SAND STABILIZATION BY AFFORESTATION IN AL HASSA OASIS, SAUDI ARABIA

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ABSTRACT

SAND STABILIZATION BY AFFORESTATION
IN AL HASSA OASIS, SAUDI ARABIA

By

Atalla Ahmed Abohassan

Al Hassa, an important agricultural oasis in eastern Saudi Arabia, is threatened by moving sand dunes from the north. In the past the loss of cultivated land to the moving sand had averaged more than two hectares per year. In 1962, the Sand Control Project was initiated by the Ministry of Agriculture and Water in Saudi Arabia to stop the sand's progress, protect the cultivated land at the oasis and its water resources, improve climatic conditions, improve the status of the people living in the oasis, and encourage them to increase their cultivated land.

Early efforts at controlling the moving sand included mechanical and physical methods. The mechanical methods included transposing and trenching. In transposing, the sand dunes in a particularly threatened area were moved by trucks or other means to other locations. In trenching, the sand dune surface was scarred with a bulldozer to

destroy its symmetry, so that the moving sand would accumulate in the trenches. These methods did not prove feasible for large scale application.

Physical stabilization methods included covering the sand with asphalt, high gravity oil, mud, a combination of rubble and cement, mud and rubble, and concrete. Generally these methods proved to be unsatisfactory. A common problem was that each of these materials was easily broken by animals and vehicles and also cracked and fell into fragments in a short time because of high soil surface temperatures. Also, they were expensive and needed to be repeated quite often; therefore, they are not applicable for large scale stabilization.

Among agricultural methods that were tried, sowing grass was effective but slow and expensive, so it was discontinued. Afforestation, both with and without irrigation was also attempted beginning in 1963. This study was conducted at the Al Hassa Sand Control Project in eastern Saudi Arabia, to evaluate sand stabilization by afforestation methods. Initially, six species were used: Tamarix aphylla, Tamarix gallica, Acacia cyanophylla, Parkinsonia aculata, Prosopis juliflora and Eucalyptus camaldulensis. These species are drought resistant, saline tolerant, and they can withstand the wide air and soil temperature extremes that often occur.

Only three species, Tamarix aphylla, Prosopis juliflora, and Acacia cyanophylla have grown successfully.

Survival and growth of *Eucalyptus* and *Parkinsonia* have been unsatisfactory, and *Tamarix gallica* proved to be unsuitable because it is a shrub. These plantings, ranging in age from three to eleven years, now form the first sand defense line, and consist of a belt of woodland about one-fourth kilometer in width between the oasis and the sand dune field to the north.

In the plantings still being irrigated, *Tamarix aphylla* has shown the best survival. Height growth of *Acacia* was about equal to that of *Tamarix*. *Prosopis* is somewhat taller than the other two species, but both *Acacia* and *Prosopis* show far lower survival than *Tamarix*. In addition, *Tamarix* can be propagated easily by cuttings whereas the other species require seedling nurseries. In plantings which are no longer being irrigated, both survival and height growth were much lower than in the irrigated plantings.

A new method of planting long cuttings (100 to 200 cm) of *Tamarix aphylla* without irrigation was started in the spring of 1975. These plantings are to form the second sand defense line. At the time of this study, these plantings were eight months old. They were made on the windward edges of the sand dunes between palm frond fences 40 cm high erected 15 to 20 meters apart at right angles to prevailing wind.

The most important factor influencing the successful establishment of *Tamarix* cutting is sand depth. Survival ranged from 99 percent at a sand depth of 55 cm to 50 percent at a depth of 200 cm. The number of stems per hectare varied from almost 1,500 at a sand depth of 55 cm to approximately 960 at a depth of 200 cm. Average stem height varied from 2.1 m. at a sand depth of 55 cm to 0.3 m. at depth of 200 cm.

Afforestation methods of sand dune stabilization at Al Hassa oasis have been successful. Although they are more costly initially than mechanical and physical methods, they are more effective. The established tree plantings also serve as windbreaks, and their contribution to aesthetics is considerable.

The new methods of planting long *Tamarix* cuttings without irrigation show great promise of achieving successful plantation establishment on sand dunes easily and inexpensively. For this method to be successful, the *Tamarix* cuttings must be long enough and the sand depth shallow enough so that the developing root systems from the cuttings can reach the moisture available in the original soil under the sand. Planting should be done between October and April when temperatures and wind velocities are lower, and rainfall and relative humidity are higher. Perennial grasses such as American beach grass (*Ammophilla brevigulata*) and European beachgrass (*A. arenaria*) should be planted experimentally. They have been successful for sand stabilization in other parts of the world.

Atalla Ahmed Abohassan

The sand stabilization problems in Saudi Arabia are important and significant enough to justify the establishment of a Sand Stabilization Research Center at Al Hassa to serve not only the Al Hassa region, but other sand control problem areas in the country.

SAND STABILIZATION BY AFFORESTATION

IN AL HASSA OASIS, SAUDI ARABIA

By

Atalla Ahmed Abohassan

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TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Figure | Page

Figure		Page

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I. INTRODUCTION

Al Hassa Oasis is a fertile area located in the eastern part of Saudi Arabia, about 40 kilometers west of the Arabian Gulf, 100 kilometers south of Dhahran, and about 320 kilometers northeast of Riyadh, the capital city.

Al Hassa has long been an important agricultural center. It is well known for the production of dates, alfalfa, rice and other vegetable crops. It also comprises the largest irrigated area in the Arabian peninsula. The water for irrigation in the oasis originates from the Neogene aquifer in the limestone layers, reaching the surface through a number of Artesian springs. The water is highly saline, and because of traditional and primitive agricultural methods used by the farmers, the productivity of the land was poor. Added to that, the water for irrigation was re-used from one field to another through open canals. As a result, water became more and more saline, and productivity of the land became increasingly worse.

In December, 1966, the Ministry of Agriculture and Water of the government of Saudi Arabia made a contract with the Swiss consulting firm WAKUTI to develop a new irrigation and drainage system which was completed in 1971. This project will add 20,000 hectares to the present cultivated area of about 8,000 hectares, which is distributed as follow:

4,750 ha of dates trees

1,150 ha of rice

880 ha of alfalfa

1,120 ha of other crops and vegetables

Al Hassa Oasis is surrounded by moving sand on three sides. On the south, there is the empty quarter (Rub Al-Khali), which is the largest sandy area in the world (355,000 square miles). On the west, there is the Nafud Desert, which is about 265,000 square miles. On the northeast, is the Jafura Desert, which forms the most threatening sand dunes. This area is comprised of small white sand grains, resulting from tide action in the Arabian Gulf. There the action of water by freezing and thawing breaks the parent materials into small sizes which eventually are thrown onto the beaches. These are then carried by wind action to form sand dunes, often at great distances, depending on wind velocity.

Northerly winds predominate most of the year causing sand dunes to encroach and overwhelm the northeast part of the oasis. Therefore, the inhabitants of the threatened areas have been forced to move south to new areas, which are in many cases less fertile. The sand dunes rise to heights of up to 25 meters above the saline flats, and their movement has caused the loss of at least two hectares of cultivated area each year.

Because of the danger that threatens the oasis, the sand dune fixation project became necessary to save the cities, the villages and the agricultural area from burial. The Sand Control Project was started in 1962 by the Ministry of Agricultural and Water in Saudi Arabia.

The objectives of this project are:

- stop the sand's progress.
- protect the cultivated land from being lost to the desert.
- protect water resources and maintain a favorable humidity ratio.
- improve the climatic conditions.
- improve the status of the urban people and encourage them to increase their agricultural land.
- exterminate diseases and insects by drying the swamps.
- improve the soil characteristics and thereby its productivity.

Several measures have been used to stabilize the sand dunes in the oasis in the past. These have included physical, mechanical and vegetative methods. The specific purpose of this study is to investigate the afforestation methods that have been used on the area, the results that have been accomplished, and to determine the most successful and inexpensive methods of sand stabilization. From this study, it is hoped that recommendations for future stabilization projects will be developed for this area or similar areas in the country.

II. REVIEW OF LITERATURE

The best estimate as to the area of the earth covered by sand dunes is about 3,200,000,000 acres. The shifting of these sand dunes has been a problem for centuries in different parts of the world. The earliest reference to sand control was in 1316 in Germany (Whitefield and Brown, 1948). Baker (1906) found that there were early attempts to hold drifting sand in Egypt, before the Christian era, where the pharaohs built great walls along the edge of the plain on either side of the Nile Valley to prevent sand from blowing and covering fertile fields and orchards.

In southwestern France, a sand dune formed as a result of receding water in the Bay of Biscay (Greenley, 1920; Lowdermilk, 1944). These dunes were stable during the Middle Ages, but in the seventeenth and eighteenth centuries they started to move inland as a result of heavy grazing and disturbance of the vegetation. The dunes moved at a rate of 9 to 27 meters per year, burying farms and villages. Therefore, various methods of stabilization were tried to stop the invasion of the sand. The most successful method was developed by Bremontier in 1784. It was based on three steps.

1. Construction of a rampart or seawall against the incoming waves of sand. This was done by piling quantities of brush up on the last dune which was forming on the beach and building up this brush wall as fast as it filled with sand until the sand could no longer break over the top.
2. Planting herbs on the dunes until their surfaces became stable.
3. Sowing seeds or planting seedlings of Maritime pine (_Pinus maritima_), a fast growing pitch pine native to the region.

About 250,000 acres of Gascon dunes were reforested by this method. As a result, this barren area was transformed into one of the most productive regions of France.

Sale (1948) described the methods of sand stabilization used in Palestine. He reported that in early measures, _Eucalyptus camaldulensis_ had been tried, but it was unsuccessful. Then in 1936, _Acacia cyanophylla_ was planted in pots or boxes in the nursery for one year where it reached four to six feet; then it was transplanted to the sandy area. The seedlings were planted in pits three feet deep. Although this method was expensive, it proved feasible, since the cost of maintenance was reduced by using big pot plants and deep pits. In some places in Palestine, _Ammophila_ and _Artemisia_ were used for temporary stabilization for a year or two before reforestation with _Acacia_.

In Chile, the sand dunes of Llico covered almost 2,500 acres (King and Kindel, 1969). The major control of these dunes was started in 1969, but some control efforts started 50 years earlier. The system used for sand stabilization comprised two steps:

1. Construction of a fence with freshly cut *Acacia* limbs which sprouted to form a green fence. Sometimes Monterey pine (*Pinus radiata*) limbs were used, but they did not form a green fence. The fence was constructed in a line trench 12 to 18 inches deep and five to ten inches wide. Into these trenches, freshly cut limbs were placed upright to form a fence four to five feet high. The fences were built at 45° angles to the prevailing wind and were spaced 15 yards apart, so the planted areas took on the form of closed squares. Within each square about 100 to 150 trees were planted.
2. Planting trees such as Monterey pine or other woody plants, such as *Pinus pinaster*, *Pinus elliottii*, *Eucalyptus globulos*, usually combined with species of *Acacia*. Trees were spaced one meter apart. *Acacia* and other legumes were the best associated species, because they have the ability to reproduce by seeds and suckers and they fix nitrogen. Three to five years were required to stabilize the sand.

Messines (1952) found that in Tripolitania, there were two kinds of sand in the dunes. The first was red sand composed mainly of very fine quartz granules. This was blown from the interior of Africa. The other kind was sand from the seashore, composed of white rounded and more calcareous grains, less able to retain water than the continental sand. These two kinds of sand met in the coastal area and formed dunes which then moved inland.

Italian foresters worked out successful techniques for stabilizing this sand. As a result of their work, several thousand hectares of dunes have been fixed and afforested. One method used to stabilize the continental sand was a network of low, thicket hedges and dead vegetative litter. Dis (*Imperata cylindric*) was most commonly used for this purpose. Natural vegetation was then able to gain a foothold on the patches of Dis. On the other hand, for seashore sand, they used high continuous barriers to help build up artificial littorial dunes and stop their inland movement.

Another and more successful method used for stabilization by Italian foresters was the artificial sowing of grasses such as *Retm* and woody species like the Castor-oil plant (*Ricinus communis*), which stabilized the sand and allowed other plants to gain a foothold. Other woody plants used were *Acacia cyanoplylla* and *Eucalyptus gomplocephala*. These were grown in pots for one year and then planted.

In Walvis Bay on the west coast of Africa, sand dunes of the Namib Desert covered an area of approximately 28,000 square kilometers, and extended in an unbroken area 460 kilometers long and 50 to 120 kilometers wide (Le Roux, 1972). Due to the low rainfall (11 mm per year), no vegetation could be establish on this area without irrigation. Therefore, the main methods used for stabilization in that region were:

1. Erection of pole barriers perpendicular to the main wind direction. These barriers allowed 50 percent of the wind-blown sand to be deposited. To be effective these barriers had to be lifted regularly. Problems such as wind undermining, difficulty in raising the barriers if sand were deposited against them, and flimsiness, however, were encountered. Plastic barriers three to five mm thick with 25 percent permeability were very successful in controlling aeolian sand at Walvis Bay.
2. Stabilization of sand near residential and industrial areas by gravel, and oil. But, all oil-sprayed surfaces were eventually broken by the wind.

Since 1970, experiments have been conducted to determine the feasibility of irrigation with sea water and reclaimed sewage water. This showed that six Atriplex species responded with reasonable growth where they were irrigated with sea water for three years. Also, a large variety of plants irrigated with 4.5 liters of reclaimed sewage water per week grew well.

In the United States, Stoesz and Brown (1957) found that artificial barriers have been used for temporarily stabilizing sand dunes that cannot be planted effectively. These barriers include oil, clay, gravel, picket fences, brush and hay. They also found that emulsified asphalt has been used in emergencies by several state highway departments. Emulsified asphalt was cut to 25 percent asphalt and 75 percent water and applied at the rate of 0.4 gallon to the square yard. This application penetrated the sand one inch and did not crust; heavier concentrations of asphalt formed a crust. Seedings made under the lighter application germinated and grew well, but failed under the crusted heavier application. They also found that the desirable concentration of emulsified asphalt depended on climatic condition. With higher temperatures, lighter concentrations were required for penetration without crusting. A crude oil spray has also been used on shifting sands especially in arid and semiarid areas in the U.S.A. Blankets of clay four to six inches thick have been spread over unstable dunes, followed by permanent seeding of the area. This treatment was effective but very expensive. Gravel or crushed waste rock was used successfully by the Corp of Engineers on a railroad relocation near McNary Dam in Oregon and Washington.

In the southern great plains, active sand occupies isolated areas adjacent to major streams and is moving inland (Eck, Dudley, Ford and Gantt, 1968). A study has been conducted to find an economical method to provide vegetative cover for these dunes. The study included species adaptation, fertilizer and mulch. The results showed that dunes are deficient in plant nutrients even for the growth of native sand-binding grasses. Therefore, it is essential to add fertilizer, especially nitrogen. They also found that species native to the dunes are more suitable for revegetation than introduced species. They concluded that it is better to stop sand movement by a mulch such as hay anchored in sand rather than asphalt, because it holds moisture and improves conditions for plant growth, in addition to stabilizing the sand. They also noticed that asphalt mulch broke within a year and vegetation did not become established adjacent to it. Sowing seeds of sand-binding grasses and using mulch in combination with fertilizer was the most successful method for that area.

In Michigan, there are about a half-million acres of sand dunes lying in an irregular belt along the eastern coast of Lake Michigan (Lehotsky, 1941, 1972; Kroodsma, 1937). These dunes range between 20 and 150 feet in height and originated from the lake bottom. The main methods that have been used for treating these sand dunes are stabilization and reforestation. In stabilization, either live or dead beach grass serves as a semi-permeable obstacle. It is used in either regular spacing 18 inches apart to form a square, or as a network consisting of squares 6.5 feet on each side. Brush is the most used dead material. It is either laid on the ground to form a mat or cut into pickets, which are arranged into a network consisting of 13-foot squares. A network of beach grass is the most economical, pickets are the most expensive, while regularly spaced beach grass as well as the brush are intermediate in cost.

The stabilized areas have to be planted with permanent vegetation as soon as sand movement stops. Woody plants used in the second step are jack pine (*Pinus banksiana*) Scotch pine (*Pinus sylvestris*) and red pine (*Pinus resinosa*). This has been a successful method of stabilization in Michigan.

Along the Pacific, coastal dunes covered more than 55,000 acres (Hotenrichter, 1967; Kellogg 1915). Some 3,000 acres of sand was moving toward resorts, highways and farm land. The stabilization methods used included three steps:

1. Building a fore dune to reduce the large amount of sand that moved inland each year. These fore dunes were built 50 feet above the tide line with two rows of picket fence 30 feet apart. Fence pickets were four feet high, four inches wide and were placed four inches apart.
2. After one year, European beach grass (*Ammophila arenaria*) was planted between the pickets starting from the windward. American beach grass (*Ammophila brevilignlata*) and American dune grass (*Elymus mollis*) were tested, but were not as successful as European beach grass.
3. Once the sand was stabilized with beach grass, permanent vegetation, such as other grasses, legumes,

shrubs or trees were planted. Grasses such as red fescue (*Festuca rubra*), alta fescue (*Festuca elation*), and purple beach pea (*Lathyrus japonicus*) were used with 300 pounds of 16-20-0 fertilizer applied at seeding time. Shrubs such as scotch-broom and shore pine have been used, and Monterey pine has been successfully established along the Pacific coastal dunes.

