should not require replacement for long periods of time. (v) They are easily propagated from seeds. (vi) They tolerate human abuse commonly occurring in urban areas, and (vii) they are decorative and accepted as ornamental plants in public areas. Unfortunately, like most cacti, these plants are slow growing under arid conditions (Nobel 1996). This study aimed to overcome that disadvantage by demonstrating the feasibility of enhancing cactus establishment and growth in eroded soil by inoculation with *A. brasilense* strains.

Our study demonstrated that the eroded urban soil in the experimental site did not support the initial establishment of these cacti, even though a relatively small amount of water was supplied during planting. Almost none of the noninoculated plants survived. This perhaps occurred because of the very poor soil conditions in the eroded area. However, inoculation with *A. brasilense* significantly enhanced establishment and later enhanced plant development compared with the growth rate of native cacti. The common estimation of native *P. pringlei* development in Baja California is an annual increase in height of 1-5 cm with a small increase in plant volume (Roberts 1989). This was confirmed by the present study.

No experimental design (by blocks) can mimic the random distribution of cactus species under the mesquite nurse tree, let alone the complex soil conditions there (A. Carrillo, 1998, unpublished data). No two nurse-tree cactus systems are alike. The distances between cacti can be from zero (attached seedlings) to 2-3 m apart, whereas the cacti in our experiment were planted in even spacings. Additionally, the possible effect(s) of transplantation on the growth of noninoculated seedlings could

not be measured, because on inoculated seedlings did not survive long enough. For these reasons, it is impossible to compare plant growth in the revegetation area and in the nurse-tree environment statistically. Nevertheless, our long-term experiment may give an indication that inoculation with *A. brasilense* enhanced plant volume in almost all the surviving plants over plants growing in their natural habitat in the "resource island" (Danin 1996). Although the average rate of increase in volume of wild cacti per month was only marginally smaller than that of inoculated transplants during 3.5 years, the difference in rate of growth in the 1st year created larger transplants. Thus, even a moderate rate of growth in later years was sufficient to create a large difference in volume of inoculated versus native plants at the end of the experiment (several thousand cm³ vs. less than 500 cm³).

The observed increase in the soil organic matter was attributed to developing of roots. Soil nitrogen increase was caused perhaps by *A. brasilense* nitrogen-fixation activity; a bacterium known to increase nitrogen content of soils (Shabaev et al. 1991). However the possible increase in insoluble phosphorus content is not explained by *A. brasilense* inoculation.

Although only nonnative *Azospirillum* inoculation was evaluated in this study, the possibility that other plant growth promoting microorganisms, especially those isolated from arid environments, would provide at least an equal benefit, might open a line of environmental application of microbial inoculants, currently used almost exclusively for agricultural crop plants (Bashan 1998).

Soil erosion is the main driving force in the desertification process of Mexico (Anonymous 1994). Our urban plantation demonstrated soil erosion there can be prevented by growing cacti having a large subsurface root system (Nobel 1996) on abandoned or eroded lands. In the inoculated revegetated area, soil erosion diminished. Furthermore, it appears revegetated plants captured and settled dust. It is unlikely that plant distribution in the experimental area, regardless of the inoculated versus uninoculated factor, would have influenced wind erosion deposit, because the basic characteristics of cacti is of having minimal surface area incapable of blocking the wind and capturing flying dust (Gibson and

Nobel 1986). Furthermore, old columnar cacti, in contrast with dense mesquite trees, are not known to form dust mounds underneath the plant in the Sonoran desert (A. Carrillo, 1998, unpublished data). One demonstrated mechanism for stabilizing dust was by the upward growth of small roots during the rainy season into the deposited dust. This eventually elevated the surface of the experimental site above its original level. The inoculated revegetated area did not lose soil during 3.5 years, whereas the noninoculated plantation did, possibly because of the poor establishment of the plants, and their death after about 1.5 years. Although the dirt road had an additional erosion factor (traffic), which the experimental vegetation areas did not have, prohibiting statistical comparison, yet, the road erosion demonstrated the potential of soil erosion occurring in desert urban soils. Because of the small size of our experiment, the dust reduction effect in the atmosphere of the area was not determined.

Azospirillum sp. is usually inoculated onto crop plants once prior to or immediately after sowing or after seedling emergence (Bashan 1986; Bashan et al. 1989). We used multiple inoculations, as a precaution to ensure root colonization under arid conditions, for a period of 2 years. However, our plant development study did not support the need of multiple inoculations. Possibly fewer inoculations, or even a single one, might have been sufficient, because the bacteria were established and survived well in the cactus rhizosphere.

The *Azospirillum* strains used in this study are known for poor survival in semiarid soils (Bashan et al. 1995) but also for their excellent survival in the rhizosphere of many crop and weed plants (Bashan and Holguin 1995). The data presented in this study extended the colonization ability of this species to three more plant species and to semiarid soils.

The mode of action of *Azospirillum* is still under debate (Bashan and Holguin 1997b). *Azospirillum* inoculation best aided crop plants under various stress conditions such as drought (Sarig et al. 1984) and low levels of nutrients, especially nitrogen (Kapulnik et al. 1981). This happened perhaps by producing an improved root system and enhancing mineral uptake (Bashan and Holguin 1997a, 1997b). These could be the possible bacterial modes of action on these three cactus species in poor soil and under sustained conditions of drought.

In summary, the potential for revegetation of eroded urban soil with large cacti appears feasible if the cacti are first inoculated with *A. brasilense*. The development of the plants is later significantly enhanced and local soil erosion is diminished.

Acknowledgements

This study is dedicated to the memory of the late Mr. Avner Bashan from Israel. We thank Ing. Manuel de Jesus Anaya Bojorquez, Francisco Rodriguez Paura, Francisco Javier Nuñez, and Sergio Mendoza Tostado from The Secretaria de Comunicaciones y Transportes, La Paz, Baja California Sur, for soil structure analysis, Mr. Ernesto Diaz and Mrs. Sonia Rocha for nitrogen analysis, Dr. Gabor Bethlenfalvay, U.S. Department of Agriculture, Agricultural Research Service Oregon, for critical reading of the manuscript, Dr. Ellis Glazier for editing the English, Ing. Angel Carrillo for assisting in graph presentation, Ing. Jaime Gonzalez-Cordova for providing the experimental site, and Mr. Edgar Yuen for providing information

services. This study was partially supported by Consejo Nacional de Ciencia y Tecnología (CONACYT), Mexico, contract 26262-B.

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