Chapter VI

Development of Low Water and Low Nitrogen Requiring Plant Ecosystems for Arid Land Developing Countries

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ABSTRACT

This paper describes a low industrial input, commodity-oriented approach to stimulating economies of arid land countries using arid-adapted plant species. It suggests legume tree biomass farms using *Acacia, Leucaena,* and *Prosopis* genera to provide increased fuelwood. Increased soil fertility and ensuing water use efficiency could be achieved by using deeply rooted, drought-adapted species such as *Acacia albida* and *Prosopis cineraria* that fix nitrogen. Arid-adapted shrubs such as jojoba *(Simmondsia chinensis),* and guayule *(Parthenium argentatum)* could provide stable production of cash crops. *Prosopis* and *Acacia* pods, atriplex forage, *Leucaena* forage, and cactus pads could increase livestock food supplies, Increased production of traditional food staples such as millet, sorghum and peanuts can be achieved by intercropping them with arid-adapted legumes. Aggressive management of these plants could help reduce the spread of desertification.

Little government support has been made available for these activities despite their widespread use by indigenous farmers at subsistence levels. A research and development program is suggested that would establish living germplasm collections and select and propagate superior clones, Several months after stand establishment, these plant systems can be grown without supplemental irrigation by using ground water within 10 m of the surface or by using a minimum of 250 mm annual rainfall. Phosphate fertilizer, micronutrients, and rhizobial inoculation are required, but the nitrogen needs will be provided by nitrogen fixing plants. Less machinery will be needed to till these systems.

Wide-scale implementation of these systems would greatly enhance agricultural productivity at the local level, where it is most needed, and indirectly stimulate nonagricultural sectors of the economy. The increased economic well-being of farming classes could lead to decreased political unrest and greater stability of governments in arid lands, Foreign policy efforts to strengthen the peace by buildup of military hardware systems has proven futile in Ethiopia, Iran, and Iraq. Development of arid land plant production systems is a viable alternative to enhancing peace in politically volatile arid land countries.

INTRODUCTION

This document was prepared at the request of the Office of Technology Assessment (OTA) of the U.S. Congress to provide guidance in development of low energy, nitrogen, and machinery requiring agricultural systems for semiarid developing countries, The format closely follows OTA's specific issues and questions. For the convenience of the reader, these requests are reproduced in appendix A.

Identifying plant physiological, morphological, and ecological characters that lend themselves to a minimal machinery, capital, and fossil fuel input is the subject of a paper by Felker and Bandurski (14) in which orchards of leguminous trees were suggested to most closely approximate an ideal system for minimizing industrial inputs. Other closely related shrub ecosystems have been suggested to achieve similar objectives (32). Identification of arid land plant species that would lead to more stable and productive ecosystems has been intensively investigated by Felger (11). Recent review volumes (42) and symposia (27,6) have dealt at length with arid land plant resources. This document attempts to synthesize the knowledge of arid land plant species, focusing on minimal energy input agriculture and a pragmatic commodity-oriented approach designed to provide major needs such as fuel, forage, and food staples required for arid land economies.

BENEFICIAL ASPECTS OF SEMIARID PLANT PRODUCTION TECHNOLOGY ON SIMIARID DEVELOPING COUNTRIES

Development of leguminous trees (14) and associated semiarid ecosystem plant components such as saltbush *(A triplex* spp.) (19), leucaena (Leucaena leucocephala) (15), cactus (Opuntia and *Cereus* spp.) (33,52), jojoba (*Simmondsia chinensis) (23),* and guayule *(Parthenium argentatum) (50)* can make a significant contribution to meeting the major commodity needs of people in semiarid developing countries. Some of the main biological needs and appropriate approaches to supplying them are as follows:

1. **Need:** increased availability of inexpensive fuelwood.
   Approach: use of leguminous tree biomass farms with *Prosopis*, *Leucaena*, and *Acacia* species.
2. **Need:** increased soil fertility to triple or quadruple water use efficiencies of food staples so that productivity is water-limited and not fertility-limited.
   Approach: use locally respected, drought-adapted, nitrogen-fixing legume tree such as *Acacia albida* and *Prosopis cineraria,* use shrubby legumes such as *Dalea* species, and use perennial arid-adapted herbaceous legume such as *Zornia* and *Tephrosia.*
3. **Need:** production of cash crops for farmers and for foreign exchange.
   Approach: use perennial arid-adapted plants, such as jojoba, guayule and high value, drought-adapted annuals, and ephemerals, such as sesame when grown in conjunction or rotation with arid-adapted nitrogen fixers.
4. **Need:** production of livestock food and forage.
   Approach: use arid-adapted, salt-tolerant shrubs, such as saltbush *(Atriplex* species) in conjunction with high water to dry matter conversion plant specialists, such as spineless cactus *(Opuntia ficus-indica)* and high protein and/or sugar content pods of leguminous tree species of *Acacia tortilis, Acacia albida,* and *Prosopis* spp.
5. **Need:** sustained production of traditional food staples, such as millet, sorghum, groundnuts, and cowpeas.
   Approach: intercrop the annual staples with nitrogen fixing trees previously demonstrated to stimulate annual legume yields such as the association with *Acacia albida* and peanuts.
6. **Need:** slow the spread of desertification.
   Approach: when intensive management of forage, fuelwood, and staple products are carried out as outlined above, desertification will slow.