McLaren (1899) found that in Golden Gate Park in California, about 700 of the 1,040 acres composing the park were originally drifting sand. The sand was stabilized by sowing barley and blue and yellow shrub lupine (*Lupinus arborex*), followed by Monterey pine. These practices were partly successful but complete success was accomplished by planting the entire area with roots of sea bent grass (*Calamagrestis arenaria*). The roots were planted three feet apart with a plow. Other species of trees have been tried such as *Tamarix*, poplar, *Acacia* and Norway maple, but Norway maple and poplar were not successful because summer winds stripped them of their leaves.

III. THE AL HASSA AREA

Location

Al Hassa Oasis is a large agricultural area in the eastern part of Saudi Arabia lying within the zone known as Area IV (Figure 1). Area IV is wholly within the northern hemisphere desert belt. This belt experiences sporadic rainfall in all areas, marginally higher along its northern and southern limits due to irregular incursions of polar air in the winter in the north, and to similar incursions of moist tropical air in the south.

The area occupied by the oasis is L-shaped and composed of two parts. The eastern part extends from the main city of Al Hofuf on its western side about 16 kilometers to the east, with an average width of 9 kilometers. The northern portion extends from the city of Al Mubarraz to about 3 kilometetets north of Al Hofuf, with a total length of 17 kilometers and an average width of 7 kilometers (Figure 2).

The total population of the Al Hassa area is about 250,000. Most of the people live in the two main cities of Al Hofuf and Al Mubarraz, but there are fifty small villages scattered through the oasis.

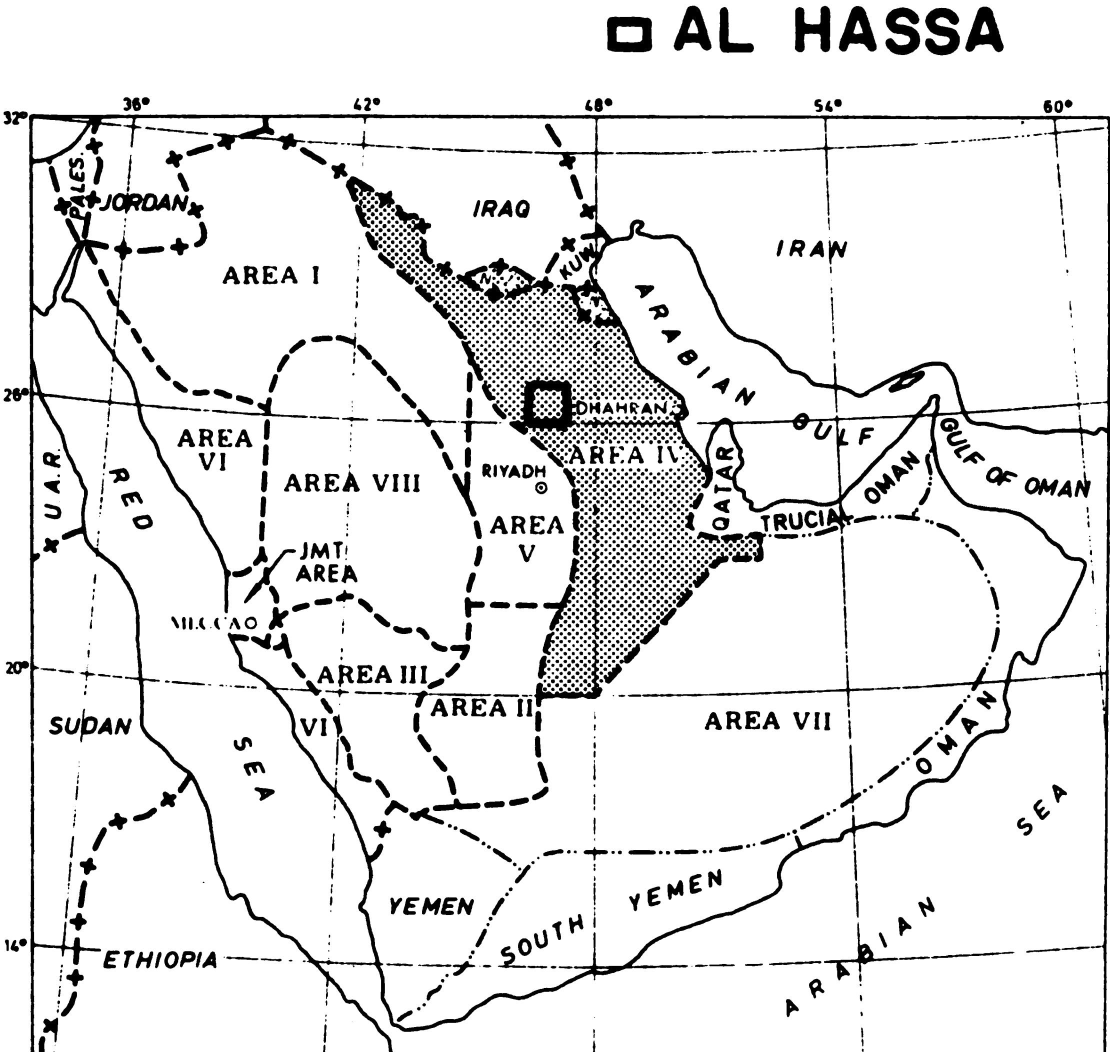

Figure I. A map of Saudi Arabia showing the location of Al Hassa oasis.

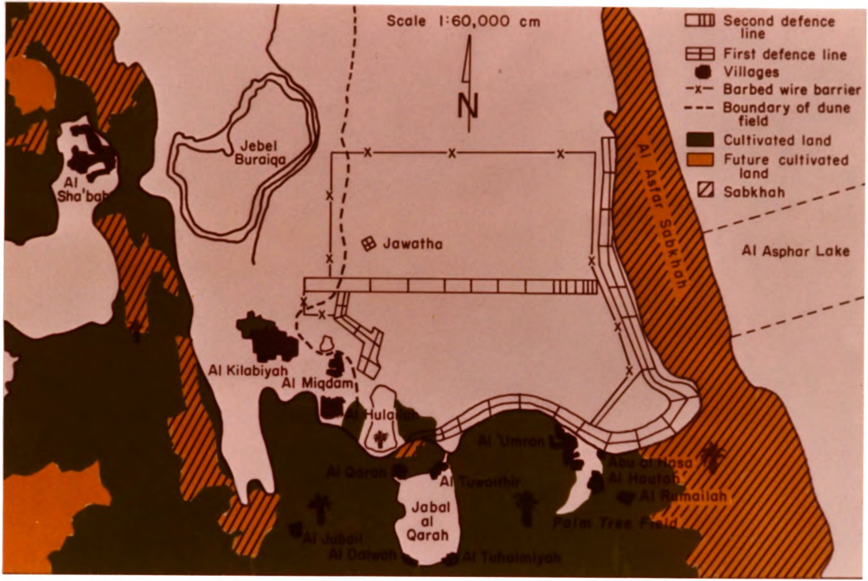

Figure 2. Al Hassa Oasis showing first and second defence sand stabilization lines.

The geological formation of the oasis is primarily the Neogene stratum, with sandy limestone, marl, schist, sandstone and conglomerate components. The Neogene stratum reaches a depth of about 180 meters, and is considered the main supplier of the artesian ground water for the oasis.

The sand dune field is situated along the northern edge of Al Hassa Oasis. It lies approximately on longitude 49° 40' East, extending to the north for many kilometers, while its southern edge is directly encroaching on the cultivated area of the oasis. To the west is Buraiqa Mountain and on the east Sabkhah Alasfor (Figure 2).

In the past, shifting sand has buried many cities in the oasis, such as Jawatha, the center of the agricultural area and the capital of the oasis at one time. Many villages, springs, and water and drainage canals have also been buried. The sand is presently advancing along a 13-kilometer front from Sabkhah Alasfor to Al Kilabiyah, encroaching upon small villages, palm trees and various gardens, and filling up drainage and irrigation ditches and canals.

The movement of the sand has been going on for centuries, slowly concentrating agricultural activities into very small areas, and causing great economic loss. It is estimated that 600 years would be required for the southern half of Al Hassa Oasis to become completely engulfed;

however, if effective sand control measures are not applied, the oasis will soon be "beyond the point of no return" (Italconsult, 1970).

The sand dune field occurs on a relatively level pavement of saline, calcareous and gypsiferous loamy soil called "Sabkhah." Some halophytic species of vegetation occur in the outcrops of Sabkhah within the dune system, and where the dune is reduced to a thin sheet, but no vegetation appears on the dunes themselves. These sand fields are moved to the south and southeast by the northerly wind called "Shamal," which blows in the summer.

Morphology of the Sand Dunes

Wind-blown sand accumulates in several distinctive ways and characteristic forms; any appreciable accumulation is loosely termed a dune. According to the definition accepted by many desert geomorphologists, a true dune is one capable of moving freely as a unit and one which can exist independently of any fixed surface fixture (ARAMCO, 1964). Therefore, sand accumulations caused directly by fixed obstructions in the path of the wind, such as clumps of bushes, projecting rocks, cliffs, and outcrops are unlike true dunes because they are dependent for their continued existence on the presence of the obstacle which caused and fixes them.

The southern front of the Al Hassa sand dune field consists mostly of interconnected cresent shaped dunes called "Barchans" (Figure 3). These dunes tend to form from a mound of sand. These typical Barchan type migrating dunes seldom exhibit a symmetrical shape. They are generally longer or wider on one limb than on the other, and their tips are unequal in size and shape. The great majority of the dunes are rounded at the tip. The sand field breaks up into single isolated "Barchan" type dunes to the west where a thin sheet of sand divides the dune zone from the rock outcrops of Kanzan Mountain and Shabah Mountain. To the east, the sand dunes change into a thick sheet of sand for a length of about 9 kilometers, bordered from north to south by Alasfor Sabkhah. The reason this strip of Sabkhah has remained free of sand is not clearly known, but it might be because the ground water drained from the oasis is collected in this area. The rise in local humidity may have engendered spontaneous, rapidly growing vegetation which, in turn, may have stabilized the shifting dunes forming a barrier that can divert the shifting sand along the border of the Alsafor Sabkhah.

Observations in the Al Hassa sand dunes (ARAMCO, 1964) showed that small crescental dunes (four and one-half to six meters in height) move at the rate of approximately 18 meters per year. The larger "Barchan" dunes (averaging 11 meters in height) move from six to nine meters per year. Also, it has been found that of the total dune movement, 75 to 85 percent occurs during the Shamal season, May through

Figure 3. The southern edge of the sand dune field, showing typical Barchan dunes.

July, when the wind blows constantly at an average velocity of 32 kilometers per hour.

Sand Movement

Wind is the main agent in moving sand dunes. Until recently no effort has been made to investigate the process of wind action upon sand as a problem of aerodynamics and thus one capable of being precisely measured. Only during recent years has the great damage caused by blowing sand led to serious studies, both theoretical and experimental, on the movement of sand by direct wind action. But experimental and field observations are particularly scarce and experimental work is not complete.

Where sand is moved by wind in deserts, three types of movement can be distinguished: surface creep, saltation[1], and suspension.

Only very fine particles, particularly those with diameters of less than 0.2 mm, are carried in suspension by winds that blow near the earth's surface. These particles vary in size from sand grains to specks of dust and tiny water droplets which constitute clouds, and may remain in suspension for indefinite periods and travel for long distances. But on encountering suitable topographic

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[1]That form of aeolian sand movement by which grains unable to remain in true suspension fall to the ground and rebound in a definite trajectory dependent on the relationship between grain mass and wind gradient (ARAMCO, 1964).

obstacles or meterological changes, these particles quickly precipitate in covering sheets or accumulation of great quantities.

The process of suspension, therefore, does not account for the greatest amount of sand movement, but rather the processes of saltation and surface creep. Bagnold's experiments (ARAMCO, 1964) in the eastern part of Saudi Arabia indicate that of the total sand moving past a given point, approximately 20 to 25 percent moves as creep with the balance moving in active saltation. Only a slight amount moves in suspension. Sand will not start moving in appreciable quantities until the wind velocity reaches about 24 kilometers per hour; this means that there is continuous sand movement during the "Shamal" or summer season in Saudi Arabia.

Climate

Al Hassa Oasis falls within Area IV, which coincides with the boundaries of eastern Saudi Arabia. The area is wholly within the winter rain zone. The climate varies from arid to desert and is affected to some extent by its proximity to the Arabian Gulf.

Precipitation

Winter rainfall in the Al Hassa area is derived from rare attenuated Mediterranean type depressions, modified particularly along the coast by the presence of the Arabian

Gulf. Rainfall distribution therefore, is directly linked to these two sets of conditions. In the extreme northwest part of Area IV, where the study area is located, rainfall is low because of a transition between extremely attenuated Mediterranean type cold fronts and localized increase in rainfall due to the presence of the Arabian Gulf. The influence of the gulf on rainfall appears to cause an increase northwards along the coast.

Average monthly precipitation at the Sand Control Project at Al Hassa over a five-year period is shown in Figure 4 and Appendix Table A. These data show that most of the precipitation occurs during the winter and spring seasons, and there is no precipitation at all in the summer months. Maximum precipitation occurs in March and April. These data differ from general information for Saudi Arabia, which shows precipitation of the more strictly winter type, with maximums in December and January. It is possible that specific data for the past five years for the study area may represent a short-term deviation. The average precipitation per year at the study area is about 70 mm. This will hardly support the growth of trees without irrigation. Ground water, however, is only about one to two meters deep, especially in the Sabkhah areas, so rainfall is not the only source of water for tree growth.

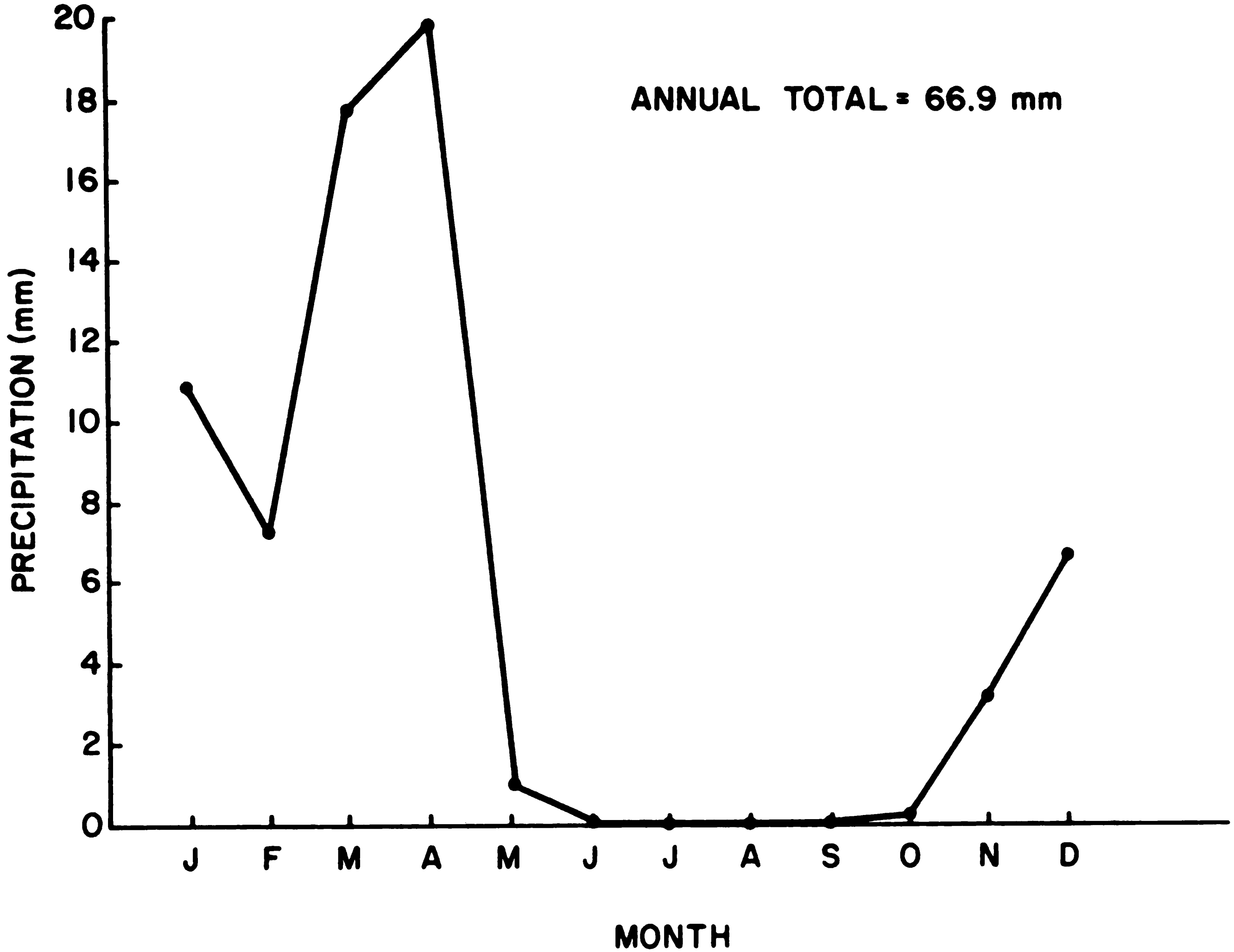

Figure 4. Average monthly precipitation at the Sand Control Project, Al Hassa, 1971-1975.

