AGENCY FOR INTERNATIONAL DEVELOPMENT
WASHINGTON, D. C. 20523

BIBLIOGRAPHIC INPUT SHEET

FOR AID USE ONLY
BATCH #16

1. SUBJECT CLASSIFICATION

A. PRIMARY
Agriculture

AF40-0000-0000

B. SECONDARY
Plant ecology

2. TITLE AND SUBTITLE
Desert encroachment on arable lands: significance,causes,and control

3. AUTHOR(S)
(101) AID/TA/OST

4. DOCUMENT DATE	5. NUMBER OF PAGES	6. ARC NUMBER
1972	61p.	ARC 333.73.A265

7. REFERENCE ORGANIZATION NAME AND ADDRESS
AID/TA/OST

8. SUPPLEMENTARY NOTES *(Sponsoring Organization, Publishers, Availability)*
(In TA/OST 72-10)

9. ABSTRACT

10. CONTROL NUMBER
PN-RAA- 832

11. PRICE OF DOCUMENT

12. DESCRIPTORS
Bioclimatology
Deserts
Ecological succession

13. PROJECT NUMBER

14. CONTRACT NUMBER
AID/TA/OST

15. TYPE OF DOCUMENT

AID 590-1 (4-74)

333.73
A265

TA/OST 72-10

DESERT ENCROACHMENT ON ARABLE LANDS: SIGNIFICANCE, CAUSES, AND CONTROL

A.I.D.
Reference Center
Room 1656 NS

Office of Science and Technology
Agency for International Development
Washington, D.C.

AUGUST 1972

TA/OST/72-10

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PREFACE

Man's attempt to settle in semi-arid regions of the world has often been hindered or thwarted by the seemingly relentless progression of adjacent deserts. Either because of climatic fluctuations or man's intervention in the fragile, delicately-balanced ecological zones bordering desert areas, or due to a complex interaction of these two factors, marginal but potentially productive land has been absorbed into the encroaching desert with attendant economic and social losses. While this situation has been experienced as long as man has inhabitated these regions, the magnitude of the problem is rapidly intensifying and its impact becoming more acute as population growth, and a shift from nomadism to a more sedentary existence, create pressure for the development of the semi-arid border lands.

During the past year, the problem of desert encroachment 1/ has been described as a significant economic problem by representatives of a number of developing countries at various international meetings, and also during direct meetings with Agency for International Development (AID) personnel. At a UN Seminar on Environment and Development in Addis Ababa, August 1971, representatives from Niger, Senegal, the UAR, and Morocco all identified this as a serious problem confronting the development of their nations. The Seminar recommended, "that the process of desert expansion in Africa be closely studied, taking into account the biological and human factors, with a view to evolving precise measures concerning control of desert creeping." National reports prepared by Niger, Libya, Saudi Arabi and the UAR for the UN Conference on the Human Environment held in Stockholm, Sweden, in June alluded to the desert encroachment problem, and the Conference itself formally endorsed a series of action proposals in the natural resources area which included proposals designed to address "increasing problems throughout the world which

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1/ For purposes of this report, "desert encroachment" will refer to the process by which arable land is laid waste either through the overriding and burial by mechanically driven desert sands, or through an expanding aridity induced by climatic changes which result in loss of soil moisture. "Desertification," a French word, appears in several of the referenced documents as a synonymous term; likewise, both "desertization" and "desert progression" are used interchangeably with desert encroachment. "Dune progression" refers to the wind-driven advance of sand dunes.

substantially impair agricultural productivity and development .... including regional modifications of climate through removal of forests and tree hedges, causing, *inter-alia*, desertification in sub-arid areas." Another recent acknowledgement of this problem came from the AID mission in Tunisia which, in responding to a request for a description of priority environmental problems in that country, cited the loss of arable land due to the "northward march of the Sahara." At the 56th session of the FAO Council in Rome this February, Algeria, Upper Volta, Chad and the Sudan requested help to stop the advance of the Sahara Desert which is causing an "alarming situation." The Algerian delegate asked the UN body to "put the problem of reforestation of arid zones at the top of its priorities." This appeal was supported by the representative from Saudi Arabia who expressed concern over the loss of grazing areas and future prospects of additional displaced populations. The Government Director of Water and Forestry Resources, Republic of Chad, spoke to this same assembly of an "emergency situation." "Our country," he said, "is already half desert, and our arable lands left are extremely reduced. But even these are now threatened by the inexorable advance of the desert sands from the north." Afforestation of Chad, he said, would also protect neighboring countries which would face a future threat should the invading desert fail to be stopped. A similar warning was issued by the Sudan.

In response to growing interest both within developing countries and development assistance agencies in preventing and controlling desert encroachment -- manifested both in the frequency of problem identification and by numerous requests for relevant information -- the AID Office of Science and Technology has prepared this overview report on the causes and significance of the problem and the state-of-the-art of control methods. From the very beginning it was apparent that, while much has been written over the last 30 years about the nature and control of desert encroachment, there are widespread and fundamental differences of opinion and a general lack of a consensus on the extent and rate of desert advance, the significance of various possible triggering mechanisms, associated economic losses, and the most effective control techniques. As a result, quantification of factors and determination of definitive answers are virtually impossible in most instances.

It is anticipated, however, that this document will be useful to program planners and managers in developing countries and development assistance agencies as a broad technical overview of the problem. It highlights causes and significance, gaps in knowledge and technology, and

the nature and potential of recent efforts to control desert encroachment. Particular attention has been paid to new experimental methods for stablizing the desert, and even reversing its advance on a target-specific, localized scale (as opposed to addressing desert expansion of a regional nature associated principally with climatic changes). In most cases, the efficacy and costs of applying these techniques on a larger than pilot study scale are unknown, and one may ultimately find that more traditional control methods based on protecting or re-establishing vegetative cover may continue to prove to be better suited for developing country needs. However, in view of the limited successes with traditional methods of control, and the promising potential of several of the experimental approaches, particularly for dealing with severe, localized problems, it was felt that this report could make a unique contribution by presenting, inter alia, information on the state-of-the-art with respect to some of the newer approaches to controlling desert advance.

The Office of Science and Technology is especially appreciative of the many suggestions, supported by a wealth of supplementary material, provided by experts both in the U.S. and abroad who were sent copies of an early draft of this report. In addition to specialists within AID offices in Washington and in overseas Missions who reviewed early draft material, we would like to acknowledge the assistance of:

- Dr. A. T. Bleak, Crops Research Laboratory, Utah State University
- Dr. Reid A. Bryson, Center for Climatic Research, University of Wisconsin-Madison
- Dr. Joseph Caprio, Plant and Soil Science Department, College of Agriculture, Montana State University
- Dr. M. B. Dickerman, Forest Service, U.S. Department of Agriculture
- Miss I. R. Dudeney, Natural Resources Research Division, UNESCO
- Professor Norman French, University of Wyoming
- Dr. Helmut Landsberg, Institute for Fluid Dynamics and Applied Mathematics, University of Maryland
- Dr. Katharina Lettau, Center for Climatic Research, University of Wisconsin at Madison
- Mr. Marvin Magnusson, U.S. Weather Service, Salt Lake City, Utah
- Dr. George B. Maxey, Center for Water Research, Desert Research Institute, University of Nevada

- Dr. William G. McGinnies, College of Earth Sciences, Office of Arid Lands Studies, University of Arizona

- Professor Cyrus McKell, Director, Environment and Man Program, Utah State University

- Mr. R. F. Neblett, Government Research Laboratory, Esso Research and Engineering Company

- Professor Norman J. Rosenberg, Department of Horticulture and Forestry, College of Agriculture, Lincoln, Nebraska

- Dr. Terah L. Smiley, Chief of Research Laboratories, Department of Geosciences, University of Arizona

- Dr. Noel Vietmeyer, Office of the Foreign Secretary, National Academy of Sciences

- Dr. Gilbert White, Institute of Behavioral Science, University of Colorado

Due to the large volume of relevant reports and analyses contributed by these experts, reflecting different experiences, perspectives, and opinions, it was necessary to be highly selective, and sometimes arbitrary, in incorporating the information in the final document. The Office of Science and Technology therefore assumes full responsibility for the scope, balance, content, and conclusions of the report.

Since much useful information was,of necessity, omitted, the report contains an extensive bibliography on desert encroachment. It also includes a compilation of organizations and individuals with experience and capabilities in the subject area who may be useful sources of supplementary information, or who can otherwise assist with desert encroachment problems.

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I. EXTENT AND SIGNIFICANCE OF THE PROBLEM

"It was in this fertile area that sand dunes developed at more than one place. These dunes moved with every storm, and in course of time, ten square miles of productive land were under sand dunes. The storms blew enormous quantities of sand from these plagued spots and dumped it on Quetta-Kalat Highway, in the habitations, water-channels or on cropland, burying crops and raising the level of orchards and fields above command of irrigation water. Fields, karezes (water channels) or orchards damaged in this way had to be abandoned. The moving of dunes on to the Quetta-Kalat highway had become a frequent nuisance by 1954 when stabilization experiments were first initiated." (46)*

This description of desert encroachment in West Pakistan illustrates the nature and scope of the problem, as well as the fact that man's attempt to fight back is by no means a new imperative. The problem exists throughout the world along the interfaces where deserts, arable lands, and man come into contact. During earlier days when the desert margins were inhabited only sparsely, and by nomadic peoples, desert encroachment was more of an annoyance than a difficult problem. Today, growing populations in search of land for living space and food production are rapidly increasing the utilization and, hence, the value of the semi-arid areas adjacent to the deserts. Based on even the more conservative projections of future population growth and food requirements, it is safe to say that the ability to prevent desert progression -- and even to push back and reclaim the deserts -- will demand increased attention in the economic planning of many of the developing nations of the world.

With deserts covering one-seventh of the earth's surface and distributed among all continents, developing countries currently faced with the problem of desert encroachment are scattered throughout the world. A very rough estimate of all the areas more or less affected is about 370,000 square miles involving approximately 60,000,000 people, in the countries straddling, or adjacent to, the desert/arable land interfaces. These boundary regions and their populations do not all suffer in the same degree from deserts encroaching onto their lands.

*Note: Numbers in parenthesis, e.g., (46) refer to items listed in the BIBLIOGRAPHY.

The most extensive desert boundary stretches across Africa at the approximate latitude 15° North, with the Sahara regions to the north and arable regions to the south. (See Figure 1.) Mauritania, Mali, Senegal, Niger, Chad and the Sudan, all face a constant threat from the southward advancement of the Southern Sahara Desert (45). The gloomy predictions by 19th Century explorers and geographers about the "inexorable destruction" of vast arable land areas by desert encroachment have not materialized. However, measurable encroachment in northern areas of these countries has occurred and is continuing. While specific areal data are lacking, a rough estimate of magnitude of encroachment south of the Sahara is that about 250,000 square miles of arable land (i.e., suitable for agriculture or intensive grazing) has been forfeited to the desert in the past 50 years. Regions of North Africa bordering the desert, especially Libya, Egypt, Algeria, Morocco and Tunisia, also suffer in varying, but unmeasured degrees of desert encroachment.