WHERE TECHNOLOGY IS USED AND STAGE OF DEVELOPMENT (SUBSISTENCE, COMMERCIAL, OR RESEARCH)

Development of Tree Legumes for Fuelwood

Areas of use: *Prosopis alba* and *P. nigra* were reported to have fired industrial boilers and steam locomotives during World War II in Argentina (10). In Chile, the leguminous trees chanar *(Geoffrea decorticans)* and espino *(Acacia caven)* have been widely harvested by Indians and present day subsistence farmers for fuel (2). Mesquite wood and charcoal *(Prosopis* species) is highly esteemed and widely used in the Southwestern United States in steakhouses for barbecues and home heating, From 1956 to 1965, 78,000 metric tons of mesquite charcoal and 200,000 m^3 of mesquite firewood were recorded as items of commerce in Mexico (29), In the Jodphur state of India, *Prosopis* was declared the "royal plant" because it provided the bulk of the fuel to the local population (20). *Acacia* forests are harvested along the Nile 400 km upstream from Khartoum, Sudan, and brought to Khartoum for brick making and other industrial uses (24). In the Sahelian zones of Africa, many of the *Acacia* species such as *A. tortilis, A. seyal,* and *A, senegal* are consumed for woody biofuel.

Research organizations: The Central Arid Zone Research Institute in Jodphur has been conducting research on leguminous trees as sources of biofuels since the early 1940s (1), Their work is meagerly documented in the scientific literature and, from the lack of recent papers in the literature, their current research on tree legumes does not appear to be very active.

The Forestry Research Institute in Khartoum, Sudan, has received about $200,000 from the International Development Research Center (Ottawa) to evaluate *Prosopis* species under 200, 300, and 400 mm annual rainfall regimes. Much of the seed material for this experiment was supplied by the University of California-Riverside mesquite project. The United Nations Development Program (UNDP) provided support for Felker to supply seeds, mesquite rhizobia, plants, containers, and consultation to conduct varietal trials with 30 selections of leguminous trees (most *Prosopis)* in the Sudan at the Forestry Research Institute, Over 400 acres of *Prosopis* have been planted along irrigation canals in the Sudan courtesy of the Sudan Council of Churches to prevent sand from blowing into and filling the canals (26).

Dr. J. Brewbaker at the University of Hawaii has been conducting extensive research in Hawaii, Colombia, and the Philippines, on the development of leucaena as a biofuel crop. In the United States, the U.S. Department of Energy has funded research on *Prosopis* under Felker at the University of California-Riverside to develop an arid-adapted germplasm collection; to evaluate the collections in field conditions under drought, heat, and frost stress; to study nitrogen fixation and salt tolerance; and to clonally propagate outstanding single trees.

Use of Nitrogen Fixing Trees to Increase Soil Fertility

Areas of use: *Prosopis cineraria* has been used on a subsistence level by farmers in the India-Pakistan region to increase the yields of their pearl millet crops. Soil chemistry studies (46) corroborated increased nutrient contents and forage yields under *P. cineraria* trees versus other trees and open control areas. *Acacia albida* is widely used on a subsistence level in the West African countries of Senegal, Upper Volta, Mali, Niger, and Chad to increase the yields of sorghum, millet, and peanuts grown beneath the tree canopies (12). *Parkia biglobosa* was observed by this author growing in sorghum fields in a 400 mm annual rainfall regime where farmers stated the *Parkia* also increased the yields of their crops.

Yields of grasses and forbs grown in a growth chamber on soil from beneath mesquite canopies were four times greater than herbage yields grown on soils from outside mesquite canopy cover (49). The stimulation of forage yields after mesquite removal in the Southwestern United States is probably due to increases in soil fertility supported by nitrogen fixation and reduction in competition for water. Mesquite nitrogen fixation and soil fertility increases on the 72 million acres (38) presently occupied by mesquite in the Southwestern United States is an unrecognized resource. Leucaena *(Leucaena leucocephala)* has been widely used in the Philippines in rotation with other crops, as a companion crop, and as a green manure with other crops to increase soil fertility.

Research organizations: Dr. Y. Dommergue, working for ORSTOM in Dakar, Senegal, West Africa, has conducted rhizobial inoculation trials with many African Acacias including *Acacia albida* and at this writing is actively involved in nitrogen fixation aspects of semiarid soils. Dr. Habish at the University of Khartoum, Sudan, published excellent papers on characterization of Acacia-rhizobia symbioses (21), but is now a dean at the University and no longer actively involved in research. A University of Arizona group, funded by the National Science Foundation (NSF), with Dr. Pepper as principal investigator, is collecting and characterizing rhizobia strains from many arid-adapted legumes.

A three-year $650,000 NSF grant has been awarded to study nitrogen cycling in a mesquite dominated desert ecosystem in southern California. This project involves: 1) an ecology group headed by Dr. Philip Rundel at the University of California, Irvine, that is conducting dry matter productivity analyses; 2) a University of California-Riverside soils group headed by Dr. Wesley Jarrell, that is converting the dry matter productivity measurements of the Irvine group into nitrogen productivity and conducting soil moisture profile measurements with 20 ft deep neutron probes, quantitating soil chemical characteristics on and around the site, quantitating denitrification, and developing in *situ* acetylene assays; and 3) a Washington University (St. Louis) group headed by Dr. D. H. Kohl that is correlating the above-mentioned findings with natural abundance $^{15}N^{14}N$ measurements to develop qualitative and perhaps semiquantitative assays of nitrogen fixation from dried plant samples,

The Department of Energy has funded studies on cross-inoculation of *13 Prosopis* species (15), has conducted greenhouse studies of the effect of heat and drought stress on *Prosopis* nitrogen fixation, and has developed models comparing efficiencies of water and nitrogen inputs to increasing productivity of semiarid rangelands (16). USDA scientists have demonstrated that fertility can dramatically increase water use efficiency of rangeland species in a lo-year study on Montana rangelands (51). The USAID-supported Niftal group at the University of Hawaii maintains large stocks of rhizobia. Basak and Goyal (3) at the Central Arid Zone Research Institute at Jodphur have published cross-inoculation data and temperature and salinity tolerance characteristics for rhizobia for semiarid adapted leguminous trees in India,

Development of Cash Crops on Semiarid Lands

Areas of use: Jojoba *(Simmondsia chinensis), a* non-legume, is one of the most promising cash crops for arid lands. Jojoba seeds contain a rancidity-resistant, non-allergenic, liquid wax with lubricating properties equivalent to an oil obtained from the endangered sperm whale. Jojoba is under development in southern California, Arizona, Mexico, and many of the semiarid less developed countries (53). Mature jojoba plantations should yield over 1,000 kg/ha^{-1} at over $1 per kg. This yield could earn a gross return of over $1,000 per hectare.