Evaporation

Throughout most of eastern Saudi Arabia, a combination of high temperature, low relative humidity and hot advective winds produce high evaporation rates. These differing climatic parameters combine in various ways to provide the energy necessary for evaporation from open water surfaces, bare soil and transpiration from vegetation.

Average evaporation data for 1970-1975 from the Sand Control Project at Al Hassa are shown in Figure 5 and Appendix Table B. The highest evaporation occurs in the summer, especially June and July when monthly evaporation is 391 and 379 mm. Then in September, evaporation starts to decrease gradually, then sharply to reach a minimum of 99 mm per month in December and January. Evaporation is a very important factor in deciding the time for cultivation and irrigation.

Air Temperature

The principal factors that affect air temperature in the region are altitude, latitude and proximity to the Arabian Gulf. In the northwest, average elevation is 400 to 500 meters and this coupled with a latitude of 28° N has the effect of reducing air temperature to a considerable degree.

The monthly averages for six years of temperature data (1970-1975) at the Sand Control Project at Al Hassa Oasis are shown in Figure 6 and Appendix Table C. The

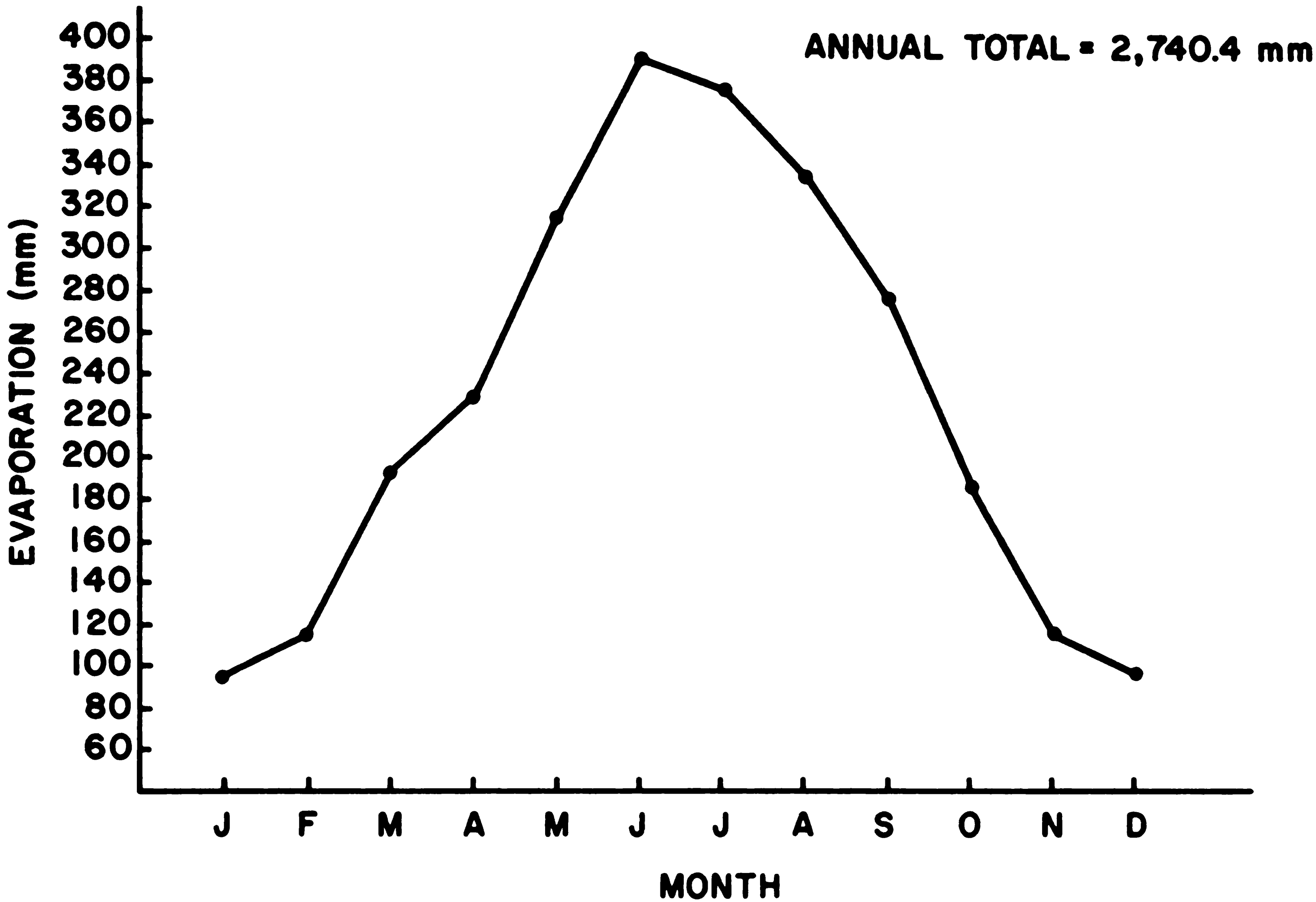

Figure 5. Average monthly evaporation at the Sand Control Project, Al Hassa, 1970-1975.

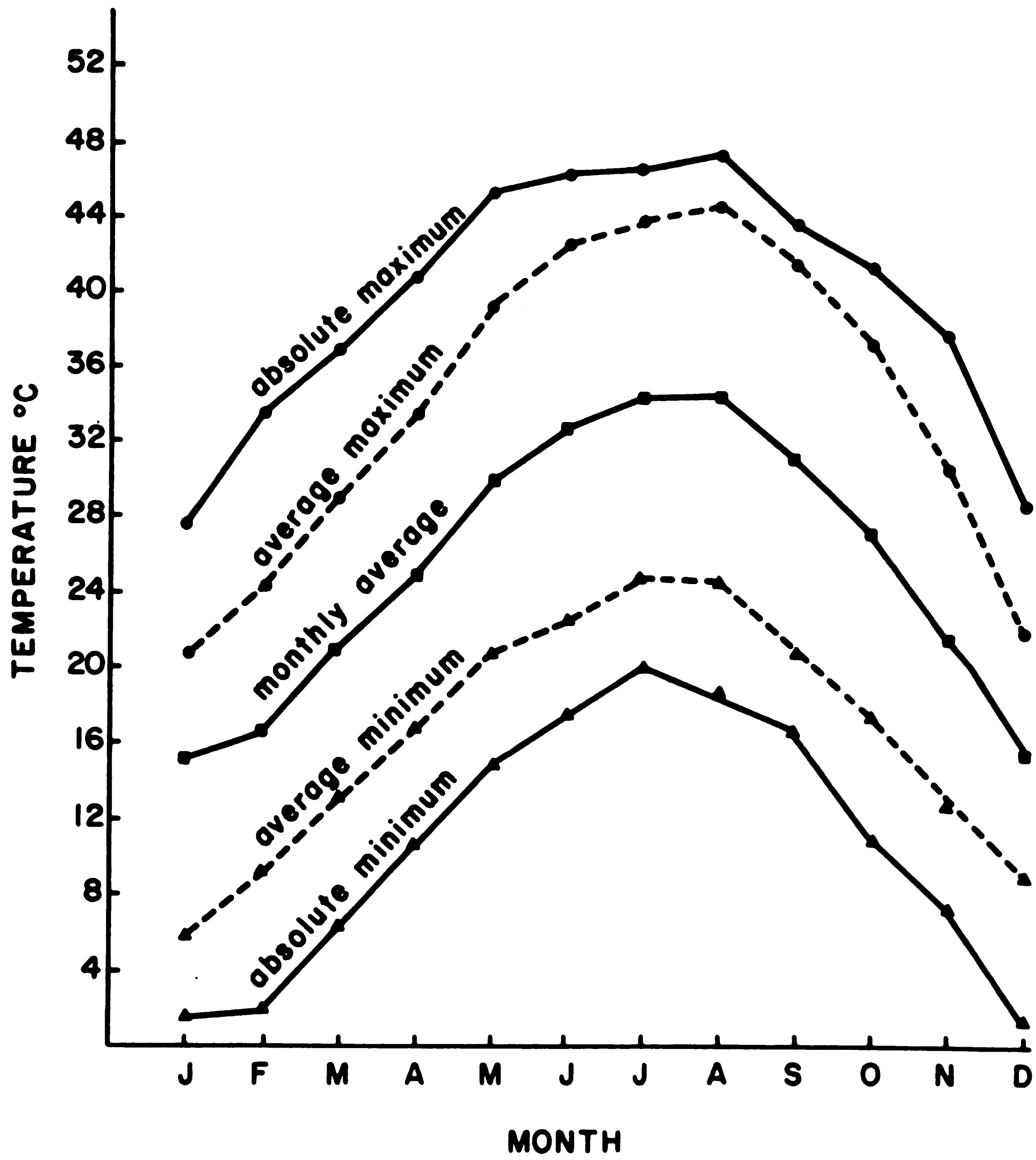

Figure 6. Average monthly air temperatures at the Sand Control Project, Al Hassa, 1970-1975.

absolute maximum, average maximum, absolute minimum, average minimum and monthly averages are included. Air temperatures remain at a low level throughout the winter months until March. Then there are relatively sharp increases through the spring and summer months. July and August are the hottest months of the year. On the other hand, December and January are the coldest months. The highest absolute maximum temperature reached was 47.3°C. in August, and the absolute minimum was 1.5°C. in December.

Relative Humidity

Annual average relative humidity data for six years have been extracted from the Sand Control Project records at Al Hassa. Absolute maximum, average maximum, absolute minimum, average minimum, and monthly averages are shown in Figure 7 and Appendix Table D. These data show that relative humidity is highest during the winter season. In December, the monthly average is 63.8 percent and in January 65.8 percent. Then it starts falling, reaching a minimum average of 32.6 percent in June.

Soil Temperature

Soil temperature is a very important factor influencing seed or planting seedling survival in sand areas, because sand usually gets very hot from the sun's rays. Plants in contact with sand may be injured, especially in the summer, unless irrigation or shade is used. Therefore,

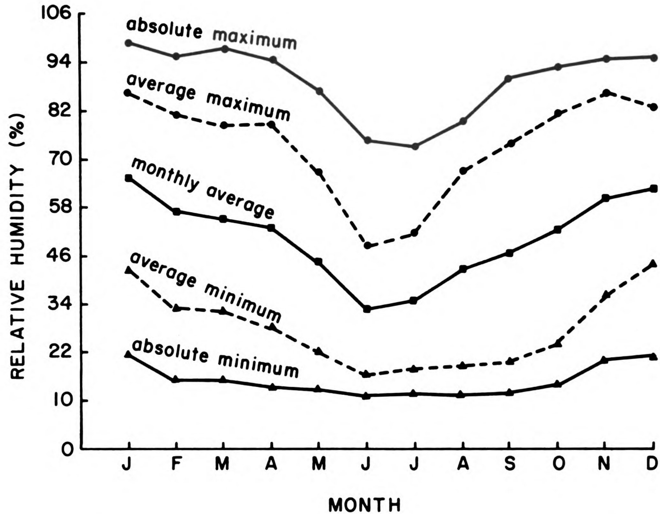

Figure 7. Average monthly relative humidity for the Sand Control Project, Al Hassa, 1970-1975.

measurements of soil temperature at depths of 30 cm, 60 cm, and 90 cm were taken at the Sand Control Project over the past six years. Monthly averages are shown in Figure 8 and Appendix Table E.

In summer, the upper 30 cm zone of the soil is warmer than at depths of 60 cm and 90 cm. In June, the difference between the 30 cm and 60 cm depths is 1.6°C., while the difference between the 30 cm and 90 cm depths is 2.1°C. In the winter, the upper 30 cm zone loses heat faster than the deeper zones which stay warmer.

Wind Velocity

The most conspicuous types of weather affecting the study area and the surrounding region are blowing dust and sand storms caused by strong northwesterly or northerly "Shamal" winds. The feature-less topography, coupled with the geographical location within the region of the winter westerlies, gives rise to wind velocities that generally exceed those found elsewhere in Saudi Arabia.

Monthly average velocities and maximum velocities for six years from data collected at the Sand Control Project are shown in Figure 9 and Appendix Table F. October and November are the calmest months of the year, with average monthly wind velocities of 2.5 kilometers per hour and 3.1 kilometers per hour. May, June, and July are the more turbulent months of the year. During the late summer, winter, and early spring months, northwesterly winds are

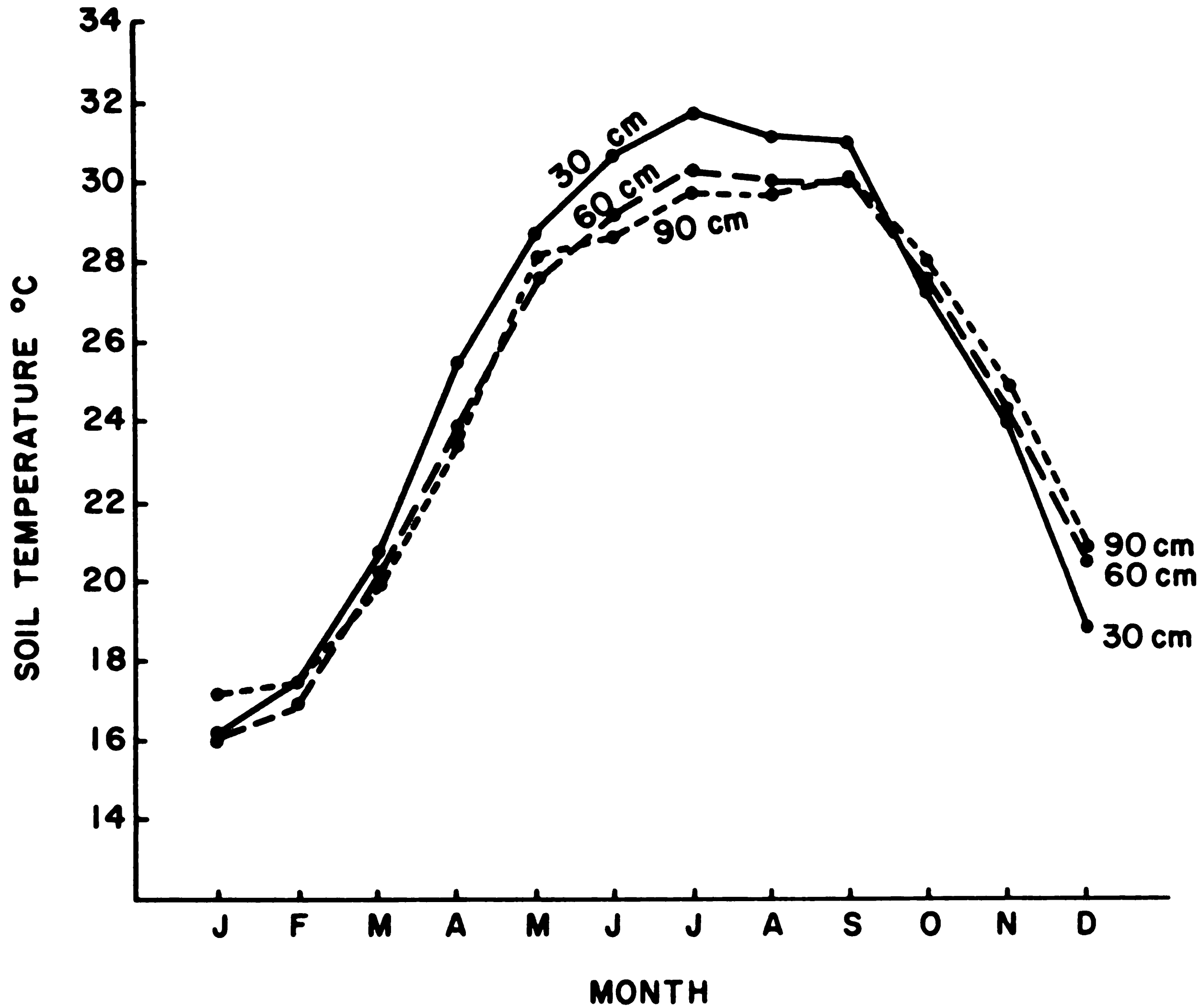

Figure 8. Average monthly soil temperature at the Sand Control Project, Al Hassa, 1970 - 1975.