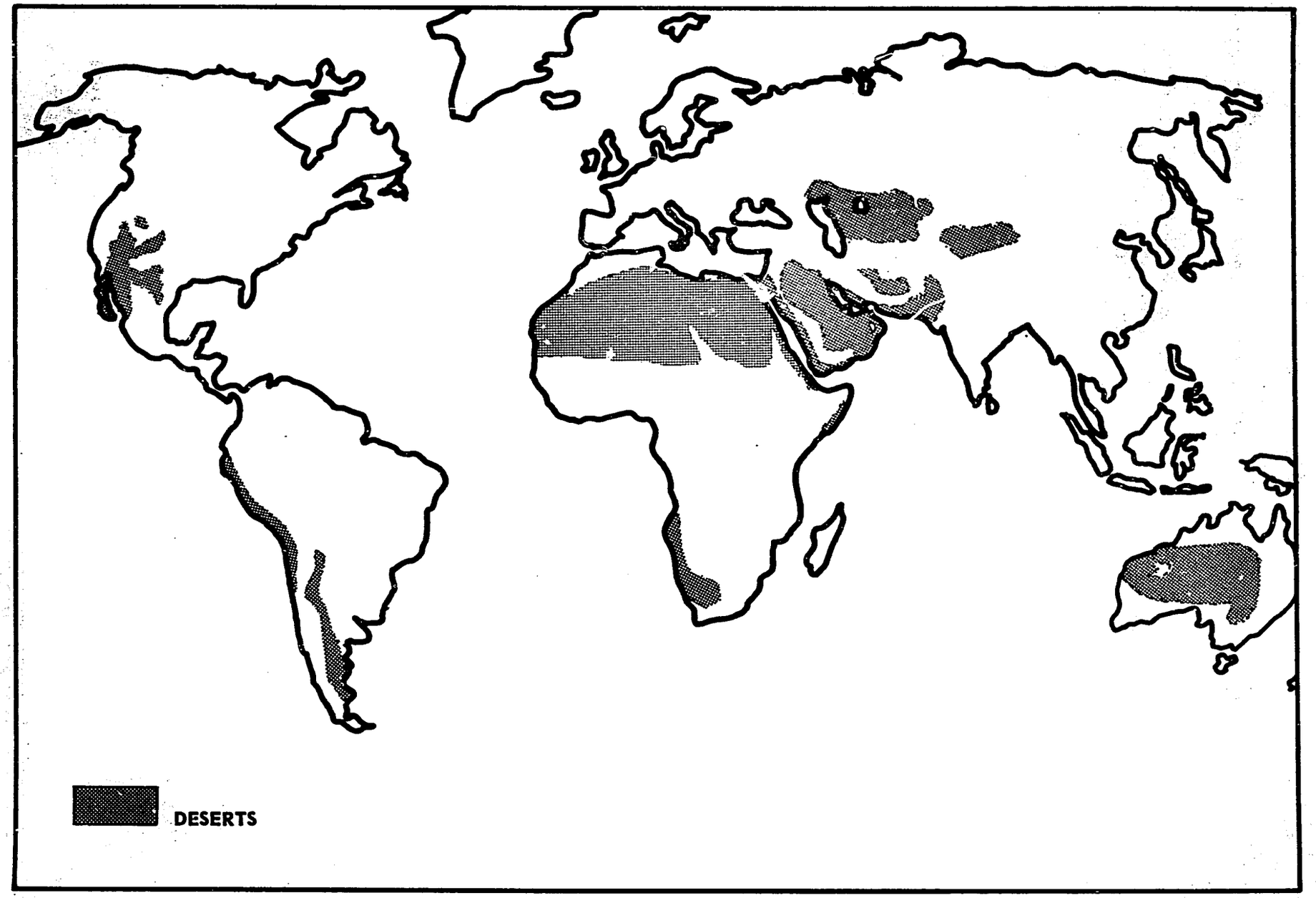
In South America, encroachment boundaries exist along latitude 5° South (across the Peruvian coastal regions) and again, along latitude 30° South (across Chile's coastal zone). A long north-south interface with interior desert regions runs unbroken between these two parallels, with the desert strip averaging about 50 miles in width.

Other less-defined interfaces exist in the Mid-East and Near-East Asia in a region bounded approximately by longitude 35° to 75° East and along latitude 30° North and which includes the Trucial States, Saudi Arabia, Persia, West Pakistan, and large areas of Turkey, Afghanistan, and India.

Encroachment may be either regional or local in nature. Local losses occur around oases, "islands" of arable land which are widely distributed in the aforementioned areas. In the southern regions of Libya and Algeria, there are pockets of agricultural and industrial development around or near oil and gas fields. These "islands" suffer constant desert infringment.

Broader scale problems of encroachment occur in the western Central African Republic, north-western Sudan, and northern regions of Ethiopia. The areas of encroachment encompass about 400-800 square kilometers in each case, with once-fertile areas shrinking into "dust-bowls" similar to U.S. experiences during the mid-1930's in Oklahoma, Nebraska, Texas and East Arizona. The aforementioned North Chilean and, also, the western Bolivian regions are other examples of broader scale encroachment. Regional desert encroachment is most evident across the Middle-North African belt, extending from Mauritania, thence across northern Mali, Niger, Chad, the central Sudan, into

Fig. 1. WORLD MAP DEPICTING PRINCIPAL DESERT AREAS



western Ethiopia. (14) However, the extent of the encroachment is not precisely known.

The rate of desert boundary changes is difficult to determine and the literature is filled with widely varying estimates of average rates of change of desert migration, both for broad regional movements and for specific, localized situations. Either such changes are relatively minute and/or extend over many years and are difficult to measure; or, where grosser changes occur even in fairly short time periods of five years or less, inadequate surveys have prevented an exact assessment of the problem.

Several studies of the Sahara have concluded that there has been a net advance in some places, along a 2,200 mile southern front, of as much as 30 miles per year. In South America, a ten-year drought in the Chilean N. Chico area (latitude 27° - 30° South) has been accompanied by a gradual southward movement of desert regions across a 50-100 mile front at the rate of one-to-two miles a year. (41) Recent meteorological modelling studies of the Rajputana Desert, lying between New Delhi and Karachi, are using a rate of desert advance of a quarter to a half mile per year, based on previously calculated values of one half mile per year. (10)

Desert encroachment has its severest economic and social impacts upon developing countries heavily dependent upon agriculture. Many have large nomadic elements which are most "at home" in, or adapted to, the desert/arable land interfacial areas. Where it is possible to halt the forward migration of the desert, valuable land is preserved; where it is possible to go a step farther and "push back" the desert, new opportunities for economic and social development are opened up. Among the incentives for halting encroachment and reclaiming desert lands are:

... with more usable acreage available, pressure is eased on existing, and often overcrowded, agricultural areas:

... reclaimed desert regions have proved to be very fertile and productive in certain areas where soil and climatic conditions are favorable;

... where grazing and browsing lands are opened, a significant increase in protein production can result;

... the reclamation of large areas may have a favorable effect upon the regional climate, by increasing rainfall and lowering mean temperatures

a situation that is self-reinforcing;1/

... an increase in flora (where that is the prime reclamation agent) tends to increase fauna, such as birds, and wildlife which in turn increase the stability, productivity, and value of the new ecosystem;

... exploitation of extant mineral and other non-living resources is made more feasible, since workers are difficult to recruit for a true desert region; and the improved ambience resulting from reclamation also permits establishment of workers' families' settlements; and

... the impact of "dust" storms, dune progression, "dust devil" storms and the like will be reduced, along with the economic losses associated with damage to crops, dwellings and equipment, interference with transportation and communication, and burial of agricultural lands, roads and railways now immediately adjacent to the desert.

The magnitude of the economic losses attributable to encroachment which are sustained by developing countries are virtually impossible to calculate. It must suffice to say that the losses are severe in terms of damage to crops and human habitation, reduction of manpower productivity, curtailment of communication and transportation, loss of valuable land, and the cost of clean-up and preventive measures. In the Middle-North Africa Belt, especially in Niger and Mali, degradation of grazing lands has caused large reductions in wildlife which formerly furnished needed protein for the indigenous population. Domesticated ruminant herds have also been reduced, as has acreage devoted to grains, and water wells have dried up. Many of the more urbanized communities wage expensive -- and sometime losing -- battles to keep roads, railway lines, and even streets clear of sand.

While losses have not been defined in terms of a money value, a $1 million/year (approx.) food relief program has been mounted in the area affected by the North Chilean desert progression, which was once self sufficient in agricultural production. In the oil and gas producing areas in the southern regions of Libya and Algeria, although the economic losses associated with reduced productivity of both the land and the drilling activity are not available, estimates of the costs of soil stabilization to retard encroachment (mostly incurred by the petroleum industry) run as high as several million dollars per year.

1/ Several reviewers noted that this relationship has not yet been satisfactorily proved, although Bryson's work on deserts in India and Pakistan indicates that reduction of atmospheric dust introduced from the desert and from cultivation could cause an increase in rainfall.

Additional qualitative analyses of the economic and social impacts associated with desert encroachment are found in most of the documents cited in the Bibliography. In order to provide a more rational and convincing basis for justifying investments in encroachment control measures, additional research is needed to quantify the various costs that will be borne if no preventative action is taken.

II. CAUSES OF DESERT ENCROACHMENT

Desert encroachment can result either from a change in climate or from human action. Invariably both factors appear to be present, reinforcing each other, and making it difficult if not impossible to quantify their respective contributions to the phenomena. A temporary or long continued deterioration of climate may accentuate the harmful consequences of human occupation of the land, and it has often been suggested that man's activities can result in increased aridity. The latter relationship is difficult to substantiate, although recent research by University of Wisconsin scientists in the Rajputana Desert indicates that the dense pall of dust over northwestern India and West Pakistan, possibly caused in some measure by land cultivation and grazing practices, surpresses the movement of monsoon rains into the present desert area. (10) Assessing the relative contribution of the two agents, climatic change and man, in the process of desertification is important in order to decide on the kind of ameliorative measures that can best be taken and to estimate the likelihood of success.

With respect to climatic factors, there is good evidence to suggest that decreasing aridity in some sections of the world is causing deserts located within to recede (i.e., deserts slowly convert along their margins into an arable state as the result of increasing moisture and/or shifts in wind direction). It has been claimed that changes in the boundaries of the Sahara are related to the dynamics of the tropical easterly air jetstream. Experts differ greatly, however, in their estimates of both the magnitude and rate of present-day desert encroachment on a broad regional scale due principally to lack of sufficiently extensive and detailed meteorological records. Although attempts have been made to analyze the rate of change of desert conditions over the last 100 years, and to forecast future trends, the results have usually been inconclusive and subject to much debate. (22)

It is only when one moves from the regional, synoptic level toward the local setting that meaningful interpretations have been made. (See BIBLIOGRAPHY citation 26 for a detailed analysis of climatic changes in Africa.) Through studies of the character of buried lake sediments, among others, and of comprehensive meteorological records which have been maintained by a few individials or institutions, changes in local conditions along desert margins have been described in some detail. Thus, in certain areas, it has been concluded that the climate is indeed becoming drier and that the desert is advancing.

While accurate measurements are lacking, changes in wind flow patterns over the long term can have a decided impact as dunes and sand strata are physically moved into previously unaffected land. In addition, dry winds can rapidly dessicate soil, leading to a conversion of fertile land to an unfertile, desert state.

Persistent anticyclonic (high pressure) air mass movement during the past decade along the latitude 15° - 30° North is thought to have contributed to middle African desert encroachment with dry northwest winds blowing sand southwards. The Chilean progression is similarly driven by a combination of intense drought and wind transport.