Guayule *(Parthenium argentatum)* a plant native to the Chihuahua deserts, contains natural rubber and is under extensive development by both the United States and Mexican governments (50). There is no reason guayule could not be cultivated in other semiarid regions of the world as a cash crop.

Hydrocarbon bearing plants such as *Euphorbia lathyris* have been suggested as raw materials for oil and gasoline production (7). The drought-adapted legume trees *Acacia senegal* exudes a gum from wounds of the trunk known as gum arabic that has many industrial and food uses (18), Eighty-five percent of the world's annual supply of gum arabic, about 50,000 to 60,000 metric tons, is harvested and exported from the Sudan at prices of about $1 per kg (18), Other *Acacia* and legume trees, such as *Prosopis,* exude gums that could be developed for cash crops. Seeds of the fast-growing, drought-tolerant, annual sesame sell for $1 to $2 per kg and show potential for an arid zone cash crop (53). The fruits of the cactus *Opuntia ficus-indica* can produce dessert or table quality fruits. This author was served an excellent cactus fruit with a meal on a Chilean airline. Commercial (5 ha and larger) *Opuntia ficus-indica* orchards are currently operating in southern California to supply these fruits to supermarket chains. There are several little-known species of cactus that possess fruits equal or superior in quality to *Opuntia ficus-indica* that could also be developed (11). Because cactus use water very efficiently, they should support fruit and cash crop production in semiarid areas.

The pods of carob *(Ceratonia siliqua)* are broken into pieces, kibbled, and separated into seed and pod fractions, The pod fractions are sold for livestock food in Europe and are imported into the United States where they are manufactured into chocolate substitutes (34). Industrial quality gums are extracted from the seeds, In 1970, the world production of carob seed gum was 15,000 tons. Prices ranged from $0,62 to $1,10 per kg (43). The pods of *Parkia biglobosa* and *P, clappertoniana,* and a fermented product of the seeds known as dawa-dawa, are sold for human food on the subsistence levels in markets in Senegal and other parts of West Africa.

Research organizations: The most extensive germplasm collections, plantings, and cytogenetic studies of jojoba are being made at the University of California-Riverside under Dr. D. M, Yermanos. This has been funded by the United Nations Development Programme (UNDP), NSF, and the California State Legislature. Another large-scale jojoba research operation is being carried out at the University of Arizona under Dr. L. Hogan. There are numerous commercial jojoba developers, some of whom are less than scrupulous. Donor agencies should contact Yermanos or Hogan before dealing with private jojoba developers, Dr. Yermanos has also developed nonshattering sesame types and mechanical harvesting devices with UNDP support. The USDA has a multi-million-dollar budget to develop guayule in the Southwestern United States.

The Diamond Shamrock Co. is supporting a multi-million-dollar project at the University of Arizona Office of Arid Land Studies to develop potential of hydrocarbon producing plants such as *Euphorbia lathyris,*

The Canadian International Development Research Center (IDRC) is supporting a research program to develop gum arabic for West Africa through the "Eaux et Foret" in Dakar, Senegal. The University of Chapingo, Mexico, has a program to develop spineless cactus (52), Dr. Richard Felger at the Arizona/Sonora Desert Museum has identified numerous arid land crops with potential including several outstanding cactus varieties.

Production of Livestock Food and Forage

Areas of use: In Mexico, *Prosopis glandulosa* var. *glandulosa*, and *Prosopis laevigata* are harvested from wild trees and sold to wholesale dealers who incorporate it into livestock rations. In 1965, 40,000 tons of mesquite pods were sold in commercial operations in Mexico (29). Undoubtedly, many more pods were used or bartered locally that were never entered into the agricultural statistics. One thousand ha of *P. juliflora* has been established in the Peruvian coastal desert under partial irrigation. By providing 250 mm of irrigation the first year and 160 mm thereafter, pod production of 6 to 7 t/ha- have been obtained from the Peruvian plantings (39), In nearby Chile, 30-year-old *P. tamarugo* trees growing in the *Atacama* salt desert have produced 6,000 kg/ha-' of leaves and pods that are used to support a sheep-raising industry (44). Twentytwo thousand hectares of *P. tamarugo* have been planted by the Chilean corporation CORFO (54). Felker has visited these areas to assist CORFO with vegetative propagation, selection techniques, and nitrogen fixing inoculants.

In the Southwestern United States, mesquite pods were the staple for Indians in southern California and Arizona deserts (13), but today are only marginally important in supporting wildlife. In West and East Africa the pods of *A. albida* and *A. tortilis* are highly regarded as a supplemental livestock feed (12,34). Some *A. albida* pods are collected and stored for later rationing to cattle on a subsistence level, but no organized or commercial use of pods has been attempted (12). The forage of *Acacia xanthophlea* and *A. hockii* supplies much of the diet of giraffes in the Serengetti National Park in East Africa, Pellew (41) has suggested that the Acacia-giraffe ecosystem be managed for meat production,

Forage systems based around the spineless cactus *(Opuntia ficus-indica)* have been widely used in Mexico and North Africa where the spineless pads are fed to cattle. Selections of saltbush *(A triplex* species) are high in protein and carotenoids and constitute a useful livestock forage. The Chilean corporation CORFO has planted thousands of hectares of saltbush in contour ridges along the Chilean coast for use as cattle food (Felker, personal observation). In Tunisia, commercial-scale, government-supported plantings of saltbush provide forage for grazing animals (22).

