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NITROGEN DYNAMICS OF THE ACACIA SENEGAL AGROFORESTRY SYSTEM IN SUDAN

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INTRODUCTION

The Acacia senegal agroforestry system is a major type of land use in Sudan and elsewhere in the African sahel. The system's effects on the region are many and varied; they include soil nutrient improvement by nitrogen fixing processes, provision of protein-rich fodder and production of gum arabic of commerce. Gum sale improves the income of the farmers and the foreign exchange of the country. Fuelwood, local building timbers, sand dune stabilization and the possibility of bee-honey production are other contributions of the Acacia system.

The recent sahelian droughts have caused a colossal mortality among Acacia trees as well as severe food shortages. Many local and international donor organizations have embarked upon planning activities to rehabiliate the degraded environment. Most of these project facilities are centered around the Acacia system. Such developments make the need for more research and information about the system imperative.

The objectives of this research were:

1. to identify Acacia senegal seed source and soil type that could yield higher rates of nodulation and biomass production;
2. to study the effect of competition on nodule number and biomass among A. senegal seedlings;
3. to find out whether inoculation of A. senegal seedlings with particular strains of Rhizobium would lead to increased N yield;
4. to determine whether high gum producers would also yield high nitrogen;

5. to determine whether A. senegal populations in different geographic areas were geneticallly similar or different and whether they varied with respect to nodulation and nitrogen yield.

GEOGRAPHIC VARIATION OF ACACIA SENEGAL

Methods

The selected study sites represented the prevailing types of soil and rainfall regimes where the A. senegal agroforestry system is largely adopted at present and where desertification problems and pressure on land are immense. The study site locations, elevation and climatological norms are summarized in Table 1.

Eight trips were conducted in total, two to each of the four study sites. Both journeys coincided with the dry season, i.e. Dec. 1987 and Dec. 1988. Our effort to stick to the proposed schedule of March and September was not successful because of various difficulties explained in the progress reports. Characteristics of sample trees, including N content, the soil, and microclimate were quantified at each site.

At each locality six trees were selected at random during the preliminary survey and composite soil samples were collected. From each tree three radii were located at 25, 75 and 175 cm from the tree trunk. At each distance three depths were selected. These were 10, 25 and 40 cm from the soil surface. We felt that 6 trees may not be an adequate sample size due to variation in the root distribution pattern and also due to variability due to tree density. Replicates were increased to 10 trees for sampling the plants and 15 trees for the gum yield study. Tissue samples were collected from each tree. These tissues included leaves, twigs, bark, root, seeds and pods. Where gum was available, samples of

it were collected. Soil samples were collected in cloth bags and later analyzed for nutrient content. The height and diameter of each tree were taken to compute the volume. The distances between trees were also recorded to determine tree density. A. senegal plantations are raised at 4x4 m spacings. Because of rainfall limitations, site selection for tree plantations is generally rigorous. We chose to select for different ages where the record of plantation age was available.

Roots of trees of varying ages were dug in an effort to study nodulation, but we were unable to find live nodules. Very few nodules were observed on one-and two-year old plants.

Tree measurements- The height and circumference of the Acacia trees were measured and their ages were obtained from a forest record book kept for each managed forest. The intent was to estimate biomass and leaf litter in order to access how much nitrogen recycles through the system. We were unable to determine how much leaf biomass an average tree produces each year. However the growth parameters in Table 5 will be utilized for growth rate comparisons between sites.

Variation among the four study sites in seed size was investigated. Ten trees from each site were chosen at random and seeds collected from each one separately. Five samples were taken from each tree and their weights determined. The number of seed per gram for each site was then calculated.

Plant tissue samples were collected simultaneous with soil samples. The tissues were dried at 80°C for 48 hours and ground using a Wiley mill. All plant tissue samples brought from Sudan were digested in a Scientific Instruments block digestor using a sulfuric

acid-hydrogen peroxide digestion. Tissue sample analyses for total Kjeldahl nitrogen (TKN) and total phosphorus (TP) were conducted with a Scientific Instruments autoanalyzer. Iron was determined with an atomic absorption spectrophotometer. Final results will be reported in a supplement to this report.