Climatic changes leading to occasional rainfall, especially if in heavy bursts, can accelerate the process of soil sterilization by leaching organic and some mineral nutrients into pockets or depressions. There, the excess nutrients are actually inimical to flora growth, while the adjacent land is of course depleted.

According to some experts, the concept of weather fluctuations of relatively short duration is basically sounder in many respects than is the more widely accepted climate-change explanation as the cause of the formation of deserts. The irreversibility of drought effects in low-rainfall areas is both inevitable and more desert-creative, because of its greater severity, than the generally postulated secular climatic change.

In a study of the factors responsible for the formation of deserts in the Near East and North Africa, McGinnies and Goldman conclude that weather-induced ecological change is the fundamental factor in the creation of deserts, and that the abuse of land and its vegetation by man and animals acts only as a possible accelerator. (6) However, most experts seem to agree that the intervention of man does make a significant difference with respect to encroachment on a localized scale over the short term, and that it is possible to retard or reverse the advance of the deserts by better management of the intervention processes.

Le Houerou reports (35) that vegetation in the arid zones of North Africa has experienced accelerated deterioration since about 1930, leading in turn to encroachment of adjacent deserts. In Tunisia, only 600,000 hectares of alfa grass remain of some 1.35 million hectares, owing to a deterioration which is currently on the order of 10,000 hectares per year. The deterioration apparently results from the great population pressure, which results in intense overgrazing, cultivation, and removal of woody plants for firewood. The removal of wood has been calculated at one kilogram per person per day. That is, an average of 0.5 to

1 hectare of woody vegetation is destroyed per person each year. Le Houerou concludes that climatic change is not a cause of the encroachment problem in this area.

Man's role in desert encroachment is an ancient one, extending from the time of his use of fire and herding of animals to present-day, high-technology activities such as river diversion, road-building and intensive forestry. The major destructive features of human activity, leading to noticeable changes in aridity and desert countries, are the following:

- burning of grasslands, forests,and scrub;
- overgrazing by livestock;
- cereal cultivation;
- woodcutting and deforestation;
- lowering of the water table due to increased water use;
- engineering construction (roads, dams, river diversions).

The burning of vegetation in place is probably not a very significant agent in the process of desert encroachment since grass and trees in vulnerable areas are generally too sparse to burn readily. An exception might be along streambanks in semi-arid regions, where removal of vegetation through burning would facilitate the advancement of the adjacent desert. Grove suggests that fire has probably been the cause of the elimination of much woodland along watercourses in the semi-arid regions of Africa. (26) On the other hand, recent studies of the regrowth potential of forest species has led some exp ts to conclude that fire damage is not as destructive as was previously thought.

Overgrazing by livestock appears to be a major factor in desert encroachment. This is illustrated in the following analysis by C. P. Bhimaya of a situation in the Rajasthan Desert in northwest India.

> "For the most part this tract is waterless but well vegetated. Where water has been developed settlements have sprung up. The settlers cleared large areas of natural vegetation to raise food crops. Their herds of livestock grazed or browsed in the forests around the settlement. The pressure of grazing could be estimated from the census of livestock population carried out during 1956. According to the Census Report 32.4 million animals were grazed on this tract. Of this total a little over 9 million were goats and camels notorious for their capacity to destroy forest vegetation. The resultant denudation of the desert soil led to severe blowing action by winds. The damage is es-

pecially pronounced during pre-monsoon periods when winds are most violent and seasonal vegetation is generally dry. In the course of time colossal sand dunes have been piled up by wind action around settlements. During storms huge quantities of sand blow into inhabited areas. The very existence of the townships is threatened by these raw dunes which tend to engulf them." (3)

It has been suggested that the Sonoran Desert of Arizona and much of the Chichuahuan Desert of New Mexico have been created by overgrazing during the last few hundred years.

The risk of desert encroachment as the result of grazing practices has increased as a result of a number of often interacting factors, First, the size and numbers of herds have been increasing rapidly in many semi-arid regions. Secondly, water development has not been carefully planned in advance. And, thirdly, an increasing proportion of small herds belong to sedentary cultivators who do not travel far from home. Consequently, local overgrazing occurs. Related to this third point is the fact that nomadic tribes are being restricted in their movements by new political and administrative arrangements, as well as by the takeover of dry season grazing lands for irrigated agriculture.

Several experts have also noted that the replacement of wild animal populations by domestic animals is a contributing factor since the former seem better able to maintain grassland conditions. Grove suggests that this has happened in the Karoo of southern Africa where "bush has moved east and north replacing sweet grass field while extensive areas in the west are said to have become virtual desert." (26)

The cutting of wood both by pastorialists and townspeople is a major cause of desert encroachment in many areas. Vegetation is harvested to feed to animals (camels), to build homes and enclosures for animals, and to use directly or sell as fuel. Grove (26) notes that three-quarters of Kana City's (Nigeria) firewood consumption of some 75,000 tons per year for a population of 300,000 is brought by donkeys from a radius of 20 km. As it and other towns like it grow at a rate of 5-10 percent per year, the adjacent woodlands can be expected to become very sparse as years go by. Woodlands in semi-arid regions are invaluable since they bring up nutrients from below to be later released to base-poor sandy soils from the decay of leaves and substances washed off the foliage; they brake the speed and, hence, carrying capacity of the wind; and anchor the soil in place. In the absence of forests, the

climate is invariably more arid, the dry season more accentuated, and there is a probable but not yet demonstrable reduction in total rainfall.

Bryson and Baerreis have described a complex situation in large areas of India (e.g., the Indo-Gangetic Plain) where growing populations destroyed forests for timber and fuel and, after the trees were gone, burned cow dung as fuel rather than use it as a manure for the fields. The loss of both trees and soil fertility combined to trigger desert encroachment problems.

Cultivation in marginal areas during periods of higher than normal rainfall is especially dangerous and perhaps the main cause of desertification against which it may be necessary to take preventive action. When dry years follow the years of plentiful rainfall, ploughed soils or soil from which the sparse cover of natural plants has been eliminated by cultivation is at the mercy of the winds. The fine clays and silts are carried away as dust, and the sand drifts into dunes. The dust bowls of North America serve as a classic example of the misuse of semi-arid and potentially productive land through failure to adopt wise agricultural management practices. Several writers on the subject believe that the real danger to the region south of the Sahara is not the advancement of sand from the north, but desertification *in situ* from intensive agricultural patterns that rapidly exhaust soil fertility and bonding properties.

The lowering of water tables is a critical causal factor with respect to desert encroachment. This situation can come about through the pumping of groundwater for drinking or irrigation purposes, or the damming or diversion of watercourses. There has been concern expressed in series of environmental articles in the *Washington Post* by Claire Sterling (Nov. 1971) that the indiscriminate and unregulated installation of large numbers of tube wells in areas bordering the Sahara is triggering an advancement of the desert onto agricultural lands, and she suggests that better planning of water development programs is required to insure that one isn't involved in a zero-sum game (viz, improved agricultural yields through irrigation aren't offset by loss of land to advancing sand).

Thus, desert encroachment can be triggered and sustained by a variety of possible mechanisms associated both with climatic changes and activities of man. In some instances, wind-driven dune progression can be clearly identified as the principal mechanism. In other areas, climatic or ground water changes may lead to loss of soil fertility and moisture, leading in turn to desertification *in situ*. Such a situation greatly complicates problem analysis and the identification of remedial measures, and recognition of this fact is implicit in the remainder of the paper.

Notwithstanding the complex nature of the problem, most experts believe that it is possible to control desert encroachment, at least on a local scale, with proper management techniques. This report will hereafter deal with desert encroachment of a sufficiently small areal and temporal extent to be amenable to control by man in the near term. Climate modification designed to prevent or reverse broad, regional desert expansion will not be considered. Rather, the emphasis will be on locally significant encroachment (in terms of impact on the economies of developing countries) that can be attacked through such methods as stabilization of sand dunes and improved agricultural, grazing, and water development practices.

III. TRADITIONAL APPROACHES TO CONTROLLING DESERT ADVANCE

In most of the world's desert/arable land interface zones, continuous attempts have been made to halt encroachment and, often, to reclaim desert lands, even in the absence of encroachment.

Efforts have not been systematic, however, except in the more advanced countries where transportation systems, communications, natural resource availability, and financial and technical capabilities provide a viable base for launching the necessary studies and programs. In less advanced countries such as Algeria and Libya, heavy commercial enterprises and/or colonial governments (e.g., oil companies, or France, before Algerian independence) have stabilized and rehabilitated various local desert regions with large inputs of materials, manpower, and managerial and technological "know-how."

There are other instances in which national governments have taken the lead. Tunisia's Ministry of Agriculture has recently completed 12 years of research in a two hectare irrigated area of Garaa Bou Flidja. (9) The study demonstrated that certain crops (food stuffs, fodder, wheat, cotton, date palms) can be produced from areas in which the sand has literally been shoved back, and prevented from forward movement by barricades and vegetative stabilization. Tremendous difficulties were involved, however, in making the area productive. In particular, the harsh climate and remoteness of the area made establishment and maintenance, transportation of fertilizer and seed, and export of crops almost prohibitive. In addition, numerous social factors entered. Local inhabitants of the area are nomadic shepherds who lack the tradition and skill necessary for developing the desert perimeter areas. As a result, a special management staff had to be recruited and trained to assist farmers and to assure that control measures are rigorously applied and maintained, particularly with respect to the use of windbreaks.

The Governments of India and Pakistan have carried out desert stabilization and afforestation programs for many years. (3)(7)These programs invariably have been of a similar integrated nature, combining improved grazing and range management practices with the control of encroaching sands both by the planting of vegetation for windbreaks and soil stabilization and by the construction of barricades. The following are policy guidelines from a program established in 1952 by India for the Rajasthan Desert, a virtual stereotype of programs implemented in

developing countries throughout the world to the present day:

> "1. Grazing that is concentrated near settlements will be decentralized. The vast stretches of good pastures a little distant from the settlements now not utilized for want of drinking water will be developed by tubewells or surface storage ponds. Diversion of livestock to the newly opened areas will then provide badly needed relief to the overgrazed pastures close to habitations.
>
> 2. Cultivation of areas very susceptible to wind erosion will be stopped. The farmers affected by this measure will be settled on areas to be irrigated by new canals. The areas safe for cultivation will continue to be cropped. However, these areas will be protected by windbreaks and use of cultural measures conducive to conservation of soil and water.
>
> 3. Standard range management principles will be applied to the whole tract. Rotational and deferred grazing will be introduced in the newly opened areas. The overgrazed areas will be allowed rest to recuperate. Denuded areas will be seeded with species of nutritive grasses. Two grass nurseries of fifty acres have been established to produce seed for the purpose.
>
> 4. The moving sands along roads and railway lines will be fixed by raising shelterbelts. About 150 miles of such plantings have already been done successfully.
>
> 5. In order to encourage tree planting by private individuals and public bodies free seedings are supplied from fifteen nurseries in the tract maintained by the Desert Afforestation and Soil Conservation Station." (46)

Most of the past work on controlling desert encroachment has focused on methods of sand-dune fixation; techniques and materials for constructing windbreaks and shelterbreaks; research on plant species best suited to fix sand and serve as windbreaks; and economic crops best adapted to conditions along the borders of stablized areas or within reclaimed acreage.