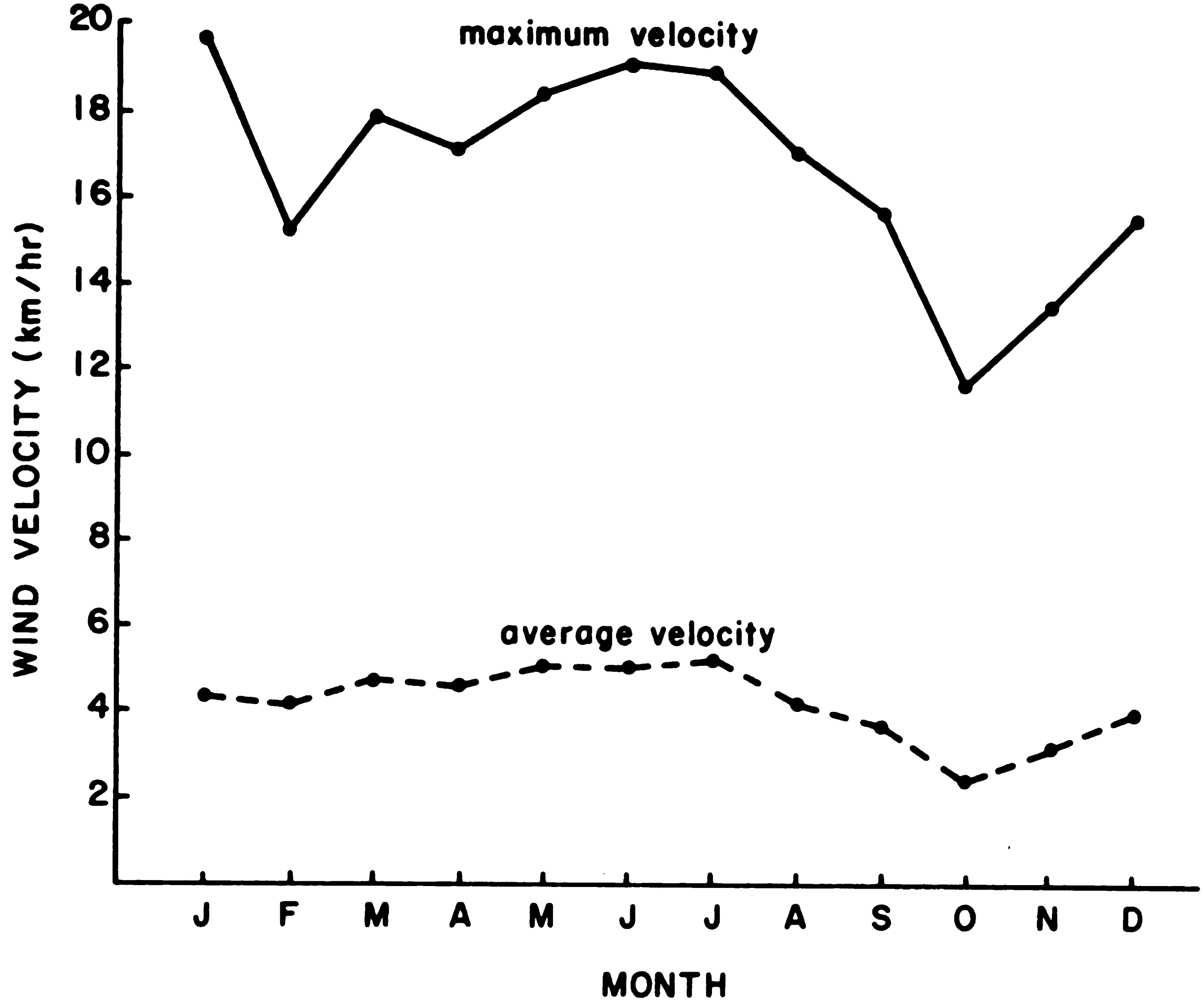

Figure 9. Average monthly wind velocity for the Sand Control Project, Al Hassa, 1970-1975.

associated with depressions or troughs moving from the north and northwest to the east and southeast. Occasional winds from a southerly direction are known as "Al Kaus" winds and these may reach speeds of up to 90 kilometers per hour just before the passage of a trough (Italconsult, 1970).

The weather station at the Sand Control Project is located in the older tree plantations. If it were located in the open, higher wind velocities would have been recorded.

Soil

The soil of Al Hassa Oasis is for the most part sandy, with small percentages of loam and clay. Soil analyses by the Leichtweiss Institute Research Team, University of Braunschweig, have shown that the average soil texture of Al Hassa Oasis consists of 79 percent sand, 11 percent silt, and 10 percent clay. Thus, the soil is classified as a sandy loam. A layer of impermeable calcium carbonate is also usually found at depths varying between 40 and 170 centimeters. Mechanical soil analysis were determined after the separation of calcium carbonate ($CaCo_3$). $CaCo_3$ concentrations at various depths were: 0-20 cm, 19 percent; 20-40 cm, 27 percent; 50-100 cm, 40 percent (Hofuf Agricultural Research Center, 1972).

The pH values of soil in Al Hassa Oasis range between 7.8 and 8.1. This is the general situation for the Al Hassa agricultural area and the southern part of the Sand Control Project.

In the sand dune area, the transferred sand dunes rest on black saline soil called "Sabkhah." This was built up by deposition of silt, clay, muddy sand and salt in shallow depressions a long time ago. Analysis of this soil showed that it contains about 80 percent sand, 11 percent silt, and 9 percent clay. Thus, this soil does not differ from the soil which is being cultivated in the Al Hassa Oasis. The aeolian sands contain only minute amounts of silt and clay, usually less than 2 percent, with over 90 percent coarse and medium sand having no structural aggregation. Mechanical analyses of the aeolian sand at the study area showed that it is composed of 41 percent fine sand, and 58.9 percent coarse and medium sand.

The predominant sand particles vary between 0.2 and 0.3 mm in diameter, and the uniformity increases upwind for all dunes in the area (Italconsult, 1970). The wilting point of the aeolian sand occurs at a moisture content of 1.7 percent by weight.

IV. METHODS OF SAND STABILIZATION

The Sand Control Project at Al Hassa was started in 1962 to stop sand movement and save the agricultural areas, cities and villages. Several methods of sand stabilization have been used, including mechanical methods, physical methods and agricultural methods.

Mechanical Methods

Transposing

In this method, sand dunes were removed from a particular threatened location to some other area. Bulldozers, carryalls, dump trucks, power shovels and hand-labor shovel crews have been used in this mechanical removal procedure. Power-driven wind-machines and windmill-driven conveyor belts have been proposed, but because of their expense and complexity they have not been used. Removal of the sand is not practical or economical, and should only be used if no other method is available. It has no place in any large scale plan for effective sand control.

Trenching

This method involves trenching of the dune surface with bulldozers both laterally and longitudinally. The streamlined symmetry of the dunes is temporarily destroyed so that excessive wastage occurs at the tips. As long as the scars are unhealed, sand will continue to accumulate on the spot. However, the dune surface is self-healing; thus, a continuous strong wind will fill up the trenches, a profile of equilibrium will eventually result, and sand accumulation will no longer be stabilized. But if the process is repeated whenever the symmetry is re-established, the dune will again undergo excessive wastage at the tips and the rate of migration will be reduced. This process can be continued until the dune is completely destroyed. This process is expensive and needs constant inspection and repetition. Both mechanical methods have proven unsuitable for large scale sand stabilization.

Physical Methods

In these methods, the sand is covered to prevent its movement, with varying degrees of success. They include asphalt stabilization; applying high gravity crude oil; covering with mud; covering with mud and rubble; covering with cement, mud and rubble; and covering with a concrete slab.

Asphalt Stabilization

As proposed by ARAMCO, low gravity asphaltic oil, such as used for roadwork, is applied as a protective sheet on top of the sand where it eventually hardens into a non-sticky surface which can be traversed by vehicles, animals or men. On the other hand, it is comparatively brittle since it is not deeply bonded and does not penetrate into the sand surface (Figure 10). The surface is easily broken by animals or vehicles, however, which exposes the dry sand beneath. The wind will then undermine the asphaltic crust at those points, and eventually the entire area will be blown out. Therefore, frequent maintenance and repair become necessary. This method may be useful in limited areas, where soiling of equipment and personnel are important factors, and if used, the asphaltic layer should be made thick with repeated applications.

High Gravity Crude Oil

This method was also used by ARAMCO in the study area to stabilize shifting sand. The use of high gravity crude oil preferably with a high wax content is less expensive and more durable than asphalt because animal and vehicle tracks in the treated surface have a tendency to heal. It is also more resistant not only to wind action, but also to the action of sand-loaded wind. However in exposed, tall, steep dune fronts, the wind can undermine the crust and cause it to slump. In this process, it breaks up into sticky fragments too heavy to be transported but which remain as residual masses and work as a stabilizing cover. Therefore, crude oil is recommended in certain areas but

Figure 10. In the background, an area stabilized with asphalt is shown, while in the foreground is an area stabilized by covering the sand with mud and rubble.

needs to be repeated every four or five years. This method has been used extensively and very successfully in stabilizing sand dunes along highways in eastern Saudi Arabia (Figure 11).

Covering the Sand With Mud

Covering the sand with a layer of up to 15 centimeters of mud has been used extensively to stabilize isolated dangerous sand dunes. But it was found that this material cracked and fell into fragments after a few years (Figure 12).

Covering the Sand With Mud and Rubble

This method was also tried in the early stages of the stabilization project at Al Hassa. Rubble and mud are mixed in a ratio of 1 to 2 and poured on the dune's surface (Figure 10). This is an inexpensive method, but these materials also cracked and fell into fragments with the high temperatures, and could not withstand strong winds. Also it was unable to stop the incoming sand.

Covering the Sand With Cement, Mud and Rubble

In this method cement, mud and rubble are mixed in a proportion 1:1:2, and poured on the sand surface. This method is very expensive and needs to be repeated every few years; therefore, it is not practical.

Figure 11. A sand dune along a major highway that has been stabilized using high gravity crude oil.

Figure 12. A sand dune which had been stabilized by a mud covering. Note the breaking of the covering mud layer into fragments.

Covering the Sand With a Concrete Slab

Cement and sand in proportions of 1 to 5 were used and poured on the sand surface. This method is again not practical, and more expensive than other physical methods. In addition, the concrete cracked and fell into fragments due to high temperatures.

All these methods tried in the early years of the project were either not permanent or needed to be repeated to be effective. Most were very expensive and have no application in stabilizing large areas.

Agricultural Methods

After trying mechanical and physical methods for sand stabilization at Al Hassa, agricultural methods were attempted to find permanent and more economical solutions. These included sowing grass and afforestration, both with and without irrigation.

Stabilization by Sowing Grass

In this method, the area to be stabilized was divided into 5-meter squares and fenced with wire and palm fronds. Then the squares were sown with quick growing grass seed such as Sudan grass, (*Sorghum sudanense*), and irrigated so that the grass would grow before the sand movement season began.

Although effective, the method was very expensive and very slow; therefore, it was abandoned in the early years of the stabilization project.

Stabilization by Afforestation With Irrigation

This method has been very successful in holding sand in place and protecting the area behind it from sand invasion. In the early years of the project, a number of nurseries were established to carry out trials to determine the suitability of different tree species for local environmental conditions, and to provide young planting stock. Species planted in the initial stages of the project included *Tamarix aphylla*, *T. gallica*, *Acacia cyanophylla*, *Parkinsonia aculata*, *Prosopis juliflora*, and *Eucalyptus camaldulensis*. All these species grew rapidly and are drought resistant and saline tolerant. They also can withstand the wide air and soil temperature extremes that often occur. The most successful has been *Tamarix aphylla* since it requires no irrigation after three to four years due to a very extensive and deep root system that taps the moisture available below the sand dune. It also has extensive adventitious roots near the surface (Figure 13) which play an important role in supporting the trees and resisting strong winds. Many tree species cannot tolerate strong winds and sand build-up. In addition *Tamarix aphylla* can be propagated successfully with cuttings from growing trees, thus eliminating the need for nurseries.

Figure 13. A large Tamarix tree showing adventitious root development. Approximately two meters of soil have been blown away from the base of this tree.

The procedure that was used for stabilization by irrigated afforestation included several steps as follows:

1. Construction of fences along the length of the area to be stabilized. The purpose of these fences is to provide initial protection for the trees, and stop the surface movement of sand grains. They also allow sand to pile up rapidly on the windward side of the fence. These fences, made locally from palm fronds which are flexible, portable, economical and easy to construct, are about six meters in height, two meters below the ground and four meters above the surface. They are sometimes damaged by high winds, however, and unless quickly repaired, severe damage to the newly planted trees can occur. Such fences to the north of Al Hassa now extend east and west for about 25 kilometers.
2. In the second step, the sand dunes behind the constructed fences are leveled by bulldozers.
3. The smoothed dunes are then covered with a layer of saline soil from "Sabkhah" to a depth of 15 to 20 centimeters. This provides initial stabilization.
4. The area is divided into 4- or 5-meter square basins.
5. The main and submain irrigation canals are constructed. These are lined with concrete to reduce water loss through the porous soils.
6. The basins are flooded, to leach out the salt.

7. The basins are planted with _Tamarix_ cuttings about 30 cm long, and other selected tree seedlings. Irrigation water is applied approximately once a week during the summer, and every other week in the winter.

The area on which this afforestation method has been applied now forms the first defence line. It consists of a belt of woodland about one-fourth kilometer in width between the agricultural area of the oasis and the aeolian sand field to the north (Figure 14). By 1974, about 645 hectares had already been afforested. To provide irrigation water, 57 artesian wells and 25 surface wells have been dug. This project was started in 1963, and up to 1974, it cost about $4.2 million.

In March 1969, the Ministry of Agriculture and Water in Saudi Arabia made an agreement with Italconsult to make a final design for a second sand advance defence line between Alasfar Lake and Kanzan Mountain to protect the northeastern part of Al Hassa. By September 1969, they submitted their report which suggested several measures that could be used. These included.

1. Planting of fast-growing species which stand up well to wind and drought, with or without irrigation, especially _Tamarix_ _aphylla_.

Figure 14. An aerial view of the sand control project on the north side of Al Hassa Oasis, as it looked in 1969. (a) is the second barrier composed of a 6-meter high palm frond fence; (b) is the first barrier composed on a 6-meter high palm frond fence and a compacted road; (c) is the belt planted to trees in 5-meter square irrigated basins. (Photo courtesy of Italconsult).

2. Spreading of bitumiuous compounds alone or after vegetation has been sown or planted, and subsequently maintaining the protective film until the seedlings have taken root.
3. Construction of barriers as windbreaks along the dune front coupled with the planting of suitable vegetation.

To date, this plan has not been implemented.

Stabilization by Afforestation Without Irrigation

The idea of planting trees without irrigation was suggested to the Ministry of Agriculture and Water in 1969 by Italconsult. The first such trial was made in October, 1972, in a chosen sand dune. Three species were tried: *Tamarix aphylla* cuttings (70-80 cm long), and seedlings of *Prosopis juliflora* and *Eucalyptus camaldulensis*. The trees were planted in east-west rows, five meters apart in the rows. One-half meter high palm frond fences were constructed every five meters running east to west, with tree rows halfway between the fences.

After three years it was found that *Tamarix aphylla* cuttings grew very successfully except near the top edge of the dune where the sand was very deep. In the lower area where sand depth is about 60 to 100 centimeters above the original soil, *Prosopis juliflora* grew quite well, and even a few *Eucalyptus* survived, but they grew much less than the other species. When *Tamarix aphylla* plants were excavated it was found that, in the good growth area, a tap root and several adventitious roots had developed (Figure 15). In the poor growth area, root development was very meager (Figure 16). It has been estimated that this method cost about $1,600 per hectare.

The planting of long Tamarix cuttings without irrigation started on a fairly large scale at the Sand Control Project at Al Hassa in 1975. Although this method is still in the early stages of its application, it appears to be very promising for the area. The method includes two steps.

The first step is to construct fences along the area to be planted. Palm fronds are cut to 60 centimeters in length, then erected at right angles to the prevailing wind. About 20 centimeters of the fence is below the ground and 40 centimeters above the surface. Fences are 15 to 20 meters apart.

The second step is to plant Tamarix aphylla cuttings. These are prepared by trained workers from the older Tamarix plantations. They are taken from branches at least two years old, and cut 100 to 120 cm long by a hand saw (Figure 17). These cuttings are immersed in water for 24 hours, and then planted immediately by hand labor. Only 10 to 15 centimeters of the cutting are left above the ground. This method depends for its success on moisture in the sand and in the original soil below the sand.

Figure 15. Root development by *Tamarix* in the good growth area (without irrigation).

Figure 16. Root development by Tamarix in the poor growth area (without irrigation).

Figure 17. Cuttings 100 to 120 cm in length are being cut from _Tamarix_ branches.

After a few days the buds start to grow. In spring plantations, the top of the cutting is usually covered with palm leaves to protect it from the sun during the summer, but this is not needed for the fall plantings.

Before this method is used, several things have to be known, such as the physical properties of the sand. Coarse sand has a tendency to move slower than fine sand. This permits wider spacing in the plantings. Sand with a higher water-holding capacity lengthens the season of planting. Also, local rainfall, wind direction, rate of sand movement, depth of sand, and depth of the water table have to be known for the plantation to succeed.

V. THE STUDY OF SAND STABILIZATION PLANTATIONS

The present study was made at the Sand Control Project at Al Hassa in the eastern part of Saudi Arabia. The study focused on the afforestation methods used for sand stabilization purposes. Therefore, the study was divided into two parts.

1. An assessment of the older irrigated plantations and their performance.
2. An evaluation of the new method of planting long *Tamarix aphylla* cuttings without irrigation.

The specific purpose of this study is to investigate the afforestation methods that have been used on the area, the results that have been accomplished, and to determine the most successful and inexpensive methods of sand stabilization.