In Mexico, cattle rations have been formulated from high energy, sweet, highly palatable mesquite pods; high protein, high carotenoid and low palatability saltbush foliage; and high-energy containing cactus pads (29). These three plants possess the complimentary physiological characters of high salt tolerance in saltbush, high water to dry matter conversion efficiencies of cactus, and nitrogen fixing properties of mesquite.

Research organizations: Surprisingly little research is being done about these forage plants. The Tunisian and Chilean governments support the largest developments of forage-producing plants, The Chilean company CORFO has planted thousands of hectares of *Atriplex*. CORFO has investigated plant spacing, canopy closure, and pod productivity as a function of age for 36-year-old *Prosopis tamarugo* plantations (44). They are just beginning to become involved with selection work, nitrogen fixation, and vegetative propagation.

The Tunisian government has employed large earth-moving equipment and water transport vehicles to establish saltbush and cactus plantings (22). The Algerian government also has initiated some *Opuntia* plantings (33). Dr. Henri LeHouerou, formerly of the International Livestock Center (ILCA) in Addis Ababa, has been a key figure in North African developments of *Atriplex* and *Opuntia*. The Chapingo Agricultural Experiment Station outside of Mexico City has made selection of *Opuntia* with promising economic characters (52). Lopez, et al. (28), at the Antonio Narro Agricultural University in Saltillo, Mexico, has conducted a thorough analysis of the productivity and ecosystem characteristics of economically important aspects of *Opuntia* production in Mexico. The International Development Research Center, Ottawa, is supporting a *Prosopis juliflora* forage production project in Peru.

In the United States, Dr. C. M. McKell, Plant Resources, Inc., Salt Lake City, and Dr. J. Goodin of Texas Tech University have conducted extensive research on saltbush as an economically important forage crop. Felker, while at University of California-Riverside, made *Prosopis* selections for pod producing characteristics in cooperation with Becker and Saunders at the USDA Western Regional Research Center. They also have conducted proximate analyses and feeding trials on the pods.

Intercropping Traditional Food Staples With Arid Adapted Legumes To Sustain High Food Staple Yields

Areas of use: *Prosopis cineraria* has been widely used in the Indian-Pakistan region on a subsistence level to increase yields of pearl millet and other forage crops grown beneath its canopy (31). *Acacia albida* has been used in West Africa to increase yields of millet, sorghum, and peanuts (9,8,12). Farmers in the 400 mm annual rainfall region of Senegal remarked to this author that *Parkia biglobosa* had the same fertilizing effect as *Acacia albida* on millet and sorghum.

Research organizations: The French overseas development organization ORSTOM commissioned soil fertility studies carried out by Dancette and Poulain (9) and Charreau and Vidal (8). AID commissioned a state-of-the-art report on *Acacia albida* in *1978 (12).* FAO supported a nursery scheduled for termination in 1978 in Kebemer, Senegal, dedicated to raising enough *Acacia albida* seedlings to plant 1,000 ha per year at 45 trees per hectare. A CARE project in Chad was involved in reforestation with *Acacia albida. No* serious field study has ever been conducted to develop improved genetic stock and management practices for arid-adapted leguminous trees.

Slowing tho Spread of Desertification in Arid Regions

Little work is being carried out to slow desertification. K. O. Khalifa, working for the Sudan Council of Churches, has planted 400 acres of *Prosopis* along irrigation canals to prevent the wind from filling them. The Indian government has been planting shelterbelts with *Prosopis* and other arid adapted trees since the 1920s and 1930s (25). No serious efforts employing arid-adapted shock, e.g., *Prosopis, Acacia,* or *Leucaena,* and modern forestry practices have been applied to control of desertification in less developed countries.

FERTILIZER, PESTICIDE, IRRIGATION, AND MACHINERY REQUIREMENTS

Irrigation Requirements

Over 90 percent of the land in semiarid regions must rely on rainfall without supplemental irrigation (excluding areas where water harvesting technologies are possible). All of the desert-adapted trees, shrubs, and ephemerals described here have the capability to grow without irrigation in semiarid zones, If water is not available, these plants can close stomates, shut down photosynthesis and transpiration, allow their finely divided leaflets to reach air temperature, and adjust their water potentials to minus 40 to 50 bars and wait for the next rain (17). Annuals would wilt and die under the same conditions.

Reasonable production from reproductive structures, such as mesquite pods, jojoba nuts, or cactus fruits cannot be expected below 250 mm annual rainfall unless they are located in water drainage areas or areas where water accumulates. Growth of vegetative parts for wood or forage production probably will continue from 150 to 250 mm annual rainfall. Deep-rooted tree and shrub systems are not as susceptible to moisture stress as are shallow-rooted annuals. To get optimal water use, an agroecosystem needs an optimal mix of nitrogen fixers and water to dry matter conversion specialists. When it is possible to use cactus, which has a fivefold greater efficiency of converting water to dry matter than legumes (17), legumes should not be used to produce the energy portion of livestock feed. However, legume leaf litter will be required to create good fertility so the cactus can achieve its maximum water use efficiency. For the same reason, cactus should not be used to produce the protein and nitrogen needs of livestock when it is possible to use legumes. Livestock need both energy and protein rations and both energy and protein producing plant specialists are required.

Fertilizer Requirements

A central component of this approach to developing country agriculture is widespread in-corporation of arid-adapted, nitrogen fixing legumes that are capable of fixing nitrogen under conditions too harsh for temperate legumes (e. g., clover, alfalfa, etc.). These legumes require no nitrogen themselves and when properly incorporated into a diversified ecosystem, they will reduce nitrogen needs for non-legumes as well. Many of these plants, both leguminous (e. g., mesquite) and non-leguminous (e.g., jojoba) have very deep root systems (13) capable of mining nutrients found in clays, bedrock, and parent materials. Additionally, these deeper rooted shrubs would be expected to have a higher capture ratio of applied fertilizers because they are less likely to allow nutrients to leach beyond the deep root zone. Also, many of these plants are perennial, and they would be expected to reduce wind and water erosion.