Electrophoretic analysis will be used to detect genetic variation among the Acacia populations. The general principle of gel electrophoresis is that any charged ion or group will migrate when placed in an electric field. Since proteins carry a net charge at any pH other than their isoelectric point, they too will migrate and their rate of migration will depend upon the charge density of the protein of interest. The application of an electric field to a protein mixture in solution will therefore result in different proteins migrating at different rates toward one of the electrodes. A preliminary study was conducted in which proteins were extracted from freshly germinated seedlings of A. senegal from each of the study sites. The seeds for this study were collected from naturally regenerated A. senegal trees from each site. Two seeds from each of 5 trees were selected from each of the four sites, i.e. 40 seeds in 4 lots. These seeds were germinated in petri plates in an incubator. Germinated embryos were taken and crushed in a porcelain spot dish using an extraction buffer. The extract was absorbed by a filter paper which was placed on starch gels with appropriate stains. When electric current was applied, variation was observed in band formation. From this preliminary trial we concluded that the application of gel electrophoresis will work using germinated A. senegal embryos. This approach will be applied to all 40 seed lots collected during the field survey.

Soil Analyses- Soil samples in powder form were placed in glass vials. They were iradiated for 10 minutes by fast, 14 Meu neutrons produced by a neutron generator. After a short waiting period the neutrons were counted for 10 minutes using a highly pure Geranium detector (HPGe) gamma-ray spectrometer coupled to a 35-Plus Canberra multichannel analyzer. Fe foils were used as neutron flux monitors. The elemental content was computed in comparison to standards of known concentration treated similar to the samples. This technique was applied to the sandy soil samples of sites E (Elobeid) and D (Dubeibat). Soil samples collected from sites G (Gedaref) and S (Singa) could not be analyzed using the neutron generation system because the system was out of order. These samples were analyzed by the Kjeldahl method for nitrogen. The results of these methods are comparable

Soil samples were dried at room temparature and crushed by pistil and mortar. 10 cc of soil were measured into a 50 ml beaker to which was added 10 ml of distilled water. The mixture was strained and allowed to sit for 15 minutes. The solution was strained again and a pH meter with glass electrode assembly was used for the determination of pH. The pH meter was standardized using pH 4.0 and pH 7.0 standards after every ten determinations. Before ending the field investigation phase in Sudan we cooperated with two scientists in Elobeid Agricultural Research Station in a soil moisture/temperature study. The aim of that study was to investigate the effect of tree cover on soil temperature and soil moisture. The study was planned to cover the period June - December 1989. We anticipate receiving raw data during January 1990.

Results

Environment - Tables with climatic data were obtained from the Sudan Meteorological Department, a government agency established in 1920 and specialized in recording and distributing weather information. Three of the study sites, viz. Elobeid, Gedaref and Singa, were equipped with weather stations. Dubeibat had a rain gauge only, and the nearest station to it, Dilling, is about 25 km away. The major climatic parameters that varied significantly between the four sites were rainfall regime, i.e. distribution and total annual, evaporation, and elevation. Sunshine duration, slope and aspect, relative humidity and wind speed did not appear to differ significantly. Table 1 shows summaries of climatological norms. The final statistical analysis will give comparisons between the four sites based on various climatological norms to verify if any significant differences existed between sites. These climatic and soil differences will be related to tree distribution and nutrient dynamics.

The final two sites, E and D, have sandy soils and lower rainfall than sites G and S, where the predominant soil type is cracking clay. During the recent sahelian droughts, the reduction in rainfall during 1981-87 compared to 1951-1980 on sites E and D was 27% and 25% respectively, but only 3% and 6% for sites G and S. The drop in annual rainfall on sites E and D has caused a colossal tree and animal mortality, droughts, famines and soil erosion by wind; desertification processes extended the southern limits of the Sahara over lands previously cultivable. Mass migration of previously settled people took place and nomadic range was greatly reduced.