Methods--Older Irrigated Plantations and Those No Longer Irrigated

The older plantations range in age from 3 years to 11 years. The 3-, 9-, and 11-year-old plantations included only *Tamarix aphylla*. The 5-year-old plantations included *Tamarix aphylla* and *Acacia cyanophylla*. The 6-, 7-, and 10-year-old plantations included *Tamarix aphylla* and

Prosopis juliflora. The 8-year-old plantations included Tamarix aphylla, Prosopis juliflora and Acacia cyanophylla.

Ten random plots of 0.01 hectare each were taken from each age of plantation. Because most of the species have multiple stems, the average height and diameter at breast height were measured for each stem class for each tree in the plot sample, to determine growth to the present age (Appendices G to P). Diameter measurements were made with a diameter tape. Heights were measured with a graduated pole or a Blume-Leiss altimeter for tall trees. Soil samples were taken on each plot from the 0-15 cm depth for pH and electrical conductivity determinations made at the College of Agriculture, Riyadh University. Notes were also taken on the depth of the saline soil layer, litter thickness and whether the trees in the plot were still under irrigation or not.

The data were summarized by averaging the measurement for the 10 plots of each age. Data for plots which were still being irrigated were kept separate from those on which irrigation had ceased.

Methods--New Plantations of Long Cuttings Without Irrigation

Although this method is still in the experimental stage, several areas were planted with long Tamarix aphylla cuttings in 1975 in the lee of the sand dunes where moist original soil is expected to be near the surface. At the time of the study in October-December, 1975, these plantings were eight months old.

Thirteen separate plantation areas were studied. Each area was divided into plots according to differences in height growth of the cuttings (Figure 18). In all, 38 plots were taken. The first plot in each area included the tallest cuttings, while the other plots were taken in portions of the planting with slower growth. The area of each plot was measured to compute the number of stems per hectare. The height of each stem in the plots was measured to the nearest half meter, and the number of surviving cuttings was counted to compute survival percentage. Average depth of the sand on each plot was measured in centimeters (Appendix Q). Several cuttings were dug from plots with differing growth to observe root growth and development. Soil samples were taken from the original soil below the sand layer in each location to be analyzed for pH and electrical conductivity.

The data for this part of the study were analyzed by regression analysis to determine the relationship between sand depth and survival, sand depth and number of stems per hectare, and sand depth and average height in meters.

Figure 18. A general view of the 8-month-old plantings of <u>Tamarix aphylla</u> established without irrigation, using long cuttings. Height growth decreases rapidly on the left side of the area where the sand becomes deeper.

Results and Discussion

Irrigated Older Plantings

In the older plantations established in the Sand Control Project which are still irrigated, the ages range from three to ten years. In these, only three of the six species planted have grown successfully: Tamarix aphylla, Prosopis juliflora and Acacia cyanophylla (Table 1). Two of the other species, Eucalyptus camaldulensis and Parkinsonia aculata, have failed completely, while the third species, Tamarix gallica, proved to be unsuitable because it is a shrub rather than an upright tree species.

Because the spacings used in making the various aged plantings were quite variable and not specifically recorded, actual survival percentages could not be computed. Further, not all species were planted in each location each year, so specific comparisons of survival between species cannot be made either. Also, only in the 8-year-old plantings were all three species used. However, the total number of plants of all three species per hectare in each age is indicative of relative survival (Table 1). This ranges from approximately 2,800 plants per hectare in the 3-year-old plantings of pure Tamarix, (Figure 19), to 5,900 in the 9-year-old plantings, also of pure Tamarix (Figure 20). In general, Tamarix has had the best survival.

Prosopis juliflora has made the best total height growth in the ages in which it is represented (Table 1).

Table 1.--Age, species, stems per plant and height for irrigated plantings, per hectare basis.

Age years	Species	Stems per plant													
		1		2		3		4		5		6		Total	
		No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)
3	Tamarix aphylla	458	2.3	498	3.3	1,000	2.7	433	2.8	300	2.7	100	2.5	2,789	2.8
5	Tamarix aphylla	1,458	3.5	1,005	3.2	782	3.2	470	3.0	-	-	-	-	3,720	3.3
	Acacia cyanophylla	648	3.2	-	-	-	-	-	-	-	-	-	-	648	3.2
6	Tamarix aphylla	588	3.1	371	3.6	521	3.4	350	3.7	100	2.5	100	4.0	2,030	3.4
	Prosopis juliflora	416	3.5	100	3.7	200	3.7	100	3.9	-	-	-	-	816	3.6
7	Tamarix aphylla	621	2.6	500	2.5	417	3.1	250	3.2	200	3.6	100	2.1	2,088	2.8
	Prosopis juliflora	400	4.6	500	4.1	350	3.8	200	4.2	450	4.5	200	5.1	2,100	4.3

Table 1.--Continued

Age years	Species	Stems per plant													
		1		2		3		4		5		6			
		No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)
8	Tamarix aphylla	1,628	3.7	839	3.6	540	4.3	266	3.8	300	4.0	-	-	3,573	3.8
	Prosopis juliflora	458	3.5	483	4.7	100	4.7	-	-	100	4.8	-	-	1,141	4.2
	Acacia cyanophylla	450	2.7	100	5.5	200	4.3	100	5.5	100	3.5	-	-	950	3.7
9	Tamarix aphylla	3,832	4.0	1,321	5.1	550	6.1	200	4.3	-	-	-	-	5,903	4.5
10	Tamarix aphylla	3,154	6.9	700	8.5	200	7.2	100	5.5	-	-	-	-	4,154	7.2
	Prosopis juliflora	400	9.3	100	8.0	-	-	-	-	-	-	-	-	500	9.1

Figure 19. A 3-year-old irrigated planting of <u>Tamarix aphylla</u>, with about 2,800 plants per hectare. The average height is 2.7 meters.

Figure 20. A 9-year-old irrigated planting of Tamarix aphylla with about 5,900 plants per hectare. The average height is 4.5 meters.

In the 5- and 8-year-old plantings where Acacia cyanophylla was also used, it has made height growth about equal to that of Tamarix (Figure 21). In general, average height for each species shows an increase with age, except for Tamarix in the 7-year-old plantings, and Prosopis in the 8-year-old plantings. The lesser average heights at these ages than the immediate younger ages were, however, rather small. No explanation for these discrepances could be found.

In general, the tallest stems of Tamarix and Acacia are in the 2- and 3-stem classes, with lesser heights in plants with fewer and more stems. In Prosopis, the pattern of stem class and height growth was irregular, but in the younger ages the taller plants were in the higher stem classes (Figure 22 and 23).

The number of stems per plant is of interest because it influences the stand density that will result from plantings made at a given spacing. Very few plants have six stems. For Tamarix and Acacia, approximately three-fourths of the plants have one or two stems, while in Prosopis, less than two-thirds of the plants have one or two stems. A sample of the saline soil covering the sand in each planting was tested for pH, and also for electrical conductivity, which is a measure of salinity (Table 2). The pH values ranged from 7.4 to 8.3, indicating a fairly significant alkaline condition. The electrical conductivity of the soil in solution ranged from 3.0 to 15.4 mmohos/cm. It is of

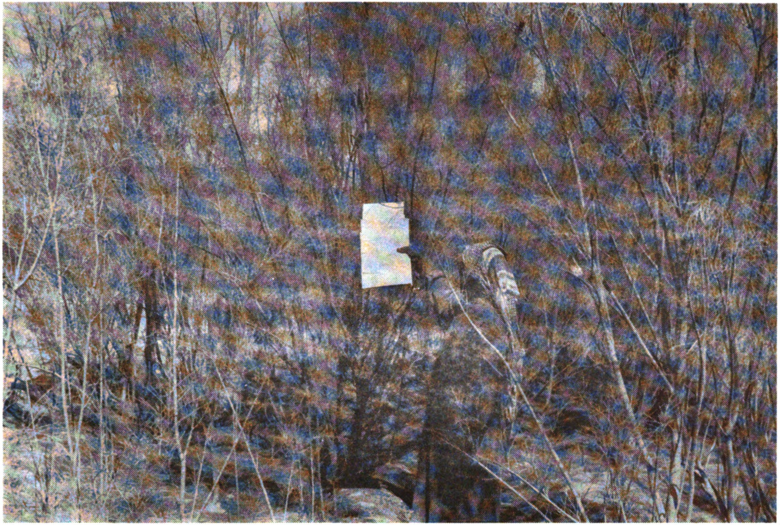

Figure 21. A 5-year-old irrigated planting of _Tamarix aphylla_ and _Acacia cyanophylla_ with about 4,300 plants per hectare. Average height of the _Tamarix_ is 3.3 meters, and of the _Acacia_ 3.2 meters.

Figure 22. A 6-year-old irrigated planting of Tamarix aphylla and Prosopis juliflora, with about 2,800 plants per hectare. The average height of the Tamarix is 3.4 meters, and of the Prosopis is 3.6 meters.

Figure 23. A 10-year-old irrigated planting of *Tamarix aphylla* and *Prosopis juliflora* with about 4,600 plants per hectare. The average height of the *Tamarix* is 7.2 meters and of the *Prosopis* is 9.1 meters.

Table 2.--Soil pH and electrical conductivity for the irrigated plantings.

Plantation age years	pH	Electrical conductivity mmohos/cm
3	7.4	8.1
5	8.3	15.4
6	7.5	9.2
7	7.5	11.4
8	7.9	3.0
9	7.9	3.9
10	7.8	5.3

interest to note that the average electrical conductivity of water used for irrigation at Al Hassa is 2.4 mmohos/cm.

No discernible relationships between survival or height growth of *Tamarix*, *Prosopis* or *Acacia* at various ages and the pH and salinity of the soil could be established. This is not surprising, since these three species are notable for being tolerant of fairly alkaline and saline soil conditions.

Older Plantings No Longer Irrigated

In some of the older plantings established in the Sand Control Project, irrigation was discontinued after the fourth year. Plantations of pure *Tamarix*, and mixtures of *Tamarix* and *Prosopis* six, seven, eight, ten, and eleven years of age were represented in this condition (Table 3).

Fairly large differences are evident in the survival and growth of both species in these plantings and those of the same ages that are still being irrigated (Table 1). In the 6-year-old plantings, the number of stems per hectare without irrigation is just over 10 percent of the number in the irrigated plantings. Also, the average height of *Tamarix* is only 1.5 meters, compared to 3.4 meters in the irrigated areas. Much smaller differences occurred with *Prosopis* at this age.

In the 7-year-old plantings, *Tamarix* showed much lower survival in the plantings no longer irrigated than in those still being irrigated, but the average height was

Table 3.--Age, species, number of stems per plant and height for plantings no longer irrigated, per hectare basis.

Age years	Species	Stems per plant: 1		2		3		4		5		6		Total	
		No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)
6	Tamarix aphylla	100	0.5	100	1.0	-	-	100	3.0	-	-	-	-	300	1.5
	Prosopis juliflora	200	2.8	-	-	-	-	100	3.5	-	-	-	-	300	3.0
7	Tamarix aphylla	300	1.5	200	3.0	300	4.2	100	5.5	-	-	-	-	900	3.2
	Prosopis juliflora	200	3.0	100	3.5	-	-	100	4.3	-	-	-	-	400	3.5
8	Tamarix aphylla	300	1.7	600	2.7	400	2.8	200	3.8	-	-	-	-	1,500	2.6
	Prosopis juliflora	500	3.7	200	4.3	200	3.0	100	3.0	-	-	-	-	1,000	3.6
10	Tamarix aphylla	1,600	4.7	-	-	200	3.8	-	-	-	-	-	-	1,800	4.8
11	Tamarix aphylla	2,780	5.7	1,438	5.4	807	5.4	100	6.0	-	-	-	-	5,125	5.6

greater in the plantings without irrigation (Figure 24). This inconsistency arises from the fact that the average height of *Tamarix* in the irrigated plantings at this age was lower than that of 6-year-old plantings as discussed earlier. *Prosopis* at seven years of age showed much lower survival and height growth than in the irrigated plantings.

At eight and ten years of age, *Tamarix* shows approximately half as many plants per hectare, and approximately two-thirds of the height growth of the irrigated plantings at the same ages. In the 8-year-old plantings, the number of *Prosopis* plants per hectare was almost the same for both irrigated and non-irrigated conditions, and the average height was only 0.6 meters less for the plantings without irrigation (Figure 25).

The 11-year-old pure *Tamarix* plantings without irrigation did not have a counterpart in the plantings still being irrigated. However, the number of plants at this age was very high (5,125 per hectare) which approaches the survival in the 9-year-old irrigated plantings (Figure 26). Since the 11-year-old plantings were the first ones established in the sand control project, it is possible that they received some care and treatment not given subsequent plantings, such as closer initial spacing, or longer irrigation than the 4-year cut-off point used later.

As in the irrigated plantings, most non-irrigated plants were in the 1- and 2-stem classes, with no 5- and

Figure 24. A 7-year-old planting no longer irrigated of Tamarix aphylla and Prosopis juliflora with about 1,300 stems per acre. The average height of the Tamarix is 3.2 meters and of the Prosopis is 3.5 meters.

Figure 25. An 8-year-old planting no longer irrigated of Tamarix aphylla and Prosopis juliflora with about 2,500 plants per acre. The average height of the Tamarix is 2.6 meters and of the Prosopis is 3.6 meters.

Figure 26. An 11-year-old planting no longer irrigated of Tamarix aphylla with about 5,100 plants per acre. The average height is 5.6 meters.

6-stem plants occurring. In general, the tallest plants were found in the 4-stems per plant class.

The same tests for pH and electrical conductivity of the saline soil covering the sand were made as those for the irrigated plantings (Table 4). The pH values ranged from 7.6 to 8.5, slightly higher than for the irrigated plantings. The electrical conductivity values ranged from 18.5 to 27.0 mmohos/cm, which are much higher than those for the irrigated plantings.

No direct relationships between survival or height growth of the three species and pH or electrical conductivity could be found within these non-irrigated plantings. However, the lower survival and growth of these plantings than in the plantings that are still irrigated is most likely a result of both a higher salinity condition, and water stress caused by the absence of irrigation since approximately age four. In agricultural soils of Al Hassa, continuing irrigation with adequate drainage has resulted in a decrease in their salinity.

The accumulation of organic matter on the soil surface is fairly low, not only because the plantings are relatively young, but also because it decomposes rapidly in that climate. In the 3-year-old plantings, the litter layer was between one-half and one cm thick, while in the 10- and 11-year-old plantings, it was up to four cm deep. There was very little litter under *Acacia* and *Prosopis* plantings.

Table 4.--Soil pH and electrical conductivity for the plantings which are no longer irrigated.

Plantation age years	pH	Electrical conductivity mmohos/cm
6	7.8	18.5
7	7.6	25.0
8	7.3	27.0
10	8.5	20.0
11	8.2	20.8

New Plantations of Long Cuttings Without Irrigation

The fairly large scale planting approach using cutting of *Tamraix aphylla* approximately 100 cm long without irrigation was begun in early 1975. These plantings are to form the second sand defence line (Figure 2, page 16). At the time of this study in October, November and December, 1975, the plantings were 8 months old. The performance of these plantings clearly demonstrates that the most important factor influencing the success or failure of long cuttings is sand depth; the thinner the sand layer, the better the plantation results (Figure 18, page 57).

Regression analysis of survival data and sand depth yielded the following equation (Figure 27):

$$Y = 118.06 - .34(X)$$

where Y = the survival percent

X = sand depth in cm.

The correlation coefficient for this relationship is 0.75.

At a sand depth of 55 cm, the average survival was 99 percent. With increasing sand depth, the survival decreased steadily, to 50 percent at a maximum depth of approximately 200 cm on which plantings were made.