Sand-dune fixation is designed to prevent the movement of sand long enough to enable either natural or planted vegetation to become established. One practice of checking the movement of sand is to erect long fences of planks, branches, mats, sacks or any material capable of preventing the sand from moving and blowing away. The fences are usually about 3 feet high and 120 feet apart, parallel to each other, and at right angles to the prevailing wind. Grazing is excluded. If natural vegetation does not appear on the stabilized sand, planting is done. However, erection of such fences on a large scale is often prohibitive because of the high cost and unavailability of material locally. Hence, in most sand-dune fixation projects, sand-bonding grasses or cuttings of quick growing trees are planted deep in the sand, in rows about 10 feet apart. Experience with the latter method in the Near East has shown that sand movement can be checked over large areas in 3 years. Then the area is planted with more valuable species which produce firewood, charcoal, tanning materials, poles, posts, and some small timber. Within the past five years, the use of asphalt, plastics, and cements to form wind resistant surface encrustations on sand dunes has increased. These techniques will be discussed in some detail in the next section.

Windbreaks and shelterbreaks usually consist of rows of trees or strips of tall grass planted along the edges of towns, agricultural plots, roads, canals and railway lines. Their main function is to reduce wind velocity and thus prevent crops from being blown down, soil blowing, and wind erosion. However, tree windbreaks are often difficult to establish in semi-arid regions because of droughts, and because, in the sapling stage, trees cannot withstand the wind. Windbreaks of reed mats or other locally available materials can be erected to shelter the young trees until they become well-established. Tall crops growing at regularly spaced intervals in fields of shorter crops have been found to be effective in many situations. Some experts believe that windbreaks favorably modify the microclimate by increasing atmospheric water vapor and relieving the moisture demand imposed on the plants by hot, dry winds. However, others have noted that windbreaks increase the amplitude of daily temperature maxima and minima, and may also increase evapotranspiration when sheltered plants grow larger and leafier than the unsheltered species. Most seem to agree that windbreaks are the only practical means available today for marginal land stabilization on a large scale.

To support encroachment control projects based on the aforementioned techniques, many countries are continuing to carry out research on plant genetics and breeding to develop species that are quick growing, disease resistant,

and tolerant of the unique and harsh climatic conditions encountered along the desert margins.

The following table describes efforts to control desert encroachment in a number of African countries:

	COUNTRY	REGION	REASON FOR ACTIVITY OR STUDY	REMEDIAL MEANS USED OR OTHER ACTIVITY	RESULTS & COSTS
1)	Algeria	South-Central	Oil & Gas Drilling sites needed dune & sand stabilization to prevent flash flood-caused silting and to act as water catch areas	Asphalt plastic & cement surface encrustation 1966-70	Water from sparse rainfall has been trapped & sand progression halted; about $2M/year spent
2)	Libya	Southern	Same as for Algeria	Ditto	Same as above; costs information unavailable
3)	Mauritania	Southeast	Sahara encroachment & heavy wind erosion of arable lands	"Dune grass" & other plantings	Information unavailable
4)	Mali	Northern	Sahara encroachment on grazing lands	Modest attempts have been made at soil stabilization & plantings	Information unavailable
5)	Niger	Northern	Sahara encroachment onto arable lands	Ditto	Information unavailable
6)	Chad	Western & N. West	Sahara encroachment on grazing lands	No specific action taken. Some attempts at education of tribesmen re overgrazing has been made.	Information unavailable
7)	Sudan	Western & Southern	Steady Sahara encroachment on forests, grazing & farm lands	Studies & assessment only 1965	Information unavailable

Table (continued)

8)	Ethiopia	South-western	Encroachment & severe wind & flash flood erosion	Some planting, building of water "traps," various studies, etc. 1950-70	Information Unavailable

Some attempts have been made to stabilize and contain deserts in the southwestern part of the United States, particularly in western Arizona and southern California. Roadside (or, in one case, irrigation canal-side) tree planting has been tried with limited success. Experiments in seeding semi-desert rangelands of Arizona with hardy perennial grasses, such as Lehman lovegrass, have been quite successful and have provided American ranchers with a dependable source of emergency forage during times of drought. Much more attention has been focused on the encroachment of shoreline sand dunes which has proceeded along many coasts (California, Oregon, the Carolinas, etc.) at an average rate of one meter per year where it is more noticeable than it would be in Africa because of higher population densities and the smaller area affected. Stablization of shoreline dunes has consequently become a science within the U.S., and is widely practiced with reasonable success. The U.S. Department of Agriculture has been leading in such efforts, with help from or in collaboration with the U.S. Geological Survey and various State agencies. The preferred stabilization technique has been the planting of a variety of resistant and durable bushes, ferns, trees, and grasses. However, these U.S. experiences are not generally relevant to situations in developing countries which have characteristically a paucity of ground water, different soil types, and a lack of local technical resources.

IV. APPLICATION OF NEW RESEARCH AND TECHNOLOGIES 1/

Effective control of desert encroachment requires both the technical knowledge and financial resources to retard mass migration of sand, and also the political will and managerial skills to prevent desertification *in situ* caused by unwise development and use of rangelands, agricultural lands, forests, and water resources. In almost every instance, concurrent efforts in both areas are necessary. The previous chapter presented an overview of the more traditional approaches to encroachment control. It is the intent of this section to describe some of the newer approaches now being tested and applied, particularly technological innovations resulting from recent research and development. Most of these newer approaches, however, are directed toward improving traditional approaches to sand stabilization based on the use of physical barriers to block the migration of the sand, or on the introduction of vegetation to hold the sand in place. Three topics are important in this regard: surface sealers; windbreaks, both natural and artificial; and introduction of vegetation.

A. Artificial Surface Sealants

1. Esso System -- Moisture sufficient to support the growth of dune stabilizing trees can often be found at about 18 inches beneath the normal level of sand, even in bleak and barren stretches such as the Sahara Desert. The difficulty, however, is getting young trees established since those planted 18 inches in the sand may be rapidly buried under drifts or have their roots exposed by the wind. The challenge then is to stabilize the sand long enough for the trees to mature to the point where they can take over. Detailed studies of sand dune behavior were first made with North African sand in a wind tunnel at the laboratories of Esso Research Limited in England.

1/ The material in this chapter is based in large measure on an unpublished informal survey by Dr. Noel Vietmeyer, U.S. National Academy of Sciences.

A model dune in this tunnel shifted in a wind of only 17 miles an hour. It was shown, however, that if the sand was treated with a surface coating of heavy oil it could resist wind velocities higher than 70 miles an hour. As a practical application of this discovery, many hundreds of acres of sand dunes in Tunisia and Libya were planted with tree seedlings and then sprayed with oil. This indeed stabilized the sand until the young trees had a chance to grow. In one experiment, eucalyptus seedlings grew within a year to healthy trees more than six feet high. By that time the oil had disappeared, but the trees were able to take over the job of stabilization. This work has been continued and it is now known that water-bearing dunes can be stabilized with oil long enough for vegetation to take hold and anchor them permanently. Not only does this bind the drifting sands but it also allows the plants to take advantage of the moisture that lies beneath the surface, for the stabilizing oil helps reduce the loss of soil moisture by creating a barrier to its evaporation. Furthermore, the insulating ability of the surface maintains a more even temperature within the soil than in normal sand which undergoes large temperature differences between day and night.

R. . Kaul has described (2) the results of a demonstration project involving the spraying of sand dune stabilization oil carried out by Esso Ltd. in 1963 near Bakaner and Jaipur in West Pakistan. The project involved protection of the sand dunes by fencing to ward off grazing animals; planting of rooted slips of grasses and seedlings; and spraying of the dune surfaces with oil (with an application rate of 2110 liters per hectare). One hose with a 12.5 size nozzle was used for spraying the oil, and the windward sides of the higher dunes were given a thicker coverage. since they face the direct impact of the winds. Kaul reported that the cost of the afforestation was approximately 2 1/2 times greater than the expenditure required for dune stabilization by another technique, developed by the Central Arid Zone Research Institute, Jodhpur, and based on the use of local shrubs to form fixed barriers in parallel strips or in a checkerboard pattern, running from the crest down to the heel of the dune to protect seedlings from burial or exposure by the blowing of sand. His conclusion was that in view of the prevailing wage structure in the country, the applicability of the oil-based method on a large scale did not seem either economical or feasible.

Further tests of the Esso Method are now underway in several places, including the Rajasthan Desert in India, two Argentine provinces, and in Cape Cod, Massachusetts. Countries with indigenous supplies of oil near areas plagued by encroachment problems, such as several Middle-East countries, may find this technique to be suitable and also cost-effective.

2. International Synthetic Rubber Company System -- A recent experimental program in Libya based on the use of a spray of synthetic rubber to bind drifting desert sands has met with considerable success. On 400 acres of desert planted with 60,000 eucalyptus trees, this process (called the"Unisol Process") has had 90 percent success in stabilizing the area and over 70 percent success in tree survival. The sealant is applied as a concentrated free-flowing water emulsion of synthetic rubber latex and oil, having a ratio of oil to latex of nine to one, this being the most suited to nearly all climatic conditions. Extensive laboratory tests established the following facts:

a. The Unisol surface membrane allows water to penetrate and at the same time helps to reduce evaporation.

b. Germination is not affected and can in certain circumstances be aided by the retention of water.

c. Application rates can vary and depend on the period of stabilization required and the climatic conditions to which it will be exposed.

There is no limit to the size of area which could be stabilized, but the larger the area the greater the reduction in the capital cost element. The price will be affected by the following factors:

a. The availability of local oil and water.

b. The topographical structure of the area to be treated.

c. The availability of suitable machinery and personnel for both the preparation and spraying of the area.

d. The type of vegetation proposed and the amount of preparation work required; viz, levelling, fertilizers, etc.

e. The transportation costs, when necessary, of raw materials.

On level terrain, standard agricultural equipment with boom sprayers is ideal. In sand dune country, manually-operated high pressure jets with a sixty-foot throw or greater throw are more appropriate since they give a very wide arc of coverage.

While the foregoing information can provide the basis for a first assessment of cost, experience gained over the past three years in treating areas in Europe, Africa, the Middle East and Australia suggests that a total cost per acre can range from upwards of $260. In view of the 50 percent water content of the material, it is recommended that the material be produced as near as possible to the area of application. For large scale operations with materials purchased locally, the raw material cost can be expected to be reduced very substantially, probably by as much as 50 percent. The actual cost in any area naturally will depend on the price of the raw materials, but since the material in drum form already includes a mixing charge by some compounder, and the concentrate in the drum then requires further dilution by mixing with water, it is obvious that the most economic way is to mix all the raw materials in situ. Whatever the cost of locally purchased materials, the differential between drums and bulk mixing on site will be similar. Illustrative costs of raw materials in drums from a U. K. firm are as follows:

Application rates	4 oz./sq.yd.	6 oz./sq.yd.	8 oz./sq.yd.
Lbs. per acre	1,210	1,815	2,420
Kilograms per acre	549	823.5	1,098
Cost per acre (at 11p per kilo, FOB)	$150	$225	$300
The expected cost per acre for on-site mixing on a large scale	$ 75	$112.50	$150

3. Hoechst Corporation System -- Research conducted by the Hoechst Corporation has led to the development of a synthetic resin which can be sprayed over large areas to consolidate the surficial materials. Large scale trials on protecting Holland's tulip fields against coastal dunes, on controlling migrating dunes in deserts, and on erosion control on highway embankments, have been carried out successfully. The synthetic resin is sprayed on the surface to be treated in the form of an emulsion which also contains grass seeds or other seeds, and a fertilizer. The plants sprout in a short time and then take over the process of consolidating the soil surface.