Soil reaction was alkaline for sites G and S (Table 2). pH ranged from 7.9 - 8.23 for site G to 9.07-9.27 for site S; site S was more alkaline than site G. Alkalinity increased slightly down the soil profile and also away from the tree trunk. Soluble salt and total

phosphorus were higher on site S than G. Nitrate nitrogen and potassium were higher on G than S. The concentration was generally higher in the top 10 cm of soil than deeper in the profile. The pH on the sandy soil ranged from acidic (site D) to near neutral (site E) (Table 3). Percent iron was much higher on site D than on E. Nitrogen and potassium concentrations were similar on both sites. The nutrient concentrations under high gum yielding trees were generally higher for all nutrients than under low yielding trees (Table 4), but the differences were insignificant.

The clay soils of sites G and S had higher potassium content than sites E and D. Clay soils were reported to contain calcium concretions. Both basic elements lead to more elevated pH on sites G and S than on sites E and D. The clay soil sites showed close resemblance in their pH (site S was 9.2 and G was 8.1), total soluble salts and nitrate nitrogen (9.8 for G versus 8.3 for S). Potassium on G was double the concentration on S; whereas, total phosphorus was higher on S than on G. On E and D sandy soils, % N and % potassium were similar for both sites. Percent Fe was higher for D soils than E. The elevated iron on site D was probably due to proximity of the igneous rock outcrops that are scattered to the south and west of Dubeibat. The acidic nature of these components caused pH to drop.

More samples from each site await analyses in order to make meaningful comparisons among the study sites and to show how variation in soil elemental concentrations is reflected in nitrogen cycling and biomass production.

Vegetation - Site E (1) represented the high yield trees of gum acacia (or gum arabic) and E (2) the normal trees (Table 5). E (3) was a bottom site and E (4) was a top site. Fifteen

trees were measured from each site (Table 5). The Acacia trees that yielded higher amounts of gum acacia (or gum arabic) also yielded higher amounts of nitrogen, iron and potassium; the differences, though, were not statistically significant. There was an inverse relationship between gum yield and biomass; the varieties low yielding in gum proved significantly more productive in biomass than varieties higher yielding in gum.

The low yield variety produced higher biomass (i.e. larger girth and height) than the high yield variety. The difference, however, does not appear to be statistically significant. The Goz bottom site was a trough that received moisture from the Goz top site. The differences in girth and height between the Goz bottom and top sites were significant. Two sites were chosen in Dubeibat based on a difference in understory grass cover density. Girth was higher on site 1 (D) while the height averages were identical.

Tree growth rate was highest at young and middle age, and tapered off at old age, exhibiting the normal sigmoid curve. Growth rates of Acacia trees raised on clay soils of site S approximated a straight line and correlated positively (r^2 = .976). The highest growth rate on clay was for four year old plants (33.2 cm/yr), which declined to 23.7 at age 13 and levelled off at 17 years. Middle- (15 yr) and old-age (21 yr) sites (G) gave higher rates than site S. For similar age groups (21 yr) raised on sand (E and D) compared to those on clay, the latter group was significantly faster growing than the former. This was expected because of the higher soil fertility on clay than sand and the higher rainfall. The higher density of trees on S site, as expected, slowed down tree growth compared to site G. A plantation 15 years old on site S would fall in between 13 and 17 with a growth rate of 21.0 cm/yr. The 15-year plantation of G was 24.1 (Table 5). Dubeibat site had a lower growth rate on the average than Elobeid site. Goz top site was a particularly poor site, deficient in moisture

and nutrients, and is expected to yield a poor crop.