Regression analysis of stem height growth and sand depth yielded the following equation (Figure 28):

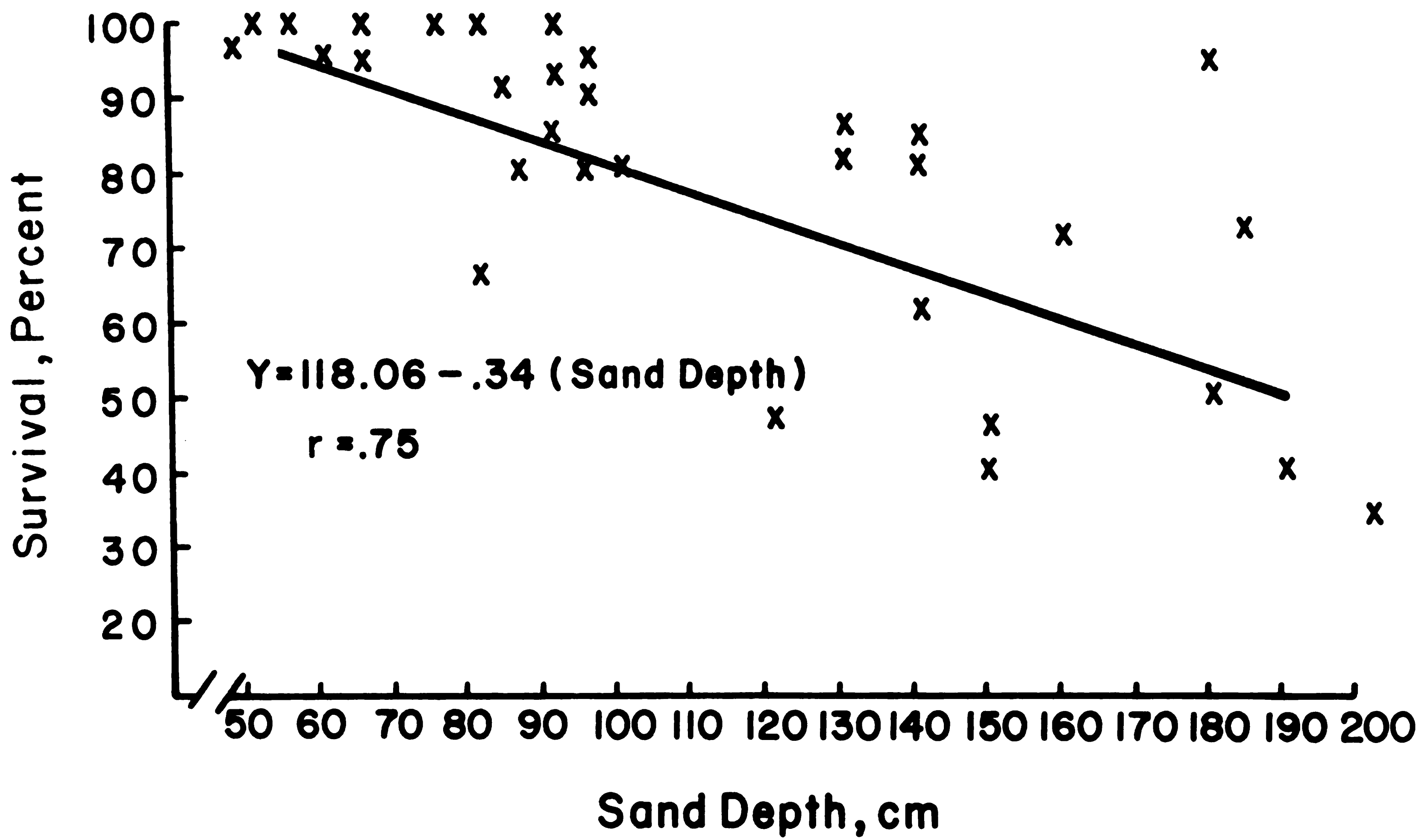

Figure 27. Survival of 8—month—old Tamarix aphylla as related to sand depth.

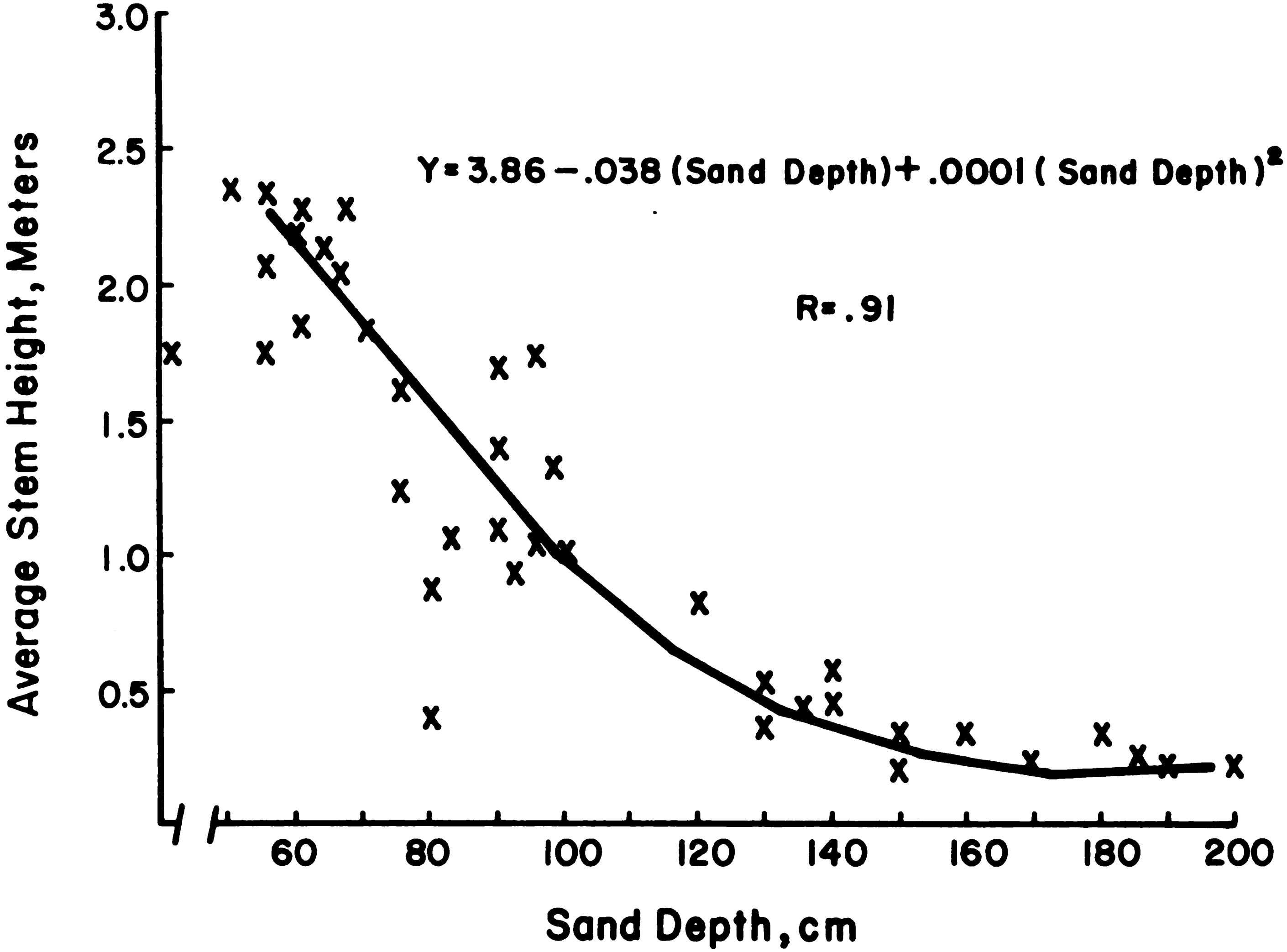

Figure 28. Average stem height of <u>Tamarix aphylla</u> as related to sand depth .

$$Y = 3.86 - .038(X) + .001(X)^2$$

where Y = average stem height in m.

X = sand depth in cm.

It is readily apparent that the influence of sand depth on stem height growth is even more significant (R = 0.91) than on survival. As sand depth increases, height growth falls off rapidly.

The regression equation for the relationship between the number of stems per hectare and sand depth is as follows (Figure 29):

$$Y = 2003.24 - 10.95(X) + .029(X)^2$$

where Y = number of stems per hectare

X = sand depth in cm.

Although there is a general reduction in the number of stem per hectare as sand depth increases, the relationship is not a strong one (R = 0.3). Each planted cutting usually produces multiple stems, but whereas the number of stems per plant is not greatly reduced with plantings in deeper sand, the growth the stems make is greatly retarded.

Several plants of *Tamarix aphylla* were excavated from various sand depths where large growth differences were evident, and the patterns of root development were examined.

It was found that in the best growth areas where the sand depth did not exceed 80 cm, the long cuttings had been inserted part way into the original soil where a fairly

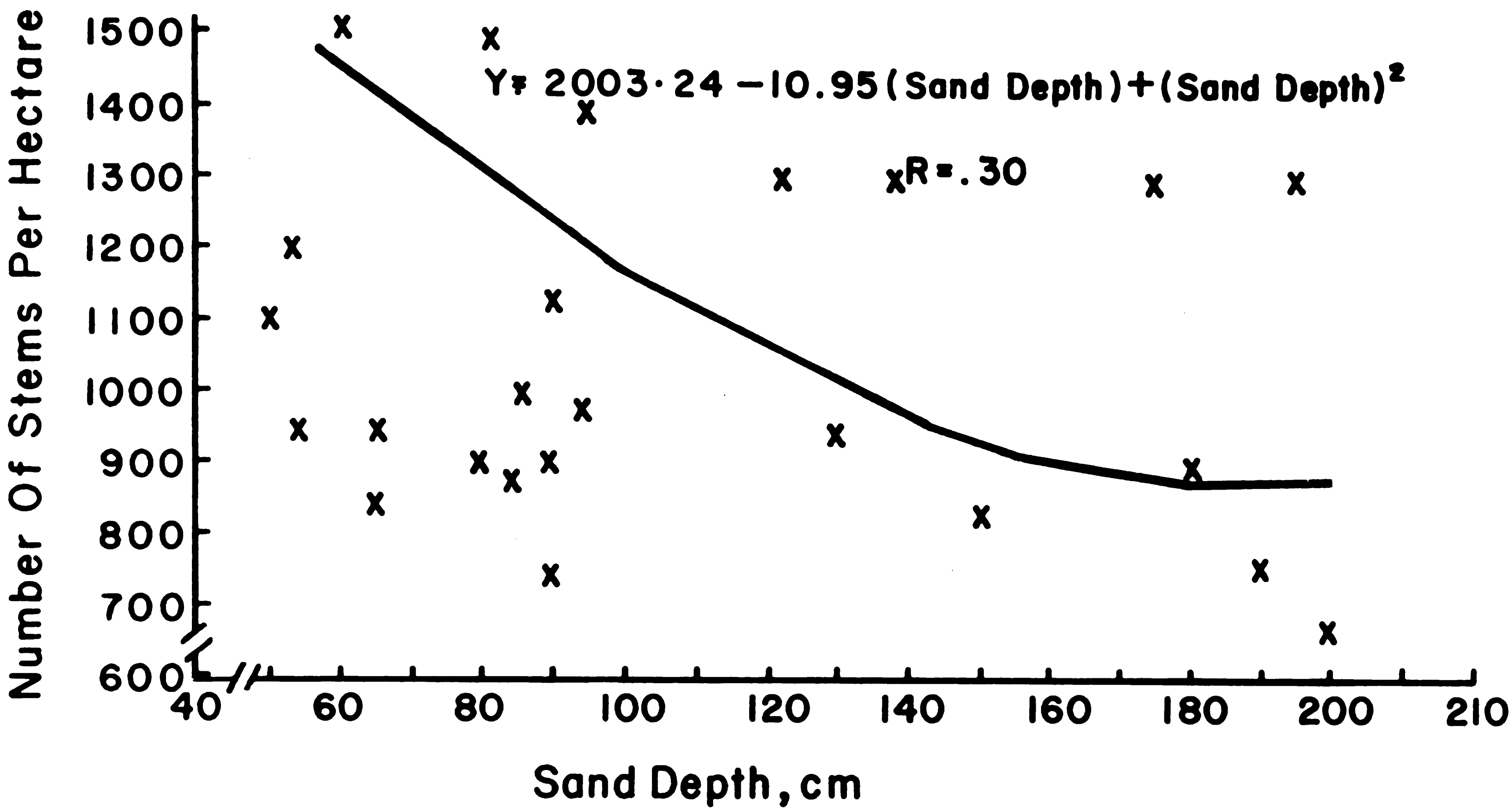

Figure 29. Number of stems of 8-month-old *Tamarix aphylla*, per hectare, as related to sand depth.

large and spreading fine root system developed (Figure 30). The original soil, although saline, contains considerable moisture, because the water table in most locations is within a few meters of the surface. Thus, the root system gets moisture from the capillary fringe above the water table. In addition to the roots that developed in the original soil, the cutting in Figure 30 shows the development of five adventitious roots from various points further up the cutting. These roots, which averaged 2.5 cm in diameter and 1.5 m in length extended through the sand layer and also reached the original soil. Height growth of the planted <u>Tamarix aphylla</u> cuttings in these good locations averaged two m at eight months of age.

In medium growth areas, the sand depth averaged 1.4 m above the original soil. In such locations, planted cuttings were not inserted into the original soil. A representative excavated plant showed a small amount of rather fine root development from the lower end of the cutting into the original soil (Figure 31). This plant had only one adventitious root about 1.5 cm in diameter and 50 cm long originating at about the middle of the cutting, which just barely reached the moist zone of the original soil. In the medium growth areas, the average height of these plants was 1.5 m at eight months of age.

In poor growth areas, where survival was low, sand depth averaged 2.5 m or more. Several excavated cuttings showed only a small numbers of fine roots scattered along

Figure 30. The strong root development of a Tamarix aphylla cutting in the good growth area with a sand depth of about 60 cm. The average stem height is about two m.

Figure 31. The moderate root development of a <u>Tamarix aphylla</u> cutting in a medium growth area, where the sand depth was about 1.5 m. The average stem height in this area was about 1.5 m.

the length of the cuttings (Figure 32). These cuttings obviously were dependent entirely on the small amount of available moisture in the sand layers, and could not reach the more abundant moisture supply at greater depths in the original soil. In such poor growth areas the average height of the living stems was about 25 cm, and their vigor was very low.

The pH of the original soil beneath the sand in these 8-month-old plantings averaged 7.8. Electrical conductivity of this soil averaged 17.8 mmohos/cm, which is much higher than in the irrigated older plantings, and lower than in the older plantings which are no longer irrigated.

In some locations with a sand depth of 2 m or more where survival and growth were very low, considerable sand had been blown away from around the planted cuttings, exposing fine roots often several meters long (Figure 33). In a few of these locations, two cuttings had been planted in one spot (Figure 33). It is doubtful that any of the cuttings in this kind of situation will be able to develop significant height growth because the sand is too deep for the roots to reach the moisture supply in the original soil, and much of the meager fine root system has been exposed by sand movement. It is highly probable that in these locations cuttings longer than 100 cm, which would more nearly reach the original soil, would grow successfully.

Because the ground water in the Neogene aquifer is the only scource for irrigation in the oasis, and there is

Figure 32. The very small root development of a _Tamarix aphylla_ cutting in the poor growth area where the sand depth exceeded 2.5 m. Here the average stem height was about 25 cm.

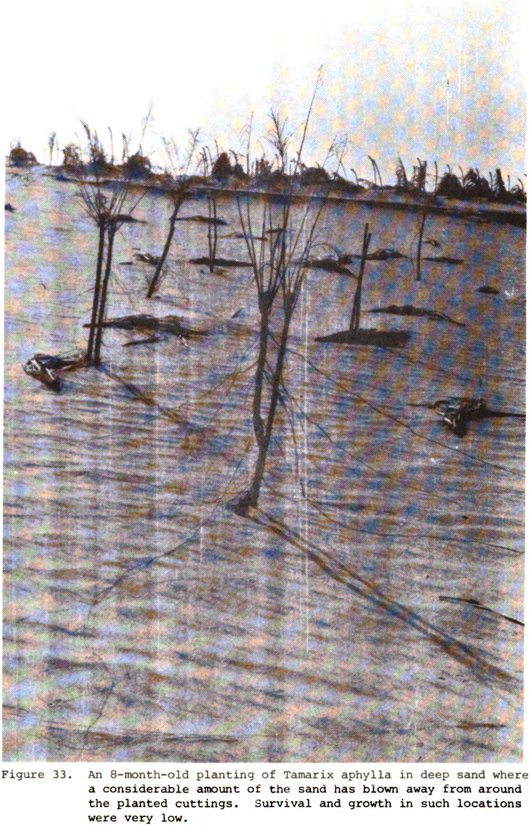

Figure 33. An 8-month-old planting of Tamarix aphylla in deep sand where a considerable amount of the sand has blown away from around the planted cuttings. Survival and growth in such locations were very low.

no significant recharge from precipitation, the water table has dropped as much as two to three meters in some locations over the past 15 to 20 years. Therefore, in the long run, the capillary fringe may drop beyond the reach of the tree root systems. At this time, there is no reliable method to estimate when such a drop in the water table might occur.

A barbed wire fence has been erected north of the second defence line to exclude camels from grazing in the area. However, breaks in the fence and sand movement which has covered the fence in some spots are permitting the camels to roam through the area (Figure 34). This is detrimental to the newly established plantings and the sparse natural vegetation, and should be eliminated.

Figure 34. A camel has entered the planted area for grazing either through a break in the barbed wire fence or over a spot where moving sand has buried the fence.

VI. SUMMARY AND CONCLUSIONS

Al Hassa Oasis, an important irrigated agricultural area in eastern Saudi Arabia, is surrounded by moving sand on the south, west and north. Northerly winds prevail most of the year, causing sand dunes to encroach upon the northeastern part of the oasis. The importance of sand control at Al Hassa had been recognized for many years, since the loss of cultivated land to the moving sand had averaged more than two hectares per year. The oasis has about 8,000 hectares presently under cultivation. A large scale new irrigation and drainage system completed in 1971 by the Swiss consulting firm WAKUTI will eventually add 20,000 hectares to the cultivated area.

In 1962, the Ministry of Agriculture and Water initiated the Sand Control Project to : (a) stop the sand's progress and protect the cultivated land of the oasis; (b) protect the water resources and improve climatic condictions by maintaining a more favorable humidity ratio; and (c) improve the status of the people living in the oasis, thus encouraging them to increase their cultivated land, and soil productivity.

Early efforts at controlling the moving sand dunes were patterned after methods used in other regions of the world. In general, these methods did not include the use of vegetation because the climate in that region of Saudi Arabia is extremely dry. Average annual precipitation totals 70 mm, with most of it occurring during March and April. Summer air temperatures and wind velocities are high, as are evaporation rates, adding to the difficult climatic conditions for vegetative growth. Early methods used primarily mechanical and physical methods in attemping to stabilize the moving sand dunes.