The quantities of concentrate to be used depend upon the period of time during which the particular type of vegetative cover needs to be protected, as well as upon the soil characteristics. Long-term protection (e.g., up to one year) will require at least 100 gallons of concentrate per acre. Prices averaging $2.50 to $3.00 per gallon would bring the cost up to $250 to $300 per acre, making it a more expensive process than the preceding one.

4. The Shell System -- A phase separating epoxy resin process for consolidating sand in oil wells was developed by Shell in 1958. This resin forms a strong bond with the sand grains and creates a hard sand/polymer composite surface since most of the sand is in grain to grain contact. This method of sand control has been successfully applied to many unconsolidated sand or sandstone formations of a small, localized nature. It has not yet been reported as being used over large areas for sand dune stabilization but appears to have potential for this.

5. ENCAP Mulch -- ENCAP is a brand name for a liquid spray-on mulch derived from petroleum. Unlike the previous formulations, ENCAP is a special water emulsion of petroleum resins. It is applied to the soil surface as a spray at normal planting temperatures. The spray is so directed over the seed rows that a continuous film is formed on top of the soil in bands which are usually 6 inches wide and 5 to 20 mils thick. Such a film properly applied in strips serves four functions: it warms the soil; it reduces evaporation; it provides protection against erosion; and it reduces leaching of minerals and chemicals from the growth zones. This material forms a uniform coating that clings to but does not deeply penetrate the soil. The mulch is not readily destroyed by winds or rains and, generally, it will remain intact for four to ten weeks or longer.

Seedlings easily break through the film, and the mulch can simply be plowed back into the soil when it has served its purpose. All tests to date demonstrate that there is no adverse effect on crops, or soil nutrient value, or on humans who may come in contact with it. This petroleum mulch has beneficial influences on two factors that are essential to vigorous plant growth -- the temperature and moisture content of the soil. The film absorbs a high proportion of incident solar radiation. This results in increased seed-zone temperatures -- usually 10 to 20 degrees higher than the base soil, depending on climatic conditions, soil type, and mulch design. And because the mulch is a continuous low-porosity film, evaporation of moisture from the seed zone is retarded. This is particularly important in areas of limited rainfall. Under proper conditions ENCAP is reported to:

a. Promote uniform and rapid seed germination.

b. Promote vigorous seedling growth for earlier and better yields.

c. Advance the planting date for a longer growing season.

d. Prevent soil crusting.

e. Reduce erosion of top soil by wind and water.

f. Improve efficiency of pesticides and fertilizers by reducing leaching.

g. Reduce losses of volatile fumigants and fertilizers.

h. Improve soil structure and tilth by admixing with soil.

6. Miscellaneous Surface Sealants -- Other possible sealants include water soluble plastics which have been developed in recent years. These could be sprayed over sand dunes in aqueous solution and allowed to polymerize in place.

It has been suggested that sand could be stabilized on a local scale by fusing it into a glass-like surficial crust using a special hand operated flame-throwing device.

A glassy resistant crust could be formed in situ without the need to import or locally produce coating materials. All that would be required would be a steady source of fuel (gas, petroleum, etc.). The minimum application temperature would be about 700 degrees Centigrade, but the higher the better since the process is enhanced by high rates of heat flux, at a constant flame density. Unknowns include rate of heat transfer needed, which determines time of application. Costs are almost impossible to estimate without a detailed study, but certainly would be quite high. This technique probably would be dangerous, and sand blowing could be a serious problem.

Chemical fusion is also possible, utilizing hydrofluoric acid (HF) which reacts with sand to form a spongy compound of mono- and bi-fluorides. The HF could be sprayed just as other coatings might be, but the cost would probably be ten times that of plastic due to higher material costs plus the special precautions needed to handle, store, and apply the highly toxic and corrosive acid. The ecological impact of this, as well as all other techniques, must be considered in advance of project implemation. The use of chemical sealants, for example, might well render the treated area unsuitable for vegetation for a long period of time.

B. Artificial Physical Barriers

The following schemes for promoting holding action against sand migration have been proposed and tested at various times, and ad hoc efforts to utilize locally available materials for this purpose are continuing:

- Burying old car carcases;
- Distributing durable junk, such as tires, wire, etc.;
- Bulldozing or forming hills and revetments to alter windflow patterns and intensity;
- Terrain alteration using explosives; and
- Building windbreaks of old telephone poles.

Effective wind breaks should be porous barriers, the optimum porosity being about 50 percent. Therefore, the first four items may prove to be of doubtful value.

Furthermore, the materials and logistical support requirements may be too costly for most developing nations. The efficiency of the schemes would also depend on the extent and nature of water and wind erosion actions -- complicated and poorly understood processes.

C. Vegetative Control

Many experts believe that the most durable and the most economical approach to controlling desert encroachment is through the establishment of natural vegetation to serve as barriers against mass dune migration or to stabilize desert sands and loose soils of the semi-arid zone. Even for localized areas (i.e., 100 square kilometers or less) where artificial coatings might be efficacious, such coatings are normally viewed simply as vehicles for holding the sand in place temporarily until newly-introduced vegetation can mature and take over the job.

Since selection, planting, and cultivation of plants appropriate for different desert stabilization plans, and for different climatic and soil conditions, involve a complex of factors and a wide variety of possible plant species, detailed descriptions and recommendations cannot be made in this report. Bibliography reference (2), "Afforestation in Arid Zones" by R. N. Kaul, presents an excellent comprehensive treatment of this subject.

However, with respect to the establishment of vegetative barriers, the following general observations appear justified:

- -- some water from rain or ground water must be available for plant life sustenance. If ground water is the only source, the water table must be within two meters of the surface -- unlikely in regions with very low rainfall (less than 25 centimeters per year);

- -- trees with deep and extensive root systems are the more likely and preferred candidates over grasses and shrubs. Trees also tend to act as windbreaks and, according to some experts, if densely planted as a forest, can achieve localized and moderate climate modification which could progressively act in a "feed-back" mode to further

improve rainfall and water retention. 1/ The extensive tree planting in northern Israel is an example of a successful program. The 130 million trees planted since 1954 have stabilized desert ground, reduced erosion and desert encroachment, and may be responsible for the cooler temperatures and greater rainfall that the region now apparently experiences. The most effective trees planted are: Aleppo Pine; Mediterranean Cypress; Carob (Ceratomia siliqua); Eucalyptus (various species); Tamarix articulata and Acacia cyanophylla;

-- the texture of the soil, its composition, water infiltration capacity, type of exposure, timing of annual rainfall, and the basic water balance must be understood before planting is undertaken;

-- indigenous trees, if any, may not be the best species for intensive afforestation. Hybrids, or alien types such as a fast-growing Eucalyptus, may be preferable; and

-- the logistics of providing seedlings is a major problem. Requirements include the establishment of nurseries, irrigation networks, trained labor, plant laboratories, and insect pest control. Direct seed sowing and pre-germination treatments may partially solve this problem having been tried successfully with Azadoracjta planting in northern Nigeria. Techniques which rely on specially coated seeds obviate the high cost of nurseries. The use of polyethylene potting for nursery seedlings has proven valuable in regions of north central and western Africa.

The concept of long linear shelter belts comprised of large trees has been advanced many times during the last century as the best means to halt desert encroachment on a large-scale regional basis. There have been schemes to create a great strip of forest across Africa to form a barrier against the encroachment of the Sahara, long linear forests have been established in the U.S. and the USSR to

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1/ There is only sketchy evidence to support contentions that the establishment of windbreaks results in climatic changes, and several reviewers challenged the validity of a feed-back mechanism which might improve rainfall.

counter "dust bowl" conditions, and attempts at growing shelterbelts of a more restricted nature have taken place in a number of African countries bordering the Sahara.

Potential benefits from such shelterbelts, according to various advocates, include: (a) creation of windbreaks to retard erosion and dune migration; (b) provision of greenery and shade for man and his herds, and incentives for settlements; (c) production of timber, on a selective cutting basis for agriculture and industry; (d) provision of employment opportunities for new settlements; and (e) stimulation of integrated grazing and forestry to concurrently provide fodder and trees, and to increase the carrying capacity of the land. However, as has happened in such countries as Algeria, Chad, Ethiopia and Northern Nigeria, attempts to stabilize deserts by large scale afforestation were often thwarted by nomadic herdsmen who burned down forests and trees, and grazing herds which ate the seedlings or otherwise destroyed older trees.

The U.S. experience with large shelterbelts includes the efforts in the 1930's and 40's to combat "dust bowl" conditions in the Great Plains which resulted from a combination of drought and improper agricultural practices. Between 1935 and 1942, about 18,600 miles of shelterbelts were planted. The area of concentration ranged from eastern Montana to western Minnesota and ran down to Oklahoma and western Texas, the center being east and west of the 100th meridian. The project, administered by the U.S. Forest Service, involved the planting of 200 million trees in six Great Plains states. The shelterbelts ranged in width from 1 to 20 rows of trees and shrubs, although most were comprised of 7 to 10 rows. Low plants such as honeysuckle formed the periphery with taller plants such as cottonwood comprising the center in order to gain maximum reduction in wind velocity. The species employed also included Russian olive, conifers, junipers, and spruces.

The results were generally successful in the northern regions of the Dakotas but less so in more arid regions such as Oklahoma and Texas. Substantial failures were experienced in areas where soil information was insufficient, e.g., highly alkaline soils, resulting in large sand blows. As time went on, it was found that rather narrow shelterbelts were needed to best fulfill a wind-erosion control function at minimum cost on the sandier soils. It is estimated that comparatively narrow and parallel one-to five-row shelterbelts, placed at intervals of one-fourth to one-eighth mile, increased small grain and corn yields 0.7 to 1.7 bushels per acre above yields of unprotected fields. This is equivalent to 39 to 95 pounds per acre or 44 to 106 kilograms per hectare.

In the USSR, deserts play an important role in the country's economy. The Middle Asia and Kazakhstan deserts comprise the richest areas, combining natural conditions which are favourable for farming and animal husbandry with extensive fuel, power and raw material resources. The main Soviet efforts at afforestation have been aimed at protection of irrigation projects and channels of communication against sand drifts. Through extensive plantings of trees such as birch, poplar, oak, elm, honeylocust and Russian olive, and shrubs such as Calligonum and Tamarix, forest belts have been created in Middle Asia and the Kazakhastan deserts for which, in all but the most arid portions, great successes have been claimed.

In addition to those of the U.S. and the Soviet Union, fairly large windbreak programs have at one time or another been active in Canada, Denmark, Australia, and Israel, and smaller programs are found in many other countries (see map, Figure 2). Based on an analysis of worldwide efforts, Ostrom and Read (48) conclude that research is needed on the selection and improvement of plant materials for introduction into semi-arid regions; genetic improvement of shelterbelt trees; methods of preparing sites and planting vegetation in areas too dry for natural tree growth; maintainence of plant vigor under drought conditions; windbreak structure design; effects of belts on microclimate, particularly on evapotranspiration; impact of belts on crop yield; and protection of trees against disease and insects.