No significant difference among sites was detectable using seed size variations. The data were also separated according to soil types (Elobeid and Dubeibat sand against Gedaref and Singa clay). Again the difference with respect to soil type was insignificant. On the same type of soil, however, there seems to be a weak trend towards larger seed number per gram, i.e. smaller seeds with higher rainfall (Table 6). This might indicate adaptation of the tree species to dry conditions. Indeed its distribution ceases at higher isohyets.

Gum acacia (or gum arabic) is one of the major products from the Acacia system. An average annual production of 35,000 tons are exported every year from Sudan. Gum samples from the four sites were analyzed to determine the quantity of nitrogen that escapes through this avenue. The leaf crude protein is a valuable source of fodder for camels and goats in the Sahelian agriculture. An estimate of leaf crude protein was obtained from each study site (Table 7). At an average concentration of 0.093 percent nitrogen, gum export from Sudan removes about 32.55 tons of nitrogen each year.

EXPERIMENTAL MANIPULATIONS OF SOIL, SEED, AND INOCULUM

Methods

Soil-Seed Combinations - Two factors (soil type and seed source) were tested. The soils and seeds were collected from each of the selected sites. Soil types from sites E and D are sandy soils, about neutral in reaction and low in nutrient levels. Soils from sites S and G are alkaline clays with higher nutrient contents than the sandy soils, but poorer in water content. The A. senegal species range covers both types of soil with more abundance on

sand than on clay soils.

From a previous study it was found that 72% of A. senegal seeds germinate. Fourteen seeds were sown per treatment to produce 10 plants per treatment. Sixteen soil - seed combinations were examined, each with ten replicates. Acacia seeds were collected, washed in water and soaked overnight. They were then placed in plastic bags filled with soil from each source and lightly covered. Water was applied once or twice daily depending on the weather conditions. Eight weeks after sowing, the seedlings were removed with the soil intact. The soil was carefully washed off and the nodules were counted. For lack of a gas chromatograph to determine the rate of nitrogen fixation in the field, we counted nodules instead. Due to a shortage of chemicals, plain water was used for seed pretreatment rather than the popular concentrated sulfuric acid treatment. Plant material was dried in an oven at 80°C for 48 hours and weighed.

It was not feasible to take the dry weight of each individual plant separately because the root system was entangled together and any effort to disengage individual root systems by pulling them apart would cause nodules to separate and rootlets to break off. However, the length of shoots and roots of each plant were taken as the nodules were counted. Groups of similarly-treated plants were dried and weighed and a conversion factor was computed for dry mass per unit length of shoot and root.

The procedure generally adopted for nodule count and examination is to allow 6-8 weeks before digging out legume plants to count nodules and weigh them. All our nodules observed at 50 days were small and fresh. We wanted to know if these nodules grow bigger and eventually degenerate releasing nitrogen. So more time (90 days) was allowed and the number of fresh and degenerate nodules were compared to those 50 days old. Seed from

site E and three soil sources, i.e. S, E and D were used. Soil from site S was Nile alluvial silt used regularly in nursery work; whereas, E and D were sandy soil. At the specified number of days the seedlings were dug up and carefully washed, and nodules were counted.

Competition - A trial was conducted to test the number of seedlings to be raised per pot and whether overcrowding would lead to adverse effects on biomass and nodulation. Plants were grown singly in plastic containers and were compared with crowded pots. Three competition intensities were compared and monitored for their effects on nodulation and biomass. Three grades of competition intensities were created: a high intensity represented by an average of 100 plants per container, a moderate intensity of 67 plants and a low intensity of 6 plants. The treatments were replicated three times. Equal amounts of soil and watering were provided for each group. The seed type used was from source E.

Variation in Rhizobial Strains - The soil/seed combination experiments shed some light on variations among the specific combinations with respect to nodulation, biomass and germination. The main objective of those experiments was to identify one or more combinations that yield higher nodule numbers than others in order to apply them for further bacteriological investigations. For each of the 16 soil/seed combinations, nodule numbers, biomass and germination percentages were determined. A ranking was adopted based on the observed parameters. Ranks started from 1 for the combination exhibiting best yield of a particular attribute, e.g. largest nodule number, biomass or germination. The rank increased by 1 for the next best treatment and so forth until rank 16, with the lowest nodule number, biomass or germination. Each attribute was ranked separately.