Under rainfall as low as 300 mm, it may be desirable to practice clean cultivation or use herbicides between rows of mesquite, cactus, saltbush, jojoba, and guayule to increase water infiltration and to reduce water competition from grasses and forbs. Once established, the risk of wind and water erosion present with clean cultivation should be less than the similar risk with annual crops, Drought-hardy shrubs and trees should make more effective use of applied nutrients than water-stressed, herbaceous, annual crops.

If drought-adapted legumes are widely incorporated into managed arid ecosystems, phosphate and sulfate will ultimately become limiting and will have to be supplied. Both nutrients stimulate legume production and can be supplied in single superphosphate.

Pesticide Requirements

It is difficult to imagine how the plant ecosystems described here would be any more or less susceptible to insect or bird attack than any other ecosystem. Once established, perennial tree and shrub crops would survive competition from grasses and forbs without weed control measures. However, their productivity probably will be greatly enhanced if herbicides or cultivation were used to eliminate water competition from grasses and forbs. For the first few years of shrub and tree stand establishment, competition from grasses and forbs must be eliminated either by herbicides or cultivation.

Machinery Requirements

A variety of options employing varying degrees of mechanization are available to establish tree and shrub plantations. This author envisions that most plantations will employ containerized seedlings planted with a liter or two of water. This can be accomplished manually with dibbles or post-hole diggers or mechanically with an 80 hp tractor pulling a transplanter capable of planting 1,000 trees per hour, It may prove useful to establish a seedbed for seedling transplant with the same level of preparation given to annual crops. However, after the first year an annual deep cultivation as required for annual crops will not be necessary. Where fruits are to be harvested (e.g., jojoba, mesquite beans, etc.), light surface harrowing or disking will prove useful for weed control, to increase water infiltration, and to provide a clean surface to pick up the fallen fruits. Pruning of tree and shrub crops will be necessary to allow access for harvesting of fruits.

In biomass farming operations, where complete canopy closure is desired, annual cultivation would be unnecessary and impossible to carry out after canopy closure. An annual ground preparation and planting, carefully timed with arrival of rains to allow germination and full use of the rainy season, will not be necessary for the tree and shrub crops. Established annual and perennial crops will not face a labor shortage at planting time as do annual crops, The light cultivation that may be useful with tree and shrub crops can be performed on a much less rigid schedule when labor, draft animals, and machinery are available. If herbicides are available and acceptable, they can be used in lieu of light cultivation. Tree and shrub crops would require much lighter equipment than annual crops and the annual site preparation necessary for annuals could be avoided.

RESEARCH, DEVELOPMENT, AND IMPLEMENTATION OF ARID-ADAPTED PLANT ECOSYSTEM PRODUCTION TECHNOLOGIES

An outline of research required to develop these plants and cost estimates to do so are given in table 1. Research centers are proposed in six locations to collect and store germplasm, to plant germplasm nurseries, to reevaluate promising nursery selections in larger sized plots, to compare input/output resource ratios of different plant systems, to evaluate monoculture and polyculture arid-adapted systems, and to provide material and administrative support for the research.

The research program outlined in table 1 is appropriate for the first phase of the research, Extensive germplasm collections and plantings would be required once at a cost of approximately $1,500,000. A funding effort 15 percent of the initial level would be appropriate after initial collections and plantings were made. Funds used for collections and plantings in the first phase should be allocated to weed and insect control, cultural operations such as harvesting, pruning, and planting methods for nursery stock, and extension short courses during the second phase of the research.

Large genetically diverse germplasm collections and promising plant selections are available for some of the plants described here such as jojoba, guayule, and atriplex species, For other plants, germplasm collections and selections of promising lines will have to be made. The plants that require germplasm collection and selection and the methodology for accomplishing that is outlined below.

Seeds should be taken and maintained as single plant selections from *Acacia tortilis* and *A. seya]* in East Africa, from *A. albida* in East and West Africa, from *Parkia biglobosa* in West Africa, from *Prosopis cineraria* in the Mideast and India-Pakistan region, and from *P. alba, P, chilensis, P. tamarugo, P. pallida, P. articulata, P. tamarugo,* etc. in Argentina, Chile, Peru, Mexico, and Hawaii. Short, shrubby legumes of the genus *Dalea* should be collected in Southwestern United States, *Tephrosia* in Texan-Mexican area, and *Zornia* in Sahelian Africa, Cactus genera such as *Opuntia* and *Cereus* should be collected in Southwestern United States. During these collections, attempts should be made to collect for as much diversity as possible as well as to collect for economically desirable characteristics, e.g., heavy pod production, size and sweetness of fruit, large trees, presence of large amounts of leaf litter, and presence or absence of thorns. The plant should be collected over its entire geographical and ecological range.

All of the collections should be evaluated in uniform plantations with a minimum of four replicates of five trees per replicate. For the trees, height measurements should be performed the first year, stem diameter measurements for biomass estimation should be performed every year, and pod productivity measurements should continue indefinitely, One germplasm planting should be evaluated in a 300 and 500 to 600 mm annual rainfall regime in the India-Pakistan region, in East Africa, in West Africa, in the United States, and in South America. The purpose of the American planting would be to provide American researchers with biological research material and exposure to these different cropping systems. An additional site should be located near a seacoast to use seawater irrigation to screen for salt-tolerant germplasm.