Based on past experiences, it appears that establishment of large, linear forest shelterbelts to retard desert advance may be practical within a particular country only under certain special circumstances and only after detailed cost/benefit analyses which include social factors have been carried out. For most developing countries, the costs of planting and maintenance will undoubtedly be unacceptable when compared to potential, quantifiable benefits. Establishment of shelterbelts on a regional, trans-national scale appears to be infeasible due to the size and cost of such projects; the difficulty of calculating monetary returns; the magnitude of the associated human disturbance and political problems; and the uncertainties with respect to the effectiveness of such barriers.

Costs associated with constructing large-scale natural barriers can be only crudely estimated since they vary so greatly, depending as they do on local conditions. If one assumes a 200 x 20 km belt (about 1 million acres or 4 billion meters^2) which contains grassland, savannah, shrub, and scattered stunted trees; has low rainfall (20-70 cm/yr); and laterized soils with heavy cracking clays, silty clays and sand; the following tentative costs for an afforestation project may be anticipated (based on the introduction of Eucalypti, probably the best typical candidate):

1. Pitting and planting seedlings would require approximately 5 man-days/acre, with one seedling planted in every 100 square meters. The plantings for the

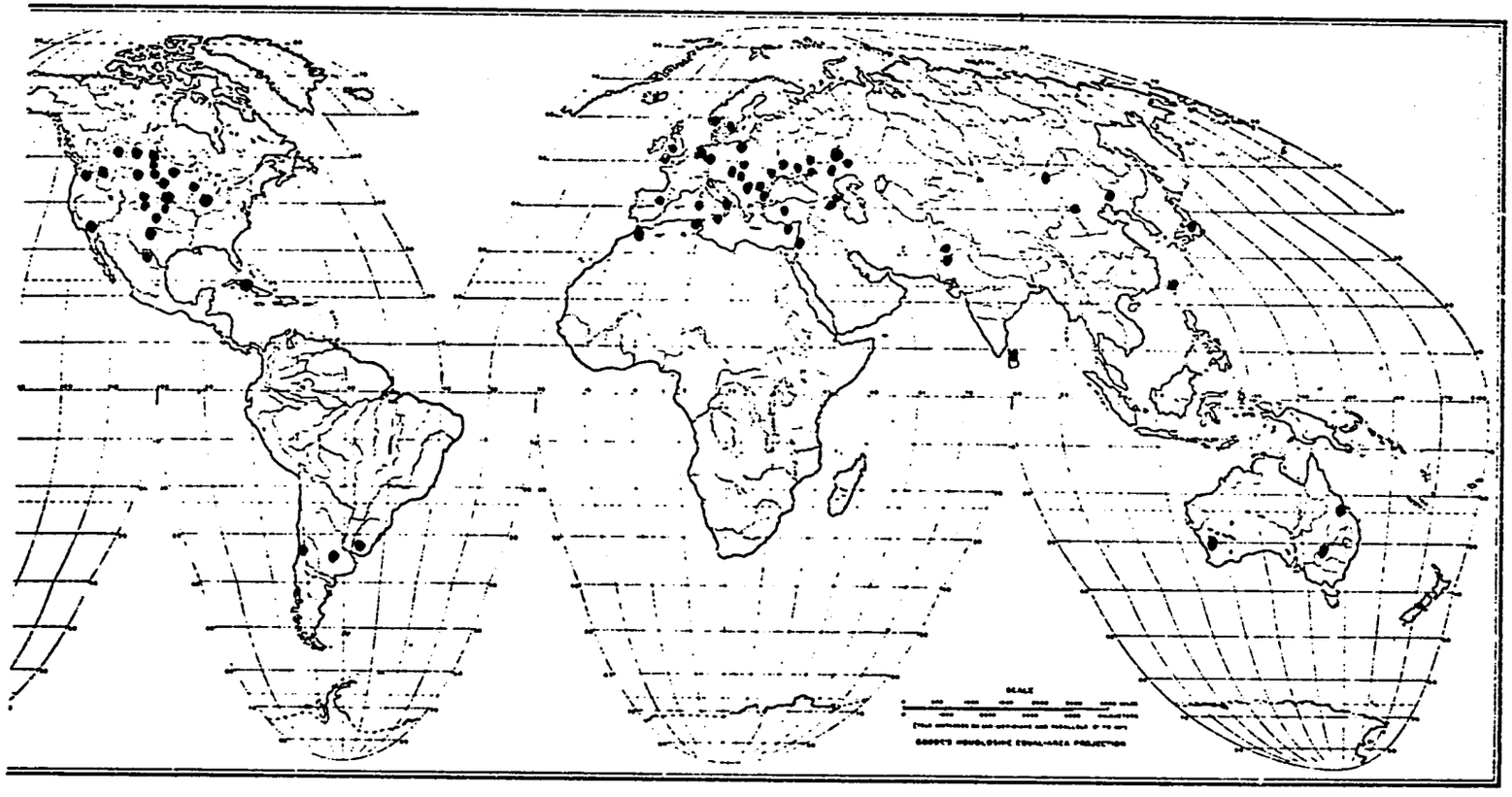

Figure 2. Locations of action and research programs dealing with windbreaks as indicated by origin of publications. (Östrom and Read, 1967; Bib. reference 48).

total area of 4 billion square meters will therefore number 40 million. The labor required is the number of acres (1M) x 5 man-days per acre -- 5,000,000 man-days for 40 million trees, and assuming one man-day in that region costs $3, then the total cost for the tree planting is $15,000,000.

2. The cost of each seedling, from nursery production is about 5¢ (optimistic). This gives a total seedling cost of $2,000,000.

3. Mechanical (tractor) preparation of the soil, grading, rock-removing, drainage implementation, etc., can be very roughly (and optimistically) estimated at about $2/acre, thus adding another $2,000,000.

Thus, the cost of the entire project would be about $19,000,000. Obviously this may be out of reach for such a region, even assuming no political or social constraints.

In the United States, the Weyerhauser Company has used aircraft to drop seedlings into burnt areas, with no soil preparation needed, at a cost of 10¢/seedling. However, these plantings have been made in natural forest land, and not in inhospitable desert and semi-arid zones. It also may be feasible to fire pellets into the soil from aircraft or rapidly moving combine planters. Such techniques might reduce the cost/acre of, for example, eucalyptus planting in arid regions, to about $1.50 per acre.

Containerized planting in which seedlings are raised in their own environment also appears favorable for desert areas. This technique is being used in the United States for revegetating eroded hill regions, particularly with pine trees. Various containers have been tested, including plastic bullets, coconut shells, bamboo tubes, tin cans, specially designed pots of peat or plastic, peat pellets and lengths of plastic tubing. Also being explored are the possibilities of molding bullets out of biodegradable substances, such as wood chips. The pellets can be planted with a compressed air gun which is attached to a small vehicle designed to operate on steep and uneven terrain. These vehicles are able to move over eroded areas during planting without disturbing the site as much as conventional planting machines. Of the various containers tested, the plastic tubes are reported to be the most adaptable to efficient reproduction of planting stock and to mechanized planting. They are lightweight, semi-rigid, and contain numerous perforations that facilitate root escape. In practice their use is simple; lengths of tubing are filled with soil and the seedlings are placed on the surface, allowed to germinate, transported to the planting site, and heeled into the ground.

Many afforestation projects, regardless of scale, rely on the planting of seeds rather than seedlings. Much research and development has been, and is being carried out on methods of introducing seeds rapidly over large areas and then insuring their survival and germination under harsh conditions. (See Bibliographic reference 2 for detailed discussion of problems and techniques).

Mechanized sowing of seeds using aircraft and truck is widely practiced. Air-sowing appears to be less efficient in the interior of deserts with more severe growing conditions because seeds are blown down to basins far away, and seedlings are covered with sand drifts. To make air-sowing more efficient, it is necessary to carry out mechanical protections in row or checkerboard designs, which is the most labor-consuming operation in phyto-reclamation projects.

One of the main agrotechnical difficulties encountered in getting vegetation started is the rapid formation of a hard crust on the upper surface of the soil, whenever it has been wetted and begins to dry out. This crust greatly obstructs seedling emergence. The problem is being attacked by preventing crust formation through the use of soil conditioners,particularly natural soil conditioners such as straw. A recent U.S. innovation has shown that straw crimped into the soil with a standard agricultural disc will remain in place on exposed surfaces even through intense wind or rain storms.

A seed's surrounding environment is very important for quick emergence after germination and a number of innovative approaches aimed at improving the seed environment have been developed in recent months in the United States. One of these is based on the compression of the seeds into small blocks which also contain various aids for their growth. Such blocks, in the form of wafers or pellets, supply the starting fertilizer, protect the young vegetable seedlings from herbicide damage, and also provide anti-crusting materials for soils where severe crusting can delay or prevent plant emergence,or may weaken it due to the extra energy expended getting through the top soil.

Often, noncommercial plants such as eucalyptus and acacia are the introduced species since they root easily in sandy soil, require minimal water, help the sand-stabilization situation by their quick growth as wind-breaks, and they leave a lot of leaves on the ground which subsequently regenerates nutrients. They are considered a good first generation device for establishing soil conditions under which something better might grow.

Obviously, quick growing plants of commercial value would enhance the cost/benefit ratio for afforestation projects. Consequently, much research on plant genetics and propagation is underway, including testing of alternative plant species under different conditions of climatic and soil types. It is reported that the planting of large areas with forage shrubs could have far-reaching consequences for the 150-250 mm (6-10 inches) winter rainfall belt where fodder grasses will not grow. Techniques for planting browse shrubs in Israel have been perfected so that it is now possible to plant successfully even with only 100 mm (4 inches) of rainfall. The plants are very long-lived and can stand hard grazing. In early trials of pasture plants, one native fodder shrub has distinguished itself, the ubiquitous Mediterranean saltbush, Atriplex halimus. Although the amount of forage in arid zone pastures in dry years can sink to zero, with saltbush there is always something to browse on even with 40 mm (2 inches) of rainfall. The carrying capacity of the improved range has been increased from one sheep per hectare up to four sheep and in one case in Israel, a ewe flock was saved by saltbush pasture. Saltbush maintained sheep to the third year after planting, even during drought years, and contrary to expectations, cattle thrive better on saltbush than sheep or goats. The shrub reaches a size of 100-150 cm (3.5 - 6 feet) thus a large planted area acts as a wind barrier, shades the ground and can obstruct the free flow of run-off water. The effects are reduced dust, deposition of wind-carried erosion products, higher humidity at ground level, slow evapotranspiration instead of quick evaporation, and reduced glare -- creating a better microclimate for an understory of herbaceous plants or even the cultivation of barley between rows of shrubs. The consistent success of saltbush in arid zones has now led to its introduction not only in Israel but also as a browse shrub in Iran and Australia.

The pricklypear (Opuntia inermis) thrives in Eritrea and on the Mediterranean coast, where it provides excellent fodder for camels and goats. It is not found extensively in semi-arid and desert areas of other regions, probably because of the extreme climatic conditions, but several experts have recommended that the possibility of its introduction into new areas certainly merits investigation. If it became established, not only would it provide food for domestic animals, but it might also help to check excessive runoff from rainstorms.

Mesquite, Prosopis chilensis (formerly misidentified as P. juliflora), was introduced into Sudan about 1928. This semitropical American species has a wide ecological range and is obviously capable not only of survival in low-rainfall environment, but also of production of some valuable plant materials. The older plantations near Khartoum date back to 1938-1939. One should not be over-persuaded by such enthusiastic statements as Wunder's: "...it is without any doubt the species which is able to change the face of the arid zone of the Sudan in a very favorable manner." (73) However, it is a species with undoubted merit in arid lands. One of its growth forms spreads like an umbrella sitting on the ground. This provides effective protection against soil erosion and is also a good shelterbelt. The mesquite green belts that were planted were intended to reduce the effects of early summer duststorms. It is a hardy plant (bush or tree); once established, it may withstand repeated cutting. Its pods provide good fodder. It is easy to grow; the pretreated seeds germinate readily, and survival on a plantation may reach 90 percent under proper silvicultural methods.