The top six treatments were selected with respect to nodulation. Bacteria were isolated from them by crushing nodules on glass plates and transferring bacteria for cultivation in yeast mannitol agar medium. Mannitol broth was used for inoculation of A. senegal seedlings raised in sterile clay soil. The broth was used at 3 ml per pot of 5 seedlings, using sterile pipettes. Seed from each of the four study sites was used in only one type of soil, i.e. Nile silty clay from the river bank near Khartoum.

The selected strains for inoculation were as listed below. Bacteria strains from A. seyal and A. mellifera were also obtained and used for comparison:

1. A. seyal strain, Sheubat (AS)
2. A. mellifera strain, Elain (AM)
3. A. senegal strain, GTEP (5)
4. A. senegal strain, STEP (9)
5. A. senegal strain, GTSP (7)
6. A. senegal strain, GTGP (6)
7. A. senegal strain, STSP (11)
8. A. senegal strain, ETDP (4)
9. Control

Each treatment was replicated five times, i.e. five pots per treatment. It was unfortunate that as seeds of this experiment were germinating, a lot of rain occurred for two consecutive days and most pots were inundated. The sterile soil was then contaminated with various bacteria strains. Seeds that rotted were removed from pots and replaced with fresh seeds.

Pot Effects - Plants that grew along the pot wall were observed to have more nodules than plants growing in the middle of the pot. Two sets of plants were tested: one where seedlings were raised in the middle of pots and another with seedlings grown along the pot

edge. Nineteen plants were raised in each set. Six weeks later nodules on each plant, shoot and root lengths and dry weights were recorded.

Results

Soil-Seed Combinations - The results of the soil/seed combination experiment showed the effect of soil type/seed source combinations on plant biomass and nodule numbers (Table 8). Clay soils produced larger nodule numbers and biomass than sandy soils. Root biomass amounted to 12.3% of total plant biomass. Most biomass was generated by the shoot system (87.67%). Germination % was significantly affected by seed source, with sites E and S showing higher germination percentages than sites D and G. Soil types, however, had no effect on germination. They had strong positive effects on nodulation; whereas, seed sources had no effect. Soils had a strong positive effect on biomass with clay soils producing the most biomass. The average conversion factors for shoots and roots were 0.00172 and 0.00016 g/cm respectively for eight week old plants. There was no significant difference between treatments with respect to conversion factors. Shoot and total biomass were strongly positively correlated (R=0.999).

Clay soils contained higher amounts of nutrients, eg. N, P and K, than sandy soils. They also contained some of the micronutrients that have been generally associated with nodulation on legume plants, eg. Co and Mo. Furthermore, clay soils are more stationary than sandy soils, which are easily transported by wind, causing the top layer with moderate organic matter to be buried. The cracks that result on exposure to drought act like underground storage for organic matter which decomposes at the onset of the rainy (growing) season. Clay soils are richer in Ca than sandy soil. For these reasons we expect

clay soils to yield higher plant biomass and more nodule formation than sandy soil. The higher amount of organic matter in clay soil than sandy soil is conducive to microorganisms which require a source of carbon and a source of energy.

In the study which examined extension of the duration of the experiment, fresh nodules were firm and mostly round, although various shapes and configurations were also observed. The outer color was generally cream to light or dark brown. The inner color was invariably pink, indicating effective nodulation. Degenerate nodules, on the other hand, were flaccid, empty sacs of brown leathery appearance. The nodules were separated into these two categories (Table 9). The younger seedlings (50 days) had all their nodules fresh; no degenerate nodules were observed. The silty clay soil of Singa affected the highest nodule per plant on both ages. Most of the nodules on the older seedlings (90 days) were degenerate.