The Hawaiian Niftal rhizobia collection should be evaluated for rhizobia for the legumes and techniques developed to ensure effective modulation of field plantings, Soil samples from native stands might contain rhizobia with unique properties and should be used to inoculate native plants for comparative purposes,

Most *Acacias* (Sief-el-Din, *1980)* and probably all *Prosopis (47)* are obligately outcrossed. As a result, trees will not breed true and seed and clonal propagation techniques will be required, Both tissue culture propagation and traditional rooting of cuttings should be examined, Rooting of stem cuttings is difficult for *Pro-*

Table 1 .—Outline of Research Procedure

Level of support per year ($ 1,000)	
	1. Develop germplasm collections where none exist
	A. Collect single tree selections of leguminous trees over broad range for:
	1) pod production
	2) large size
	3) thorn characteristics
	4) leaf litter
	B. Collect following genera:
100	1) *Acacia tortilis* and *A. seyal* in East Africa
100	2) *Acacia albida* in East and West Africa
100	3) *Parkia biglobosa* in West Africa
100	4) *Prosopis cineraria* in Indian-Pakistan region
200	5) *Prosopis alba, P. articulate, P. chilensis, P. nigra,* and *P. tamarugo* in Mexico, Hawaii, Southwestern United States, Argentina, Chile, and Peru
100	6) Make cactus collections in Southwestern United States and Mexico
100	7) Short, shrubby legumes, *Dalea* in Southwestern United States, *Tephrosia* in deep South, and *Zorrria* in Sahelian Africa
	2. Obtain good selection of following arid crops already subjected to germplasm collection and screening:
25	A. Jojoba—Drs. Yermanos and Hogan
	B. Guayule—USDA
	C. Euphorbia—Dr. Calvin
	D. Atriplex— Drs. McKell and Goodin
	E. Leucaena—Dr. Brewbaker
	3. Plant out four replicates of five trees (plants) of all accessions for germplasm nursery at a 300 mm and 500-600mm annual rainfall regime in:
100	A. East Africa, e.g., Sudan
100	B. West Africa—Senegal
100	C. India-Pakistan region
100	D. South America
100	E. Southwestern United States
100	F. Site along coast to irrigate with seawater for salinity trials
60	4. Evaluate Niftal collection of rhizobia suitable for tree legumes. Develop techniques to insure effective modulation.
100	5. Conduct protein, sugar, fiber, and toxicity analyses on pods that are produced.
120	6. Develop clonal propagation techniques at central facility:
	A. Rooting of cuttings
	B. Via tissue culture
450	7. Evaluate germplasm nursery for:
(6 sites x *75)*	A. Height measurements first year
	B. Stem diameter measurements yearly
	C. Pod production and/or pod chemical characters
	D. Make clones of outstanding single trees
1,200 (200 x *6* sites)	8. Evaluate clonal outstanding material in replicated 0.1 ha minimum-sized plots.
180 (30 x *6* sites)	9. Multiply and distribute best selections to interested individuals and organizations.
1,200 (200 x *6* sites)	10. Evaluate comparative advantages of selections developed above in mono- and poly-culture with *Opuntia,* jojoba, guayule, atriplex, etc.
400 (200 x 2 sites)	11. Evaluate large N fixing trees with staple cereal crops in field plantings.
600 **(200 X 3** sites)	12. Evaluate short N fixers with jojoba, guayule, saltbush, etc.
5,735 ‘	**Total direct research**
4,265	Support facilities, travel, secretarial, library, statistical analyses, computer services, etc.
	Grand total

sopis. To achieve success for large-scale plantings, a thorough evaluation of rooting methods including evaluation of mist, atomized fogging, and tent humidification devices, screening trials of hormone mixtures, evaluation of out-of-doors and greenhouse grown stock, and use of growth chambers to determine optimal light, temperature and humidity level for cuttings will be required.

Most annual legumes are highly self-fertile and breed true to type. These selections will not require vegetative propagation, but germplasm multiplication areas will be required. Laboratory analysis of crude protein, sugar, and fiber should be conducted on pods, fruit or other economically important plant structure.

Single tree selections should be made from the germplasm nursery on the basis of: 1) height and biomass determinations, 2) pod production and pod chemical characters, 3) presence or absence of thorns, and 4) other characteristics deemed important. These selections should be clonally multiplied and reevaluated with four replicates of 0.1 ha minimum sized plots per selection. Sufficient quantities of the clonally multiplied material should be made to allow distribution to requesting individuals and organizations.

Once reasonably productive selections of the leguminous trees and cactus have been developed, they should be compared with advanced strains of jojoba available from Yermanos and Hogan, from guayule available from USDA, and from saltbush available from McKell and others. The comparative advantages and relative resource requirements for these crops should then be evaluated as monoculture and polycultures. The large nitrogen fixing trees P. *cineraria* and *A. albida* should be evaluated in various spatial configurations with the staple crops millet, sorghum, and peanuts. The short shrubby and herbaceous legumes of the genera *Tephrosia, Zornia,* and *Dalea* should be evaluated with jojoba, guayule, saltbush, and opuntia.

As with all crops, solutions to weed problems, insect problems, and cultural practices will have to be developed for these ecosystems. Herbicide and cultivation methods should be examined for weed control and insecticide, biocontrol, and integrated pest management should be evaluated for insect control. Harvesting, pruning, plant spacing, and planting methods also require development.

It has been the experience of Dr. Yermanos with jojoba and of this author with mesquite that once genetically superior strains have been produced the demand for the strains and the technology associated with them will greatly outstrip the supply. Elderly ladies with 100 square feet of desert in their backyard in Yucca Valley, California, business executives, and ministers of agriculture in arid developing countries will ask the project leader to visit their backyard or country to set up the appropriate technology. It is imperative to develop sufficient plant material for further multiplication and to train extension personnel to help farmers, businessmen, or government leaders use the technology. Short extension courses provided by staff involved in germplasm nurseries and evaluation centers would be an ideal method of disseminating the information.