Bibliography reference (9) presents a detailed account of a 12-year experiment on desert encroachment control in the Ksar Rhilane area of Tunisia. Tests were carried out on requirements for irrigation and soil amendments, the efficiency of various crops and plants in terms of both retarding desert advance and economic productivity, the suitability of different types of artificial sand stabilizers. Among the conclusions of the study was that date palms are the principal trees to plant; olive trees do quite poorly; insects proliferate despite the harsh climate and may be the single greatest obstacle to a viable agricultural program; barley and wheat offer the best hope of all the cereals; and protective measures should include supervision of grazing by cattle (in terms of number of acres and rotation of pastures), limits on cutting of trees within a zone bordering the perimeter, and construction of outer bulwarks of artificial dunes and windbreaks. The necessity of strict measures to protect soil fixing vegetation in the border zone cannot be understated and, to be effective, may necessitate furnishing fuel at very low prices to discourage trade in charcoal. The latter observation is well supported by situations which have arisen in other regions of the world, Somalia being an excellent case in point, where a large charcoal export trade has led to

intensive desert encroachment over vast areas of the country.

Despite a growing array of new and improved techniques and methodologies for combatting desert encroachment as a result of research, development, and testing, many experts believe that the key to significant improvements in the situation over the long term is improved land use policy making and implementation at the national level. Cloudsley-Thompson (7), for example, observes that:

> "The only solution to the problem of desert expansion...appears to lie in governmental policies that would change the entire economy of the population of the arid regions involved. At present, such policies appear to be directed largely toward the settlement of nomadic populations, although the nomadic way of life is probably the only one that will ever produce anything of economic value from large areas of the world. If traditional nomadism disappears, as seems likely, it will be impossible to re-create it. Vast areas that are now productive will then become permanently useless to mankind. It would be better in the long run to encourage and modernize the nomadic way of life. The hardships that nomadic people have to endure can be ameliorated by the provision of emergency aircraft and mobile hospitals, shops, and schools. Grazing could be controlled and improved, news of distant rainfall would be transmitted by radio, and so on."

V. WATER MANAGEMENT TECHNIQUES

Many experts have observed that irrespective of the adoption of other control techniques, desert encroachment can be effectively prevented or contained only through proper management of the limited water resources of the area. Not only is moisture required to sustain vegetation that is deliberately introduced as barriers against encroachment, but encroachment is often triggered and sustained by unmanaged exploitation of groundwater which results in a lowering of the watertable, and subsequent induced aridity. As the result of marked seasonal variations in an already sparse rainfall regime, water conservation in arid lands requires the application of innovative water management techniques. New advances in the water resources field are helping to overcome formerly insuperable problems of aridity. Where progress is made, it may then become feasible to both prevent the initiation of new localized encroachment problems and also to carry out vegetative-based remedial programs to mitigate or control ongoing problems.

However, a limiting factor with respect to the implementation of water management projects is the expense involved; they will usually not pay for themselves in the near term unless the objective is the development of intensive, high-value agriculture -- rather than prevention of desert encroachment per se. Recent research and demonstration projects indicate that it may be possible, through a combination of new water conservation techniques and use of new varieties of commercial crops, to develop economically viable agricultural production along desert interface areas, and concurrently benefit from the deleterious affect of the vegetation on the climate and soil/sand stability.

Sandy soils actually have many advantages for agriculture production despite low water-holding capacities: they are well aerated and promote fast decay of crop residues; their balance of nutrients can be quickly modified; sand accepts heavy rains without large runoff losses and readily yields its moisture to crops; sand is easily tilled; it is fast draining to permit timely field work; and nutrients are more readily accessible to plants growing in the sand. Furthermore, recent advances in the utilization of saline water for desert irrigation have significantly increased the alternatives for crop development.

Efforts have been made in recent years to develop irrigation techniques and practices for arid lands which foster the maximum economy of water use. In particular, research and testing have been carried out on a completely underground irrigation system which feeds water directly to the plant roots. Known as "trickle" or "drip" irrigation, the system relies on the use of a plastic pipe with nozzles spaced 0.5 - 1.2 meters apart and placed in the rooted layer of the soil. The water enters the soil through these nozzles and spreads by capillary action into the root zone of the plants. Soil scientists in Israel have been getting between 50 to 100% greater yields on their sandy desert soils using about half as much water as would be applied by normal irrigation methods. It is noteworthy that the water used is so saline that only mediocre yields were obtained when it was applied via surface or sprinkler irrigation.

In trials of this new technique in a region of Tunisia in which enormous amounts of water were previously required to support one (or at best two) crops per year, three harvests were realized in barely 10 months with a quantity of water which amounted to a quarter of the usual volume. This technique uses less water because it reduces or eliminates two forms of water loss which occurs in soil surface irrigation system, namely, the losses during conveyance of water to the site and the evaporation from the soil surfaces. Since the feed can be so controlled that the moisture limit lies ten to twenty centimeters below the surface, only the crop roots reach the water; weed seeds in the surface soil are condemned to drought and cannot germinate. Various plant diseases caused or aided by moisture do not occur and the very precisely controllable water feed makes more exact fertilization possible.

Experiments have indicated that there are a number of serious problems associated with drip irrigation systems although they have been effective for certain types of high value crops such as pomegranates, bananas, and ornamental in Israel. Drip systems can pose severe salinity problems in certain soils and in several instances have not proved to be reliable. Additional research and testing is needed to pinpoint the combinations of plant types and soil conditions best suited for the application of this technique.

In many arid zones of the world, much of the benefit that could be gained from the rainfall that does occur is lost because the water is not gathered into utilizable quantities. Various methods have been developed to modify land surfaces in arid zones so as to capture this runoff water and direct it to the most useful areas.

When a population is almost entirely dependent on its flocks and herds, it is clearly impossible to counter the rape of the earth that results from overgrazing. Nevertheless, the situation certainly could be improved. Multiplication of the number of points at which livestock can secure water helps to widen the area of grazing. This is being done in the Sudan by the boring of new wells and by the construction of *hafirs*, or artificial ponds, in which rainwater may be stored for 3 or 4 months. The capacity of a hafir ranges from 10,000 to 80,000 cubic meters of water. Hafirs are relatively inexpensive to construct but are extremely wasteful, because much of the water they contain is lost through seepage and evaporation. Seepage could be eliminated by lining newly constructed hafirs with thin plastic sheeting. In order to protect this sheeting from attack by termites, however, a double envelope containing earth and insecticide would have to be used and the whole buried in the soil, so that it would not be damaged by the hooves of grazing animals. A problem would still be posed by the fact that both layers of plastic would be vulnerable to termite attack above the water level.

A six year development program in Israel has resulted in the development of micro-catchments which are small depressions in the soil so constructed that the run-off from rainfall will reach a plant growing in the center of the catchment. Preliminary results on trees planted in micro-catchments show that the additional water obtained from micro-catchments of 250 to 1000 square meters in size is sufficient to ensure the establishment and development of a variety of fruit trees on barren desert plains. It has also been clearly demonstrated that saltbush can be grown effectively in micro-catchment basins smaller than 10 square meters. These saltbushes fully exploited all the available water from the catchment and showed considerably stronger growth than if they were planted without the catchment system. The cost of constructing this system of microcatchments is very low -- between $5 and $20 per hectare depending on the catchment size. The increased annual returns economically justify their construction since costs are repaid within two to three years. This work is experimental at present, but micro-catchments can be expected to turn some of the barren desert plains into range lands. This technique has been developed especially for desert regions with rainfalls in the 4"per annum range; besides saltbush it has been used for growing fruit trees (pomegranates, olives, carob, apricot, and vine) and pasture shrubs.

The Food and Agricultural Organization (FAO) is carrying out a project on the evaluation of plastic "Aprons" as an aid for afforestation in 11 arid land countries.

Small plastic sheets (approximately 4 feet square) are placed loosely over small basins with the seedling protruding from a hole in the center. The objective is to determine the effectiveness in moisture catchment from dew in arid areas, and the reduction of evaporation and suppression of weed growth near the seedling.

Other examples of the application of catchment systems to runoff collection abound. A "syrup pan" system for spreading run-off from a 500 hectare watershed onto 50 hectares of cultivated land in Texas increased crop yield two to three fold. Contour level benches in North Dakota with a catchment-to-cultivation area ratio of about 2:1 increased grain sorghum yields about 300 kilogram/hectare, while run-off water spread on levelled land in Colorado, resulted in up to twofold yield increases in field crops. In Australia, a catchment cultivated ratio of about 25:1 increased yields of range plants by ponding run-off water behind low earth banks. In South Africa, in the 150 to 200 mm rainfall area, water-spreading ("saidam" cultivation) is practiced to take advantage of run-off from late summer storms.

Even though rainfall in deserts is very scant, the limited percolation of water in some arid soils and the resulting excessive run-off, cause sudden tremendous flash floods in the valleys and depressions. After a rainfall of as few as 10 mm on the watershed, it is no rarity to see a flood of 30,000m^3/hour crashing for four to five hours through a "wadi" draining a 50 square kilometer catchment basin. These great quantities of water are practically the only source of irrigation water in many areas but, unless they are harnessed, they are lost and create nothing but extensive soil erosion. Various types of dams, dykes, terraces, and spillways were, and still are, the answer to this problem. Dams can be reinforced by the planting of bushy plants such as saltbush in front of each dam. A "bush-dam" alone may be sufficient and at times even better than a stone dam. The considerations are: (a) a bush-dam is pliable and may be better able to withstand the force of the flood than solid stone or earth dams, (b) the dam would grow in size concurrently with the silting processes, (c) the bush-dam filters the flood water, thus enriching the soil with organic matter, (d) the costs of construction are lower, and (e) the plants themselves may provide grazing.

Most sandy soils do not retain water very well, and the cost of irrigating them can be prohibitive. If the problem of moisture and nutrient retention can be economically solved, sandy soils hold considerable production potential. A new approach to this problem uses an impervious barrier which is placed 2 feet below the surface of the soil. This barrier, made of asphalt, controls the

percolation rate of moisture and nutrients in deep sandy soil and was jointly announced by Michigan State University and American Oil Company in the fall of 1966. By reducing water needs the subsurface asphalt barrier could make irrigation agriculture feasible and utilize more of the arid sandy areas of the world. It is almost ready for commercial application and appears to be technically and economically feasible. The asphalt strip, 1/8-inch thick, is spread under the surface with a machine having a plow-like shoe. As it moves through the soil, the asphalt emulsion sprays into a gap underneath this shoe. Ammonia sprayed on the asphalt hardens it instantly. Where labor is cheap and available an alternative is to remove the sand and put the barrier in place manually before replacing the sand.