The clay silt soil seedlings continued to produce more nodules than sandy soil ones. The difference between the nodule numbers on the two soil types was statistically significant. The Nile clay silt was richer in nutrients and organic matter than sandy soil and is expected to cause more nodule formation than sandy soil.

The increase in degenerate nodule numbers with time may indicate that nodule formation is cyclic. All nodulation starts fresh and as time proceeds more nodules degenerate to release their nitrogen to plants or the soil. At a certain time all nodules are expected to degenerate. The reduction of fresh nodule numbers indicates that formation of fresh nodules was not continuous. A time may come when all fresh nodules become degenerate and older degenerate ones fall off the plant into the soil. A new flush of nodule formation may coincide with the plant phenological cycle, in order to satisfy the need for

nitrogen for processes such as leaf, flower and fruit formation.

Competition - Plants growing singly produced double the average shoot mass per plant (0.286 g), double the average root mass (0.092) and more than the average nodule number per plant (7.47) compared to crowded plants (Table 6). The crowded plants produced 0.153 g/day shoot mass, 0.049 g dry root mass, and 5.87 nodules per plant. From this we concluded that competition leads to reduced average plant mass and nodule number. High competition expressed as high plant density per unit volume of soil resulted in low individual plant biomass and no nodules. Total plant biomass was not significantly affected. Moderate competition did not affect total biomass but reduced nodule numbers, as compared to low competition which caused a drop in total biomass but gave the highest nodule numbers of all treatments. Competition appears to affect the shoot more than the root biomass.

Plants competed for limited nutrients, moisture and space resources. The more intense the competition the more severe the reduction of individual plant biomass. The total plant biomass under the two highest competition intensities was not significantly different from one another, which might indicate that the site potential was fully utilized by 67 plants. An increase in plant number to 99 did not yield significant increase in biomass. The least competition resulted in highest nodule numbers and highest individual plant biomass. Total biomass, however, was less in moderate and high competition treatments, which indicates that the site potential was not fully utilized under moderate and low competition intensities. A plant number between 100 and 67 would represent a biomass threshold above which no further increase in biomass will acrue as a result of

increase in plant number. As a prerequisite to the nitrogen fixation process, which is highly demanding of energy, nodulation takes place in systems whose energy reserves are high. When plants compete for limited water and nutrient resources, their ability to grow, form nodules or fix nitrogen would be low. This was apparent in the high intensity competition group.

Variation in Rhizobial Strains - Singa seeds produced the highest average nodule number (Table 11). *Rhizobium* strain GTGP (both seed and soil from G site) resulted in highest nodulation on Singa seedlings. Singa seedlings also gave the second and the third best nodule numbers with ETDP bacteria strains and *A. mellifera*. Strain ETDP also produced highest number of nodules with G seedlings. *Acacia mellifera* strains resulted in the highest nodulation with E and D site seedlings and gave a high nodule number with seedlings from S site. *A. seyal* strains produced very low nodulation in all seedlings.

There is no clear explanation as to why *A. mellifera* strains result in the highest nodule numbers; whereas, *A. seyal* was least. Gedaref and Singa seedlings were expected to yield high nodule numbers because they both originate from soils that cause nodulation to occur. Singa came true to expectation, but Gedaref failed. Because of the contamination that occurred when all the pots were flooded with unexpectedly high rains, the results from this study are considered only preliminary and need to be further ascertained by additional study.

Pot Effects- Plants raised in the middle of pots in the usual manner had longer shoots (19.7 cm), longer roots (20.7 cm), greater biomass (0.306 and 0.085 g/plant for shoot and

root) and larger average nodule number (8.3) than plants grown near the edge (Table 12). The plants grown on the pot edge were shorter and lower in shoot mass (13.1 cm and 0.152 g) and root mass (17.3 cm and 0.0659 g) and had fewer nodules (4.2).