The mechanical methods included transposing and trenching. In transposing, the sand dunes in a particularly threatened area were removed by trucks or other means to some other location. This method did not prove to be feasible on the large scale necessary for success.

In trenching, the sand dune surface was scarred with a bulldozer to destroy its streamlined symmetry, so that the moving sand would accumulate in the trenches. This method was not feasible for large scale application because it needed constant inspection and repetition.

Physical stabilization methods included covering the sand with asphalt; high gravity crude oil; mud; mud and rubble; cement, mud and rubble; and concrete. These methods generally proved to be unsatisfactory. The asphalt covering over the sand was brittle, and easily broken by animals or vehicles, which then permitted the sand to blow again. The high gravity crude oil was more effective than the asphalt, because it is more durable, and animal and vehicle tracks in the surface tend to heal. On steep dune fronts, the oil layer was sometimes undermined by the wind, but the fragments remained as a stabilizing cover. The Arabian-American Oil Company (ARAMCO) has used the crude oil method successfully to stabilize many dunes along major highways in eastern Saudi Arabia.

In covering the sand with mud, mud and rubble, concrete, and a mixture of cement, mud and rubble, a common problem was that each of these materials usually cracked and fell into fragments in a short time because of the high soil surface temperatures. In general, they were also expensive, and needed to be repeated quite often, so they were not applicable to large areas.

After the generally unsatisfactory results with mechanical and physical sand stabilization efforts, agricultural methods were tried. These included sowing grass and afforestation, both with and without irrigation. Sudan grass (Sorghum sudanense) was sown in 5-meter squares protected with wire and palm frond fences and then irrigated. This was an effective method, but slow and expensive, so it was discontinued.

Sand stabilization efforts by afforestation with and without irrigation were begun in 1962 along the northern edge of Al Hassa Oasis. The major portion of this study consists of an evaluation of these forest tree plantings.

In the initial stages of the afforestation project, six species were used, including Tamarix aphylla, T. gallica, Acacia cyanophylla, Parkinsonia aculuta, Prosopis juliflora, and Eucalyptus camaldulensis. These are all drought resistant, saline tolerant, and can withstand the wide air and soil temperature extremes that often occur.

Establishment of these early plantings consisted of several steps. First, palm frond fences extending about four meters above the sand surface were built. Next, the sand dunes behind these fences were leveled by bulldozers and covered to a depth of 15 to 20 cm with saline soil from "Sabkhah." Basins five meters square were then constructed, concrete irrigation canals installed, and the basins planted with the various tree species. Cuttings 30 cm long were used for Tamarix aphylla and the other species were planted as seedlings. Plantings were irrigated once a week during the summer and every other week during the winter.

This afforestation project now forms the first sand defense line, and consists of a belt of woodland about one-fourth kilometer in width between the oasis and the sand dunes to the north. By 1974, 645 hectares had been planted. To provide irrigation water for these plantings, 57 artesian wells and 25 surface wells have been installed. Total costs of the project exceed $4.2 million.

In those plantings which are still being irrigated, ages ranged from three to ten years. Plantations in which irrigation had been discontinued after the fourth year ranged from six to eleven years old. Although various species mixtures were used in some of the plantings, most of them consist of *Tamarix aphylla*.

Only three species--*Tamarix aphylla*, *Prosopis juliflora*, and *Acacia cyanophylla*--have grown successfully. Survival and growth of *Eucalyptus* and *Parkinsonia* have been unsatisfactory, and *Tamarix gallica* proved to be unsuitable because of its shrub by habit.

In the plantings still being irrigated, *Tamarix aphylla* has shown the best survival, ranging from 2,800 stems per hectare in 3-year-old plantings, to 5,900 in 9-year-old plantings. Average stem height ranged from 2.7 m at age three, to 7.2 m at age ten. Height growth of *Acacia* was about equal to that of *Tamarix*, while *Prosopis* was somewhat taller than the other two species. Both *Acacia* and *Prosopis* showed far lower survival than *Tamarix*.

The plants usually developed several stems, which influneces directly the stand density resulting from a given plantation spacing. For the range of ages, two-thirds to three-fourths of the plants have one or two stems. Very few plants have six stems. The tallest plants are in the 2- and 3-stem classes.

The pH of the saline soil used for covering the sand ranged from 7.4 to 8.3, and the electrical conductivity of of the soil in solution ranged from 3.0 to 15.4 mmohos/cm.

No relationships among these soil characteristics and survival or height growth of *Tamarix*, *Prosopis* or *Acacia* were found.

In plantings ranging from six to ten years which are no longer irrigated, both survival and height growth were much lower than in the irrigated plantings. The average number of stems per hectare ranged from 300 at age six, to 1,800 at age ten. Average height ranged from 1.5 m at six, to 4.8 at age ten.

The 11-year-old plantings no longer being irrigated had no counterpart in the irrigated plantings. These plantings had 5,125 stems per hectare, with an average height of 5.6 m. Their high survival may be due to the fact that these plantings were the first ones made in the sand control project, and they may have received some treatment not given subsequent plantings, such as closer initial spacing and more than four years of irrigation.

The pH of the saline soil covering the sand in the non-irrigated plantings ranged from 7.6 to 8.5. The electrical conductivity of the soil in solution was higher than in the plantings still being irrigated, ranging from 18.5 to 27.0 mmohos/cm. These factors did not appear to influence either survival or height growth of these plantings.

Litter accumulation in irrigated and non-irrigated plantings did not differ appreciably at comparable ages. It ranged from less than one cm in depth in the youngest plantings, to four cm deep under the oldest plantings. *Acacia* and *Prosopis* plantings had less litter than *Tamarix* plantings.

A small trial planting of *Tamarix aphylla* cuttings about 80 cm long and *Prosopis juliflora* and *Eucalyptus camaldulensis* seedlings was made in a sand dune without irrigation in 1972. The *Prosopis* and *Eucalyptus* showed poor results, but the *Tamarix* grew very well where the sand was fairly shallow.

The results obtained with the long cuttings of *Tamarix* were so encouraging that in the spring of 1975, large-scale plantings of cuttings from 100 to 120 cm long were begun. These are to form the second sand defense line. At the time of this study, these plantings were eight months old. They were made between palm frond fences 40 cm high erected 15 to 20 m. apart at right angles to the prevailing winds.

Regression analysis of data from these plantings showed that the most important factor influencing establishment is the sand depth. Survival ranged from 99 percent at a depth of 55 cm, to 50 percent at a depth of 200 cm. The number of stems per hectare varied from almost 1,500 at a sand depth of 55 cm, to approximately 960 at a depth of 200 cm. Average stem height varied from 2.1 m at a sand depth of 55 cm, to 0.3 m at a depth of 200 cm. This relationship was highly significant.

Several plants were excavated from various sand depth locations showing large growth differences. Where sand depth did not exceed 80 cm, and growth results were good, the cutting had been inserted part way into the original soil ("Sabkhah") beneath the sand. A fairly large root system had subsequently developed to draw on the substantial moisture supply in the original soil. As the sand depth increased and the distance between the bottom of the cutting and the original soil increased, root development into the original soil decreased rapidly, and so did growth. The pH of the "Sabkhah" beneath the sand in these plantings averaged 7.8. Electrical conductivity averaged 17.8 mmohos/cm.

Most of the surviving plants have developed two or three stems each. The plantings are too recent to have deposited any organic material on the sand surface. Some undesirable camel grazing is continuing in the area and should be controlled.

Results of this study lead to several conclusions and recommendations:

1. Afforestation methods of sand dune stabilization along the northern edge of Al Hassa Oasis in Saudi Arabia have been successful. Although they are more costly initially than mechanical or physical methods, they are more effective. The established tree plantings also serve as windbreaks, and their contribution to aesthetics is considerable.

2. Of the six species used in the Sand Control Project--*Tamarix aphylla*, *Tamarix gallica*, *Acacia cyanophylla*, *Parkinsonia acaluta*, *Prosopis juliflora*, and *Eucalyptus camaldulensis* only three have grown successfully--*Tamarix aphylla*, *Prosopis*, and *Acacia*. However, *Tamarix aphylla* appears to be the most suitable, not only because its survival rates are much higher than the other species, but because it can be propagated easily and successfully from cuttings. The other species require seedling production in nurseries.
3. Most plants develop multiple stems, which is highly desirable in increasing stand density of the plantings. The number of stems per plant decreases with increasing age of the plantings.
4. The new method of planting long *Tamarix* cuttings without irrigation shows great promise of achieving successful plantation establishment on sand dunes easily and inexpensively. For this method to be successful, *Tamarix* cuttings must be long enough and the sand depth shallow enough so that the developing root systems from the cuttings can reach the moisture available in the original soil under the sand (Sabkhah). If the roots cannot reach the moist zone of the original soil, survival and growth will be unsatisfactory.

5. The planting of short Tamarix cuttings with irrigation should be discontinued. Additional plantings in the second sand defense line should be continued with long Tamarix cuttings. There is reason to believe that even longer cuttings, perhaps two meters long, would extend successful plantation establishment to areas where sand depths exceed two meters. Initial plantings should be made at the windward edge of the sand dune where the sand layer is the shallowest. Palm frond fences will still be needed to provide initial protection for the young trees.
6. Planting should be done between October and April when temperatures and wind velocities are lower, and rainfall and relative humidity are higher. A meteorological station in the actual sand dune area should be established to provide actual data for the sand field conditions.
7. Fertilizer should be applied experimentally to some plantings to determine its effects on tree growth.
8. Perennial grasses such as American beach grass (Ammophila brevigulata) and European beach grass (A. arenaria) should be planted experimentally.

   They have been used successfully for sand stabilization in other parts of the world.
9. The established forest tree plantations are now an indispensable asset to the Al Hassa Oasis, and should

be protected from fire, grazing and trespass cutting. They can also serve as highly desirable recreational areas for residents in the region.

10. The sand stabilization problems in Saudi Arabia are important and significant enough to justify the establishment of a Sand Stabilization Research Center at Al Hassa, comparable to the Agricultural Research Center at Al Hofuf. Research at such a Center would build upon and expand the significant achievements already attained, not only for application at Al Hassa, but for application to other sand control problem areas in the country.

VII. LITERATURE CITED

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Arnst, A. 1942. Trees against the wind. American Forests, 48:12, pp. 543-562.

Baker, H. P. 1906. The holding and reclamation of sand dunes and sand wastes. Forestry Quart. 4:12, pp. 282-288.

Brigadier, R. A., and R. A. Bagnold. 1951. Sand formations in southern Arabia. Geographical Journal, 117:3, 78-86.

Bagnold, R. A. 1973. The physics of blown sand and desert dunes. Chapman and Hall Ltd., 11 New Fetter Lane, London EC4P4EE, 265 pp.

Elkhatib, A. B. 1974. Seven Green Spikes. The Kingdom of Saudi Arabia, Ministry of Agricultural and Water, pp. 117-129.

Eck, H. V., R. F. Dudley, R. H. Ford, and C. W. Gantt. 1968. Sand dune stabilization along streams in the southern Great Plains. Journal of Soil and Water Conservation, 23:July-August, 131-134.

Greeley, W. B. 1920. The forest policy of France. The control of sand dunes and mountain torrents. American Forestry, 26:1. pp. 3-9.

Hafenrichter, A. L. 1967. Lassoing the west's rampaging dunes. U.S.D.A. Yearbook of Agri. pp. 317-321.

Hofuf Agricultural Research Centre, Saudi Arabia. 1972. Leaching requirement for soil reclamation. Publication, No. 4.

Hofuf Agricultural Research Centre, Saudi Arabia. 1973. Properties of Soil and Water in the Hofuf Agricultural Research Centre. Publication No. 6.

King, R. C., and K. K. Kindel. 1969. One step control of coastal sand dunes in Chile. Journal of Forestry, 67:11, 810-812.

Kroodsma, R. F. 1937. The permanent fixation of sand dunes in Michigan. Journal of Forestry, 35:4, 365-371.

Kellogg, F. B. 1915. Sand-dune reclamation on the coast of northern California and southern Oregon. Proceedings of the Society of American Foresters, X:pp.41-64.

Kerr, R. C., and J. O. Nigra. 1964. Analysis of aeolian sand control. ARAMCO, N.Y.

LeRoux, P. J. 1972. Drift sand reclamation at Walvis Bay, southwest Africa. Republic of South Africa, Department of Forestry, Grootfontein, S.W.A.Mimeo. Report. 15 pp.

Lowdermilk, W. C. 1944. Les Landes. American Forests, 50:8, pp. 380-382.

Labban, S. A. 1974. Agriculture in the main oases of the Eastern Provence of Saudi Arabia. ARAMCO, Dahran. pp. 9-10.

Lehotsky, K. 1941. Sand dune fixation in Michigan. Journal of Forestry, 39:12, 998-1004.

Lehotsky, K. 1972. Sand dune fixation in Michigan, thirty years later. Journal of Forestry, 70:3, 155-160.

Ministry of Agriculture and Water, Saudi Arabia. 1962. Sand dune project in Al Hassa, pp. 1-5.

Ministry of Agriculture and Water, Saudi Arabia. 1970. The sand advance defence line in Al Hassa area, Vol. 1.

Ministry of Agriculture and Water, Saudi Arabia. 1970. The sand advance defence line in Al Hassa area, Appendices to Vol. 1.

Ministry of Agriculture and Water, Saudi Arabia. 1971. Sand dunes fixation project in Al Hassa, pp. 2-7.

Messines, J. 1952. Sand dune fixation and afforestation in Libya. Unasylva, 6:pp. 50-58.

McLaren, J. 1899. The reclamation of drifting sand dunes. The Forester, 5:10, pp. 222-223.

Peters, J. R. 1943. Continental drift and ancient dunes. Science Vol. 98, p. 60.

Short, A. M. 1949. Sand control--Dahran district. Recomendation for location of sand fences. ARAMCO, Dahran, Saudi Arabia.

Short, A. M. 1950. Sand control--Dahran district. Long range program. ARAMCO, Dahran, Saudi Arabia.

Stoesz, A. D., and R. L. Brown. 1957. Stabilizing sand dunes. U.S.D.A., Yearbook of Agriculture, pp. 321-326.

Sale, G. N. 1948. Notes on sand dunes fixation in Palestine. Emp. For. Rev., 27:77. pp. 60-61.

Stevens, J. H. 1974. Stabilization of aeolian sand in Saudi Arabia's Al Hassa Oasis. Journal of Soil and Water Conservation. 29: May-June, 129-133.

Whitfield, C. J., and R. L. Brown. 1948. Grasses that fix sand dunes. U.S.D.A., Yearbook of Agriculture, pp. 70-74.

VIII. APPENDICES

Table A-1.--Monthly precipitation at the Sand Control Project, 1970-1975.

Month	Precipitation (mm)
January	10.9
February	7.2
March	17.8
April	19.9
May	1.0
June	0
July	0
August	0
September	0
October	0.2
November	3.2
December	6.7
Total	66.9

Table B-1.--Monthly evaporation at the Sand Control Project, 1970-1975.

Month	Evaporation (mm)
January	95.0
February	117.8
March	190.4
April	228.0
May	316.7
June	391.4
July	374.4
August	335.5
September	279.4
October	188.2
November	119.4
December	99.2
Total	2,740.4

Table C-1.--Monthly air temperature at the Sand Control Project, 1970-1975.

Month	Absolute maximum °C.	Average maximum °C.	Absolute minimum °C.	Average minimum °C.	Monthly average °C.
January	27.7	20.8	1.6	7.6	15.1
February	33.6	24.1	1.9	8.9	16.5
March	37.0	29.1	6.1	13.0	21.1
April	41.0	33.1	10.5	16.7	24.9
May	45.3	39.4	15.0	20.6	30.0
June	46.2	42.5	17.6	22.4	32.8
July	46.3	43.9	20.0	24.6	34.3
August	47.3	44.6	18.8	24.3	34.4
September	43.4	41.5	16.8	20.9	31.2
October	41.2	37.1	11.1	17.3	27.3
November	37.8	30.6	7.3	12.6	21.6
December	28.7	22.0	1.5	8.8	15.4

Table D-1.--Monthly relative humidity at the Sand Control Project, 1970-1975.

Month	Absolute maximum °C.	Average maximum °C.	Absolute minimum °C.	Average minimum °C.	Monthly average °C.
January	98.4	86.2	21.6	42.4	65.8
February	95.4	81.6	15.4	33.0	57.2
March	97.4	78.4	15.4	32.4	55.6
April	95.0	78.5	13.5	28.5	53.8
May	87.8	66.8	13.3	22.8	44.5
June	74.4	48.8	11.8	16.8	32.6
July	73.8	52.0	12.2	18.2	35.2
August	79.8	67.5	11.3	18.8	43.3
September	90.4	74.4	12.0	20.0	47.4
October	93.8	82.0	14.2	24.6	53.4
November	94.6	84.6	21.4	36.4	60.6
December	95.6	83.2	21.6	44.4	63.8

Table E-1.--Monthly soil temperature at the Sand Control Project at various depths (1970-1975).