In retarding the downward movement of soil moisture the system establishes a temporary water table perched above the barrier, and reduces water seepage through sand from 8 cm per hour to about 2 cm per hour. It is this ability of the asphalt barrier to decrease water and nutrient losses that improves crop yields. Because the barrier is not 100 per cent water-tight it permits leaching to prevent salt build-up, and also prevents "ponding" after heavy rainfalls. The barrier also permits higher plant populations and has produced better yields than irrigated non-barriered controls. In many of the trials, asphalt barriers made irrigation unnecessary in areas where crops could not ordinarily be grown under dryland conditions. The soil above the barrier holds about twice as much water as untreated soil and the crops require about half as much nitrogen and fertilizer and about 1/3 as much water. Thus, it results in very great irrigation water savings. Yields of vegetables grown in sandy soils over asphalt were 50 to 100% higher than those on adjacent plots without the barrier, and in tests with sugar cane in Taiwan it used only one third as much irrigation water as previously and yet the yield increased by 400% in one year. The largest single item of cost in the process is that of the asphalt itself. It is expected that 1,000 gallons per acre is satisfactory in terms of effectiveness and lifetime. In the U.S. with asphalt delivered to a typical job site the cost of the asphalt is between $100 and $150 per acre (10¢ per gallon), and the total cost is between $200 and $300 per acre for the system. The asphalt barrier is guaranteed to last 15 years and is expected to last considerably longer than that. In Michigan the largest barrier of 25 acres has been down for over 3 years and has shown no sign of deterioration.

To put additional land into agricultural production and where sandy land is available. the asphalt moisture barrier could be used to:

1. reclaim areas of sandy soils now considered non-arable, either with irrigation, or where rainfall is sufficient, without it;

2. make water available for additional land by conserving water on sandy land already irrigated; and

3. save water transportation cost, where water and sandy land lie close together.

Another approach to conserving soil moisture which also provides for a more favorable soil temperature is the use of organic materials as soil mulches. Bituminous mulches developed for warm, semi-arid areas of southwestern United States have promoted improved crop yields and at the same time prevented soil erosion by wind and water. Additional information on this subject is found in Chapter IV of this report, and also in Bibliography references (68) and (72).

DEW RETENTION - A yearly water balance of certain desert plants shows that they do not rely only on the water taken up from the soil. It seems well-established that dew is taken up by leaves, and may even be transported from the leaves to the roots where it can be secreted into the soil. Plants growing under arid conditions benefit decisively from the uptake of dew. There have been several systems developed to artificially create better climatic conditions for the formation of dew on plants and in soils. In Chile a system of nylon strips hung on wires a few inches above the soil has shown promise as a means of increasing the dew run-off and the condensation of mists, and an insulated plastic which is brilliantly white in daytime and completely black in terms of nighttime wave lengths has been developed by Royal Dutch Shell. The latter is reported to perform as a very efficient dew collector for small scale irrigation purposes though trials are not yet complete. And, as noted earlier in this chapter, the FAO is testing plastic "Aprons" which, among others, seeks to concentrate and collect dew.

EVAPORATION - EVAPOTRANSPIRATION SUPPRESSION - A simple means for reducing water stress on growing plants is through application of whitening materials to the soil or, possibly, directly to the plant. Applied to the soil during periods of fallow, these materials increase the

reflectivity of the surface to incoming solar energy. A dark brown soil will normally reflect 10-15% of the short-wave solar energy incident on it. Application of whitening materials (Kaolin, lime, whitewash) can increase the proportion reflected to perhaps as much as 50%. The energy reflected is not available then to evaporate water stored in the soil.

The principles of shelter-effect and of increased reflectance can be combined and applied to the serious problem of reducing evaporation in impoundments. In western Rajasthan, for example, many small shallow ponds have been constructed and these supply an important share of all the water available to the human and animal populations of the region. In Rajasthan, annual evaporation from free water can be 250 cm. This may be 50-75% or more of the pond storage capacity. Floating mats or rafts of jute or other local materials would, by reducing the extent of exposed water surface, reduce the evaporation therefrom. These mats can be painted white and treated to maintain that color. Reflection would reduce the total energy incident upon the water. Mat fences bordering the ponds would reduce the inward transport of air (which becomes heated in passage over dry land) and would further tend to decrease evaporation.

Much research has been carried out on the retardation of transpiration by plants by means of chemical agents which close the minute pores on leaf surfaces. A number of agents, including abscisic acid and silicon sprays, have been used effectively on certain crops under controlled conditions. There is evidence, however, that anti-transpirants result in reduced photosynthesis and plant growth and, in addition, the overall ecological effect of some of the chemicals (which may be toxic above certain levels) is not known. For these reasons, plus the high cost of procuring and applying the chemicals, the use of anti-transpirants in arid regions of developing countries does not appear attractive at the present time.

VI. CONCLUSIONS AND RECOMMENDATIONS

For the purposes of summarizing the needs and potential remedies with respect to combatting desert encroachment, the following comments by A. T. Grove at the UN Seminar on Development and Environment are worth reproducing here:

> "Except for those arid parts of Africa that yield oil, and the limited areas near the Nile and Niger that are irrigated, the lands at the margins of the desert in Africa are poor and not likely to be highly productive. There is little to be said in favour of great schemes for climatic amelioration involving, for example, the diversion of great rivers such as the Zambezi and the creation (or reformation) of great lakes like those that existed in the humid periods of the Pleistocene. Such lakes would be extremely expensive to make, they would flood land which is not productive, and it is unlikely that they would lead to an increase of rainfall that would yield returns in any way commensurate with the costs involved. It is conceivable that destruction of rain forest in the Congo basin, for example, may have reduced the rainfall of areas further from the equator; by how much it is impossible to say. But there is no question of afforestation in such a region on a scale sufficient to restore the situation. In special circumstances cloud-seeding may be found to be rewarding and it is possible that in the future ways will be found of modifying the general circulation advantageously. But I would not regard any of these as being of much concern to us at present.
>
> "Linear forests have been established in the USA and USSR as parts of programmes to combat desert and there have been schemes to create a great strip of forest across Africa to form a barrier against the encroachment of the Sahara. The enormous size and cost of such a project have prevented much progress being made with it; the monetary returns are incalculable; the human disturbance and political problems involved would be great; and the effectiveness of such a barrier is uncertain.

"I would suggest that, with the limited resources available it might be advantageous at the present time to concentrate them in attempts to improve the amenities and the productiveness of relatively small areas in the desert marginal areas, where natural conditions and transport facilities are already favourably disposed, rather than to spread efforts at combating desert encroachment over the entire frontal areas.

"The problem is a long-term one and one must view it in the light of long-term developments in the geography of the desert marginal areas in Africa. At present populations in the semi-arid lands of the continent are increasing at rates of about 3 per cent annually as they are elsewhere in Africa. In the near future, however, it is possible that the rural population, especially the pastoral population, may decline. This has already happened in parts of the Sahara and Libya affected by oil production. There are three trends that are more generally effective. Firstly, young people going to school are becoming literate and have greater expectations than their parents had; secondly, people are consuming more and have the desire to consume more than they did; thirdly, people are congregating more near roads and in large towns. It is just as important to keep track of these changes in the human geography of the desert margins as it is to monitor changes in the vegetation cover and calculate trends in precipitation.

"In fact, of course, if effective measures are to be taken against desertification, the people involved must be persuaded of the advantages to them. Wherever possible measures should be of a positive rather than a restrictive character. By this I mean that if it is seen to be inevitable that people are going to concentrate in large settlements in sensitive areas, then as well as attempting to regulate the felling of trees for fuel and timber, authorities may be able to cheapen alternative supplies of fuel and construction materials, provide young fruit trees at low cost, and so on.

"Perhaps the main problems are presented by pastoralists and pastoralism. The traditional systems do not fit neatly into the framework of a modern state. Nomadic flexibility is an advantage to people

living in such unpredictable environmental conditions, and nomadic mobility allows good use to be made of the variable grazing. Settlement of the pastoralist is expedient politically and has some economic advantages, but the greater rigidity seems to me to involve considerable risks of disaster when the drought years come as they will. In UNESCO's Use and Conservation of the Biosphere (1970, p. 35), it is noted that nomadism as a careful pastoral continuum is the least traumatic of human influences and as a form of husbandry utilizes areas which could not be utilized by man in any other way." (26)

Based on the analysis of the extent and significance of desert encroachment problems facing developing countries, and the current and projected short-term state-of-the-art for coping with these problems, the following recommendations are proposed:

1. Since quantitative physical and economic data on desert progression are lacking, and since palliatives or cures must be tailored to specific climatic and geographic conditions, intensive technical and cost analyses should be undertaken for particular and geographic-specific situations in countries which are experiencing pressing but seemingly manageable encroachment problems. Analyses of the benefit-cost relationships should be given high priority, for most desert encroachment control projects will be funded only if the ratio is positive. One model study concluded that an investment of $1 million per square kilometer on desert retardation would have to be offset by creation of permanent arable land with a cash crop produce/annum of at least $200/hectare ($30,000/km^2). Such models have not been rigorously refined and tested, and the many potential non-agricultural benefits from such a holding action quantified.

2. Experimental projects should be carried out using repetitive satellite imagery to establish baselines of land use patterns and to monitor seasonal changes in desert interfaces, soil moisture, vegetation, and human settlements. Toward this end, desert encroachment experiments in developing countries should be incorporated into the ERTS-B and Skylab earth resources satellite programs. Satellite imagery may provide a breakthrough in providing the broad scale data needed for rational land use planning in the desert margins. In addition, aerial black and white and color photography spanning many years exists in some countries and should be utilized for comparative studies.

3. The impact on desert margins of developmental activities should be carefully evaluated during the project planning and design stages. This is particularly essential for new groundwater development programs, road construction, the damming and diversion of rivers and streams, agricultural activities, and resettlement programs for nomadic peoples, since all have the potential for triggering or aggravating encroachment situations.

4. Experimental trial plots should be established in developing countries to examine the results of different kinds of land use on vegetation cover with, for example, the exclusion of animals or fire, or both. Experiments should also be carried out on various natural and artificial means of immobilizing soils and desert sands. The cost, feasibility, and direct and indirect benefits of these activities should be carefully evaluated.

5. Steps should be taken to improve the quality and useability of meteorological and hydrological data collection in interface areas to strengthen indigenous capabilities for recognizing and monitoring changes in desert boundaries on a regional basis. Consideration should be given to including this aspect as an element of any global environmental monitoring system which may emerge as the result of actions endorsed by the UN Conference on the Human Environment this June.

6. Research and development should be intensified on low cost, practical techniques for stabilizing desert sands, particularly on the use of indigenous raw materials and on the breeding and establishment of rapidly growing vegetation suited to arid lands, preferably of commercial value. At the same time the possibility of heretofore unknown "breakthrough" approaches should not be ruled out and explorations should continue into the use of new sealers and water manipulation approaches.

7. Inasmuch as amelioration of the desert environment is necessarily bound up with the availability of moisture, strong efforts should be exerted in the direction of refining and developing water management techniques which will conserve and ensure an adequate and sustained water yield.

8. Improved techniques and methodologies for carrying out integrated land use planning in the semi-arid and arid zones are essential if desert encroachment is to be controlled more effectively over the long term. Such planning must be aimed at bringing population and the limited and fragile land resources (soil, water, forests) into proper balance, and must therefore place strong emphasis on both the social and physical factors associated with readjustments in traditional modes of land use. Expertise in this area is limited and fragmented, and consolidation of the required scarce skills should be considered, both in the developed and developing countries.

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SOURCES OF ADDITIONAL INFORMATION AND EXPERTISE ON DESERT ENCROACHMENT PROBLEMS

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