The original observations were made on plants in transparent polyethylene bags. To test that observation, the same type of containers were used and sufficient time was allowed for roots to develop. Plants raised in the middle grew bigger and produced larger numbers of nodules per plant. Although the volume of soil and space allowed for both groups were similar, the edge plants only partially utilized those resources and expectedly were less efficient in biomass and nodule production.

MEETINGS, PRESENTATIONS AND PUBLICATIONS

Dr. Day attended the American Institute of Biological Sciences (AIBS) meeting held at the University of California at Davis in August 1988. We presented a poster titled "Gum production in Acacia senegal in Sudan: influence of tree age, precipitation and genetic variety."

We also attended the 40th annual meeting of AIBS which was held in Toronto, Canada in August 1989. We presented a poster titled "Effects of soil, seed source and planting density on nodulation and biomass production of Acacia senegal in Sudan". We are in the process of developing the second poster into a paper to be presented at the ASB (Association of Southeastern Biologists) 51st annual meeting in Baltimore, Maryland during 19-21 April 1990.

Mr. Saad attended the "Planning For Agroforestry" symposium held in Washington State University at Pullman, Wa and presented a paper titled "Planning for agroforestry

research in Western Sudan: Approaches, issues and lessons learned - the evolution of a management approach" which he coauthered during his field surveys in Sudan.

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Our thanks are also due to the Western Sudan Agricultural Research Project staff in Khartoum and Elobeid for acting as host to our project and for participating in the data collection and sample handling. We are also thankful to Dr. A.A. Mahdi and Mr. Othman Saad of the Faculty of Agriculture, Khartoum University for their participation in the field surveys and laboratory and greenhouse investigations. The Forest Administration in Sudan allowed us the use of their nurseries and plantations in Singa, Gedaref and Elobeid. Their field staff were helpful and cooperative. We are thankful to them. This project is still on-going as far as chemical and statistical analyses are concerned. The final results and conclusions will be embodied in a doctoral dissertation which Mr. Saad will prepare and present to Old Dominion University for his degree, under Dr. Day's supervision. We will furnish the USAID with a copy of the dissertation and all published papers.

Table 1. Study Site Location, Elevation and Climatological Norms, NA = not available

	Sites			
	Elobeid	Dubeibat	Gedaref	Singa
Latitude (°N)	13 05	12 45	14 02	12 44
Longitude (°E)	30 14	29 30	35 24	34 08
Elevation (m)	570	523	600	445
Atmospheric Pressure (MB)	944.4	948.5	941.6	957.3
Mean Daily Temp. (°C)	27.3	27.0	28.7	28.2
Highest Max. (°C)	44.4	44.1	45.1	45.5
Lowest Min. (°C)	4.4	5.6	6.6	5.7
Radiation (MJm^{-2})	NA	NA	NA	21.98
Annual Rainfall 1951-80 (mm)	361	450	593	557
Annual Rainfall 1981-87 (mm)	263	335	570	521
Mean Relative Humidity	36	40	44	46
Relative Humidity Range	14-72	18-74	24-73	22-76
Bright Sunshine Duration (hrs)	9.4	8.8	9.3	8.8
Bright Sunshine Duration %	78	75	77	74
Evaporation (mm)	15.5	12.3	11.9	12.1
Wind Speed (mph)	7.4	7.2	5.5	7.0

Table 2. Results of Soil Analyses for the Gedaref and Singa field research sites in Sudan.

Site	Distance From Tree (cm)	Soil Depth (cm)	pH	Salts (%)	Total P (ppm)	NO_3 - N (ppm)	K (μg/100 ml)
Gedaref	25	10	7.88	.10	4.33	10.67	20.67
		25	8.05	.09	2.67	9.17	16.33
		40	8.18	.09	2.33	7.00	16.67
	75	10	8.07	.09	3.67	9.00	19.33
		25	8.13	.09	3.00	8.83	18.67
		40	8.22	.09	2.67	12.00	16.67
	175	10	8.08	.09	3.33	10.33	23.00
		25	8.20	.09	3.00	8.50	20.00
		40	8.23	.09	3.33	12.33	20.00
Singa	25	10	9.07	.12	6.33	9.00	10.83
		25	9.10	.11	5.67	8.83	11.27
		40	9.20	.11	6.00	7.33	9.73
	75	10	9.10	.11	4.00	12.33	10.13
		25	9.14	.11	5.00	10.20	10.87
		40	9.27	.11	5.00	5.17	11.17
	175	10	9.17	.12	4.67	5.50	8.33
		25	9.22	.12	5.33	11.00	10.83
		40	9.25	.12	5.33	5.83	11.20