The staff of the germplasm nursery and evaluation centers would require a Ph.D. project leader for: 1) *Acacia tortilis* and *A. seyal*, 2) *Acacia albida*, 3) *Prosopis cineraria*, 4) *Parkia bioglobosa*, 5) the American *Prosopis* species, **6)** the shrubby and herbaceous legumes, 7) the cactus, 8) the atriplex complex, **9)** guayule, 10) jojoba, and 11) other overlooked species. A central tissue culture and clonal propagation center should develop the techniques for clonal propagation and have at least two Ph.D.'s, six B.S. 'S and/or master's level technicians and six to eight support personnel preparing media, washing dishes, etc. Each research center should have two B.S. or M.S. full-time personnel and six nonskilled laborers rooting cuttings and/or multiplying germplasm for research and/or further distribution. The availability of a statistician and computer for analysis of field experiments is essential.

A major effort will be required to develop support facilities for research in arid developing countries of Africa. Telephone service, mail service, ground transportation, and freight services to and from Europe are too unreliable to make effective research possible in East Africa and perhaps other countries. It is absolutely essential that the plant research be conducted in the climate and on the soils where it is to be used and this requires development of support services for the research.

CONSTRAINTS FACING DEVELOPMENT AND IMPLEMENTATION OF ARID-ADAPTED PLANT PRODUCTION TECHNOLOGIES

There are no major or theoretical scientific constraints on using these technologies, but applied research efforts are required in several areas. Techniques need to be developed for clonal propagation of the species described here—both rooting of cuttings and tissue culture. Planting techniques, greenhouse and field cultural practices need to be optimized. A continued effort to identify and propagate better genetic selections is required,

Environmental constraints to development of these systems are minimal, as increased vegetation in arid developing countries has the effect of halting desertification. There are, however, serious cultural constraints to development of perennial production systems, For instance, in Sahelian Africa the perennial vegetation is viewed as community-owned (48), Thus, the pods or fruits from trees can be taken by anyone, even if the trees are on privately owned land,

Similarly, people can cut branches from nonprotected species of trees for fuelwood even if the landowner planted the trees for his own fuelwood use. Freely roaming goats that eat young seedlings constitute a major problem in establishing perennial production systems. Control of the movement of goats is probably an insoluble cultural problem and thus goatproof devices to protect young seedlings will have to be devised,

Political constraints on the development of these technologies stem from politicians' and bureaucrats' unfamiliarity with use of these perennial crops, This is most accurately described in Pelissier's explanation of why *Acacia albida* is not more widely used in West Africa (14).

> One cannot help but be astonished that an agronomic research center established to study the Serer people (in Senegal, West Africa) is not more interested in the methods and effectiveness of native farming systems. These researchers ignore the milieu of naturally-regenerating *Acacia* stands by which they are surrounded. This mark of indifference and incomprehension for African techniques is too often manifest by European specialists or those trained in Europe. In order to promote their own cultural values, these researchers use the terms "modern" and "scientific" as if laboratory and field techniques are completely inapplicable, for social or economic reasons, to the truly native farming systems.
>
> *Acacia albida* suffers from the division of the technical services. The agronomist regards the presence of the tree in the field as an adversary to be eliminated. The forester is not interested in the tree because *Acacia albida* does not grow in what could be termed a forest and is, therefore, not capable of being dealt with by standard silviculture concepts. The role of *Acacia albida*, including its growth and germination conditions, illustrates its marvelous character which cannot be dissociated from its genuine agricultural setting and illustrates the necessity for deep-seated action to aid the farming population. At this time in our intimate knowledge of political techniques for rural management, an end must be placed to the absurd division of agriculturally related disciplines which enclosures agricultural development specialists. It is not lack of concern in the development specialists that causes this problem but rather their overspecialized training, and above all the administrative structures that thwart their action and hinder an integrated development plan which alone can be effective,

EFFECT OF TECHNOLOGY IMPLEMENTATION ON CAPITAL, LABOR, AND LAND REQUIREMENTS

The initial inputs required for the systems described in this paper are low but the output/input ratio of the system is high. Yield increases will tend to stimulate more investment in the technology. For example, assume a farmer will plant 1 ha with 200 *Prosopis* trees, The wholesale seedling cost should be approximately $0.15, requiring an outlay of $30. These seedlings could be planted on his own land with only a shovel, and some buckets for watering the seedlings after transplant. If planted in regions at 500 mm annual rainfall, at year 10 the tree should be producing 4,000 kg of pods per hectare (16). These pods typically have protein and nitrogen contents of 12.5 percent and 2.0 percent, respectively (4). Thus, the pods contain 80 kg of N, which is worth $40 at today's price of $50 per 100 kg of N. To achieve capture of 80 kg of N in pods from chemical fertilization, at least double the amount of nitrogen in the pods, or 160 kg of N, would have had to have been applied. Thus, the cost to provide the nitrogen found in the pods would have been $80 per year. Recalling that the farmer's cash outlay for seedlings was $30, his annual return on the seedling investment from nitrogen alone is 270 percent. His $30 investment in seedlings probably would be returned from 60 kg of N fixed by the plants in 2 to 3 years.

Because most of these trees are outcrossed and planted only once every 30 to 50 years, it would be most advantageous to plant clonal material from outstanding individual trees. Thus, commercial tree nurseries would be required to supply young trees to villages in the countryside. Hopefully, farmers would recognize the importance of obtaining high quality, clonally propagated seedlings for long-term plantings, and would support commercial village level nurseries that would deliver superior genetic stock to the local population,

Fertilizers other than nitrogen would be required. Phosphate and, to a lesser extent, sulfate fertilizers stimulate nitrogen fixation in legumes and would be a worthwhile investment. Phosphate fertilizers have approximately the same unit price as nitrogen fertilizers but only 10 percent as much phosphate is required. Annual crops such as maize may capture only 40 to 50 percent of applied fertilizer partially because of leaching beyond the root zone (37). Shrubs and trees such as *Acacia*, *Prosopis*, and jojoba commonly root to 10 meters (13) and would achieve higher capture ratios of applied fertilizer.