Month	Soil depth		
	30 cm	60 cm °C.	90 cm
January	16.2	16.2	17.1
February	17.4	16.9	17.4
March	20.6	20.2	19.7
April	25.4	23.9	23.4
May	28.7	27.5	28.1
June	30.7	29.1	28.6
July	31.6	30.3	29.7
August	31.1	30.0	29.7
September	31.0	30.1	30.1
October	27.3	27.5	28.0
November	23.9	24.1	24.9
December	18.9	20.5	20.7

Table F-1.--Monthly wind velocity at the Sand Control Project, 1970-1975.

Month	Average velocity	Maximum velocity	Prevailing wind direction
	Kilometer/hour		
January	4.3	19.7	NW
February	4.2	15.2	NW
March	4.7	17.9	NW
April	4.6	17.1	NW
May	5.0	18.5	Varies
June	5.0	19.1	NE-NW
July	5.2	19.0	N-NW
August	4.1	17.1	NE-NW
September	3.7	15.8	Varies
October	2.5	11.6	Varies
November	3.1	13.5	Varies
December	4.0	15.5	NW

Table G-1.--Data for 3-year-old irrigated plantings, per hectare basis.

DBH class cm	Average number of stems and height for each stem class													
	1 Stem		2 Stem		3 Stem		4 Stem		5 Stem		6 Stem		Total	
	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)
							Tamarix aphylla							
0 to 2	333	1.9	230	2.9	750	2.4	333	2.6	300	2.7	100	2.5	2,046	2.5
4	125	3.3	143	3.3	150	3.3	100	3.5	-	-	-	-	518	3.3
6	-	-	125	4.2	100	4.1	-	-	-	-	-	-	225	4.2
Total	458	2.3	498	3.3	1,000	2.7	433	2.8	300	2.7	100	2.5	2,789	2.8

Table H-1.--Data for 5-year-old irrigated plantings, per hectare basis.

DBH class cm	Average number of stems and height for each stem class													
	1 Stem		2 Stem		3 Stem		4 Stem		5 Stem		6 Stem		Total	
	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)
	Tamarix aphylla													
0 to 2	520	2.5	450	2.5	457	3.0	100	3.0	-	-	-	-	1,527	2.7
4	610	3.7	455	3.2	325	3.4	220	3.0	-	-	-	-	1,610	3.4
6	228	4.6	100	4.0	-	-	150	3.2	-	-	-	-	478	4.1
8	100	4.5	-	-	-	-	-	-	-	-	-	-	100	4.5
Total	1,458	3.5	1,005	3.0	782	3.2	470	3.1					3,715	3.3
	Acacia cyanophylla													
0 to 2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	200	3.0	-	-	-	-	-	-	-	-	-	-	200	3.0
6	157	2.9	-	-	-	-	-	-	-	-	-	-	157	2.9
8	166	3.0	-	-	-	-	-	-	-	-	-	-	166	3.0
10	125	4.0	-	-	-	-	-	-	-	-	-	-	125	4.0
Total	648	3.2											648	3.2

Table I-1.--Data for 6-year-old irrigated plantings, per hectare basis.

DBH class cm	Average number of stems and height for each stem class													
	1 Stem		2 Stem		3 Stem		4 Stem		5 Stem		6 Stem		Total	
	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)
							Tamarix aphylla							
0 to 2	322	2.3	171	2.5	133	2.6	150	2.9	100	2.5	-	-	876	2.5
4	166	3.8	-	-	238	3.4	100	4.0	-	-	-	-	504	3.7
6	100	4.3	100	4.7	150	4.2	100	4.5	-	-	100	4.0	550	4.3
8	-	-	100	4.5	-	-	-	-	-	-	-	-	100	4.5
Total	588	3.1	371	3.6	521	3.4	350	3.7	100	2.5	100	4.0	2,030	3.4
							Prosopis juliflora							
0 to 2	183	3.3	100	3.7	100	3.0	100	3.9	-	-	-	-	483	3.4
4	133	3.8	-	-	-	-	-	-	-	-	-	-	133	3.8
6	100	3.5	-	-	100	4.3	-	-	-	-	-	-	200	3.9
8	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	416	3.5	100	3.7	200	3.7	100	3.9	-	-	-	-	816	3.6

Table I-2.--Data for 6-year-old plantings which were irrigated for the first 4 years, per hectare basis.

DBH class cm	Average number of stems and height for each stem class													
	1 Stem		2 Stem		3 Stem		4 Stem		5 Stem		6 Stem		Total	
	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)
Tamarix aphylla														
0 to 2	100	0.5	100	1.0	-	-	-	-	-	-	-	-	200	0.8
4	-	-	-	-	-	-	100	3.0	-	-	-	-	100	3.0
6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	100	0.5	100	1.0			100	3.0					300	1.5
Prosopis juliflora														
0 to 2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	100	2.5	-	-	-	-	-	-	-	-	-	-	100	2.5
6	-	-	-	-	-	-	100	3.5	-	-	-	-	100	3.5
8	100	3.0	-	-	-	-	-	-	-	-	-	-	100	3.0
Total	200	2.8	-	-	-	-	100	3.5	-	-	-	-	300	3.0

Table L-1.--Data for 7-year-old irrigated plantings, per hectare basis.

DBH class cm	Average number of stems and height for each stem class													
	1 Stem		2 Stem		3 Stem		4 Stem		5 Stem		6 Stem		Total	
	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)
	Tamarix aphylla													
0 to 2	471	2.0	400	2.3	267	2.6	150	3.0	100	3.4	100	2.1	1,488	2.4
4	150	4.3	100	3.3	150	4	100	3.5	100	3.8	-	-	600	3.8
Total	621	2.6	500	2.5	417	3.1	250	3.2	200	3.6	100	2.1	2,088	2.8
	Prosopis juliflora													
0 to 2	100	2.7	200	3.3	100	3	-	-	-	-	-	-	400	3.1
4	100	3.8	100	3.2	150	3.5	100	3.8	150	5.3	100	5.5	700	4.2
6	100	6.5	100	4.5	-	-	100	4.5	300	4.1	100	4.7	700	4.6
8	-	-	100	6.0	100	5.2	-	-	-	-	-	-	200	5.6
10	100	5.5	-	-	-	-	-	-	-	-	-	-	100	5.5
Total	400	4.6	500	4.1	350	3.8	200	4.2	450	4.5	200	5.1	2,100	4.3

Table L-2.--Data for 7-year-old plantings which were irrigated for the first 4 years, per hectare basis.

DBH class cm	Average number of stems and height for each stem class													
	1 Stem		2 Stem		3 Stem		4 Stem		5 Stem		6 Stem		Total	
	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)
							Tamarix aphylla							
0 to 2	200	1.5	200	3	100	3.5	-	-	-	-	-	-	500	2.5
4	100	1.5	-	-	100	3.5	100	5.5	-	-	-	-	300	3.5
6	-	-	-	-	100	5.5	-	-	-	-	-	-	100	5.5
Total	300	1.5	200	3.0	300	4.2	100	5.5	-	-	-	-	900	3.2
							Prosopis juliflora							
0 to 2	100	2	-	-	-	-	-	-	-	-	-	-	100	2
4	-	-	100	3.5	-	-	100	4.3	-	-	-	-	200	3.9
6	100	4	-	-	-	-	-	-	-	-	-	-	100	4
Total	200	3.0	100	3.5	-	-	100	4.3	-	-	-	-	400	3.5

Table M-1.--Data for 8-year-old irrigated plantings, per hectare basis.

DBH class cm	Average number of stems and height for each stem class													
	1 Stem		2 Stem		3 Stem		4 Stem		5 Stem		6 Stem		Total	
	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)
							Tamarix aphylla							
0 to 2	1,022	3.5	500	3.0	212	3.5	166	3.0	100	3.9	-	-	2,000	3.4
4	356	3.5	214	4.3	228	4.6	100	5.0	100	4.5	-	-	998	4.2
6	100	4.6	125	5.0	100	5.5	-	-	100	3.5	-	-	425	4.7
8	150	5.0	-	-	-	-	-	-	-	-	-	-	150	5.0
Total	1.628	3.7	839	3.6	540	4.3	266	3.8	300	4.0	-	-	3,573	3.8
							Prosopis juliflora							
0 to 2	233	2.4	150	2.5	-	-	-	-	-	-	-	-	383	2.4
4	100	4.5	133	5.1	-	-	-	-	-	-	-	-	233	4.8
6	125	4.8	100	5.9	100	4.7	100	4.7	-	-	100	4.8	425	5.0
8	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	-	-	100	6.2	-	-	-	-	-	-	-	-	100	6.2
Total	458	3.5			100	4.7	100	4.7			100	4.8	1,141	4.2

Table M-1.--Continued

DBH class cm	Average number of stems and height for each stem class													
	1 Stem		2 Stem		3 Stem		4 Stem		5 Stem		6 Stem		Total	
	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)
							Acacia cyanophylla							
0 to 2	150	2.0	-	-	-	-	-	-	-	-	-	-	150	2.0
4	100	4.0	-	-	100	3.8	-	-	-	-	-	-	200	3.9
6	-	-	100	5.5	100	4.8	100	5.5	100	3.5	-	-	400	4.8
8	200	2.5	-	-	-	-	-	-	-	-	-	-	200	2.5
Total	450	2.7	100	5.5	200	4.3	100	5.5	100	3.5	-	-	950	3.7

Table M-2.--Data for 8-year-old plantings which were irrigated for the first 4 years, per hectare basis.

DBH class cm	Average number of stems and height for each stem class													
	1 Stem		2 Stem		3 Stem		4 Stem		5 Stem		6 Stem		Total	
	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)
							Tamarix aphylla							
0 to 2	300	1.7	500	2.5	300	2.5	200	3.8	-	-	-	-	1,300	2.5
4	-	-	100	3.5	100	3.5	-	-	-	-	-	-	200	3.5
6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	300	1.7	600	2.7	400	2.8	200	3.8					1,500	2.6
							Prosopis juliflora							
0 to 2	200	3	100	3.5	200	3.0	100	3.0	-	-	-	-	600	3.1
4	200	4	100	5.0	-	-	-	-	-	-	-	-	300	4.3
6	100	4.5	-	-	-	-	-	-	-	-	-	-	100	4.5
Total	500	3.7	200	4.3	200	3.0	100	3.0					1,000	3.6

Table N-1.--Data for 9-year-old irrigated plantings, per hectare basis.

DBH class cm	Average number of stems and height for each stem class													
	1 Stem		2 Stem		3 Stem		4 Stem		5 Stem		6 Stem		Total	
	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)
							Tamarix aphylla							
0 to 2	2,400	2.8	488	3.2	100	3.8	100	4.5	-	-	-	-	3,088	3.0
4	610	4.7	300	4.7	133	4.8	100	4.0	-	-	-	-	1,143	4.7
6	367	5.9	183	5.9	117	6.0	-	-	-	-	-	-	667	5.9
8	155	6.9	150	7.3	100	7.2	-	-	-	-	-	-	405	7.1
10	100	7.7	100	7.8	100	9.3	-	-	-	-	-	-	300	8.3
12	100	7.5	100	8.0	-	-	-	-	-	-	-	-	200	7.8
14	100	8.5	-	-	-	-	-	-	-	-	-	-	100	8.5
Total	3,832	4.0	1,321	5.1	550	6.1	200	4.3	-	-	-	-	5,903	4.5

Table O-1.--Data for 10-year-old irrigated plantings, per hectare basis.

DBH class cm	Average number of stems and height for each stem class													
	1 Stem		2 Stem		3 Stem		4 Stem		5 Stem		6 Stem		Total	
	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)
							Tamarix aphylla							
0 to 2	650	3.4	-	-	-	-	-	-	-	-	-	-	650	3.4
4	650	4.6	100	4.0	-	-	-	-	-	-	-	-	750	4.5
6	500	5.7	100	5.8	100	6.9	100	5.5	-	-	-	-	800	5.8
8	350	7.7	100	6.7	100	7.5	-	-	-	-	-	-	550	7.5
10	300	9.0	100	9.3	-	-	-	-	-	-	-	-	400	9.1
12	171	10.0	100	10.5	-	-	-	-	-	-	-	-	271	10.2
14	200	12	100	10.0	-	-	-	-	-	-	-	-	300	11.3
16	133	13.5	-	-	-	-	-	-	-	-	-	-	133	13.5
18	100	13.0	100	13.0	-	-	-	-	-	-	-	-	200	13
20	-	-	-	-	-	-	-	-	-	-	-	-	-	-
22	100	12	-	-	-	-	-	-	-	-	-	-	100	12
Total	3,154	6.9	700	8.5	200	7.2	100	5.5					4,154	7.2

Table O-1.--Continued

DBH class cm	Average number of stems and height for each stem class													
	1 Stem		2 Stem		3 Stem		4 Stem		5 Stem		6 Stem		Total	
	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)
	Prosopis juliflora													
0 to 2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	100	8.2	100	8.0	-	-	-	-	-	-	-	-	200	8.1
10	100	8.0	-	-	-	-	-	-	-	-	-	-	100	8.0
12	100	10.0	-	-	-	-	-	-	-	-	-	-	100	10.0
14	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	-	-	-	-	-	-	-	-	-	-	-	-	-	-
18	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20	100	11.0	-	-	-	-	-	-	-	-	-	-	100	11.0
Total	400	9.3	100	8.0									500	9.1

Table O-2.--Data for 10-year-old plantings which were irrigated for the first 4 years, per hectare basis.

DBH class cm	Average number of stems and height for each stem class													
	1 Stem		2 Stem		3 Stem		4 Stem		5 Stem		6 Stem		Total	
	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)
							Tamarix aphylla							
0 to 2	600	3.1	-	-	-	-	-	-	-	-	-	-	600	3.1
4	300	4.0	-	-	200	5.8	-	-	-	-	-	-	500	4.7
6	400	5.3	-	-	-	-	-	-	-	-	-	-	400	5.3
8	200	6.4	-	-	-	-	-	-	-	-	-	-	200	6.4
10	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	100	10.0	-	-	-	-	-	-	-	-	-	-	100	10.0
Total	1,600	4.7	-	-	200	5.8	-	-	-	-	-	-	1,800	4.8

Table P-1.--Data for 11-year-old plantings which were irrigated for the first 4 years, per hectare basis.

DBH class cm	Average number of stems and height for each stem class													
	1 Stem		2 Stem		3 Stem		4 Stem		5 Stem		6 Stem		Total	
	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)	No. stem	Avg. ht. (m)
							Tamarix aphylla							
0 to 2	320	2.8	222	2.9	200	3.2	-	-	-	-	-	-	742	2.9
4	590	3.7	260	4.0	150	4.8	-	-	-	-	-	-	1,000	3.9
6	660	5.3	456	5.5	217	6.6	100	6.0	-	-	-	-	1,433	5.5
8	730	6.6	300	6.6	140	7.1	-	-	-	-	-	-	1,170	6.7
10	180	7.3	100	8.0	100	7.5	-	-	-	-	-	-	380	7.5
12	100	10.3	100	7.5	-	-	-	-	-	-	-	-	200	8.9
14	100	10.5	-	-	-	-	-	-	-	-	-	-	100	10.5
16	-	-	-	-	-	-	-	-	-	-	-	-	-	-
18	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20	-	-	-	-	-	-	-	-	-	-	-	-	-	-
22	100	10.5	-	-	-	-	-	-	-	-	-	-	100	10.5
Total	2,780	5.7	1,438	5.4	807	5.4	100	6.0					5,125	5.6

Table Q-1.--Individual plot data for plantations of 8-month-old cuttings of _Tamarix aphylla_ without irrigation.

Area and plot	Percent survival	Average no. stems per hectare	Average height m	Average depth of sand cm
1-1	95.2	826	2.0	65
1-2	62.8	558	0.9	80
1-3	48.6	372	0.8	120
1-4	38.9	289	0.7	150
2-1	100.0	750	1.7	40
2-2	100.0	779	1.1	90
2-3	44.4	853	0.6	150
3-1	100.0	1,093	2.4	50
3-2	83.3	1,151	1.7	90
3-3	72.7	606	0.4	160
4-1	100.0	980	2.3	55
4-2	52.0	442	0.4	180
5-1	100.0	1,500	2.4	60
5-2	80.0	1,000	1.8	85
5-3	61.5	571	0.5	140
6-1	100.0	2,000	2.2	57
6-2	100.0	903	1.1	80
6-3	88.2	926	0.4	130
7-1	100.0	1,583	1.7	75
7-2	95.2	893	0.4	180
8-1	100.0	923	2.3	65
8-2	93.0	903	1.4	90
8-3	85.7	1,319	0.5	140
9-1	100.0	2,143	2.1	55
9-2	90.5	880	1.1	83
9-3	73.7	2,500	0.5	185
10-1	100.0	2,857	1.8	60
10-2	90.9	2,273	1.0	95
10-3	84.0	2,000	0.6	140
11-1	100.0	1,750	2.1	64
11-2	94.7	1,818	1.4	95
11-3	90.5	1,727	0.5	130

Table Q-1.--Continued

Area and plot	Percent survival	Average no. stems per hectare	Average height m	Average depth of sand cm
12-1	100.0	2,143	1.7	55
12-2	84.2	1,616	0.7	100
12-3	33.3	667	0.3	200
13-1	100.0	1,728	2.1	62
13-2	80.0	992	0.8	93
13-3	41.2	769	0.3	190