There is no reason to suspect that any more or less pesticides would be required than in other kinds of systems since insects would be just as likely to attack tree or shrub crops as annual crops. Due to the low till or no tillage requirement for many of these shrub and tree-based production systems, agricultural machinery requirements would be expected to be less than those of conventional plant production systems. Most harvesting in arid developing countries is done by hand. With increased yields of traditional crops stimulated by association with leguminous companion crops, the demand for labor at harvesting time will increase. Production of large quantities of tree legume pods, jojoba nuts, and fuelwood will also increase the labor demand for harvesting operations,

The low requirements for tillage machinery and the lack of a nitrogen fertilizer requirement will greatly reduce credit requirements for these two traditionally high credit requiring areas, On the other hand, the several years' wait prior to harvest of perennial crops will require credit to pay for the seedling costs.

IMPACT OF WIDE-SCALE TECHNOLOGY IMPLEMENTATION ON THE SOCIOECONOMIC STRUCTURE OF AGRICULTURE IN DEVELOPING COUNTRIES

Most of the plant systems (technologies) discussed in this report are widely used by subsistence farmers in the developing countries. The plants used are primarily volunteer seedlings of unselected genetic stock that the farmers may prune and care for (40). This system is comparable to use of unselected races of maize and wheat as would have been done in the late 1800s in the United States and Europe. Placing these widely used, but scientifically unmanipulated plants into a research and development framework will probably yield increases similar to that achieved by first inbred and then hybrid lines of maize and other cereals.

Vigorous, naturally occurring tree legume hybrids have been observed and clonally propagated by this author and demonstrate the ease with which hybrids can be formed. Maize yields increased from less than 20 bushels per acre in the early 1900s to close to 100 bushels per acre at present. The plant systems described here probably have the potential of achieving the same yield increases. Perhaps a two- to three-fold increase in plant productivity can be expected in 5 to 15 years and a five- to ten-fold increase in 50 to 100 years. Unlike maize, these systems are based around nitrogen-fixers and will not require fossil-fuel-derived and energy-intensive nitrogen fertilizers.

Assuming these kinds of yield increases in tree legume pod production, fuelwood production, cash crop production, soil fertility, and ensuing staple food production, returns to farmers can be expected to increase in the same approximate fashion. As the farmers income rises, his demands for goods and services will rise and stimulate the economy as a whole. A greater tax base will then be available to support more roads, schools, and health services, which will in turn decrease unemployment.

The economy of a country with an agrarian society is inextricably tied to the primary productivity of the ecosystem. As long as substantial progress is being made toward achieving the economic goals of the rural population, there will be fewer economic grounds fostering political instability. Past efforts to stabilize the political systems of arid developing countries, such as Iran, with military hardware systems have proven futile. It is imperative to develop plant systems that have the capability to directly impact the smallest farmers on the local level to increase his well-being and decrease economically fostered political unrest.

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Work Statement

Topic

Development of low energy input technologies to increase and stabilize productivity of agricultural ecosystems in dry regions of less developed countries. The contractor shall:

1. Describe how the technologies operate and what beneficial or adverse impacts they have or might have on enhancing the sustained production of food and forage from tropical and subtropical soils.
2. Describe where the technologies are being used. Describe whether each technology is being used on a commercial level, a subsistence level, as a pilot program, or is being applied only in the research state. Describe who is conducting the major research on the technology. Describe what organizations (AID, FAO, and others using U.S. funds) are funding development of the technology and what organizations are implementing it on a project scale.
3. Explain in some technical detail how these technologies increase or decrease the need for fertilizers, pesticides, irrigation, and machinery when applied to tropical/subtropical soils.
4. Discuss the potential role of these technologies being used to restore, improve, or sustain in perpetuity the food and forage productivity of tropical and subtropical soils, and the likelihood that they will be used widely.

We appreciate that the author may not be a specialist in economics or sociology; however, his experience and insights on the following questions are still of interest to OTA, especially as they relate to lesser developed countries. Therefore the contractor shall:

5. Describe a plausible research, development, and implementation scenario in which these technologies realize their potential in enhancing productivity of tropical soils. What organizations would be involved? What levels of capital and trained personnel would be necessary? What degree of attitudinal changes would be necessary for consumers, farmers, government agricultural experts, bureaucrats, politicians, foreign advisors, policy makers in foreign aid or lending institutions, etc. ? What biophysical (soils, climate, topography), cultural, and socioeconomic conditions would be most conducive to successful implementation of the technology? Where do these conditions exist or where are they likely to develop? To indicate the priority of the various steps that need to be taken on this technology, contractor shall discuss how he (if he were the head of a wealthy foundation) would spend $10 million on research, development, or implementation of the technology.
6. Describe the major scientific, environmental, cultural, economic, and political constraints on development and implementation of these technologies.
7. Describe how implementation of these technologies would affect the need, in the region where they were implemented, for inputs of capital (agricultural chemicals, machinery, credit, seed, and other materials from the implemention farm), labor, and land.
8. Describe what the impact of wide-scale implementation of these technologies would be on the socioeconomic structure of agriculture in the implementing regions. For example, does the technological implementation give rise to economies of scale, or diseconomies of scale, that would make large or small farm units more competitive? How would the technologies either displace or create demand for farm laborers.

Deliveries

The contractor shall deliver to OTA the original copy (not a reproduction) of the typewritten 25- to 35-page report, acceptable to OTA, with abstract and literature citations, by November 24, 1980.