Table 3. Results of Soil Analyses for the Elobeid and Dubeibat Field Research Sites in Sudan.

Site	Distance From Tree (cm)	Soil Depth (cm)	pH	% N	% Fe	% K
Elobeid	25	10	6.6	0.80	0.58	0.18
		25	6.9	0.74	0.57	0.25
		40	6.4	0.87	0.50	0.14
	75	10	6.6	0.70	0.48	0.11
		25	7.0	0.78	0.49	0.22
		40	6.3	0.81	0.44	0.14
	175	10	7.2	0.72	0.39	0.12
		25	7.2	0.74	0.34	0.06
		40	7.3	0.67	0.44	0.13
Dubeibat	25	10	5.2	0.69	0.76	0.55
		25	4.9	0.70	0.79	0.17
		40	4.8	0.82	0.70	0.24
	75	10	5.3	0.71	0.77	0.20
		25	5.1	0.79	1.01	0.08
		40	4.7	0.66	0.90	0.14
	175	10	5.2	0.73	0.54	0.15
		25	4.9	0.79	1.03	0.11
		40	4.7	0.70	0.60	0.11

Table 4. Soil nutrient concentrations under low versus high gum arabic yielding Acacia senegal trees.

Site	Gum Yield	Distance From Tree (cm)	Soil Depth (cm)	Total N (%)	Fe (%)	K (%)
Dubeibat	High	25	10	.68	.88	.49
			25	.67	.68	.18
			40	.79	.70	.14
		75	10	.68	.74	.10
			25	.78	1.03	.09
			40	.63	.95	----
		175	10	.64	.68	.15
			25	.81	1.11	.21
			40	.71	.73	.15
Elobeid	High	25	10	.82	.63	.29
			25	.77	.35	.15
			40	.67	.36	.13
		75	10	.76	.49	.14
			25	.78	.62	.29
			40	.95	.27	.18
		175	10	.80	.33	.12
			25	.75	.52	.05
			40	.62	.49	.19

Table 4. (Continued)

Site	Gum Yield	Distance From Tree (cm)	Soil Depth (cm)	Total N (%)	Fe (%)	K (%)
Elobeid	Low	25	10	.78	.52	.06
			25	.79	.61	.35
			40	1.03	.65	.15
		75	10	.55	.38	.07
			25	.77	.45	.15
			40	.72	.26	.11
		175	10	.73	.45	.12
			25	.69	.17	.08
			40	.62	.38	.08

Table 5. Tree growth parameters.

Study site	Variable	Age (yr)	Girth (cm)	Height (cm)	Stocking (#trees/ha)	Growth Rate (cm/yr)
E	(1) High Yield	21	50.3	386	625	18.4
E	(2) Low Yield	21	51.8	405	625	19.3
E	(3) Go[z] Bottom Site	21	42.9	395	625	18.8
E	(4) Go[z] Top Site	21	39.4	314	625	14.9
D	Site 1	21	37.7	323	625	15.4
D	Site 2	21	33.3	323	625	15.4
S	Plantation, young	4	11.3	133	2010	33.2
S	Plantation, closely spaced	17	27.6	324	2190	19.2
S	Plantation, closely spaced	13	31.0	308	2300	23.7
S	Natural, moist site		53.4	425	277	
G	Plantation	15	27.0	361	625	24.1
G	Plantation	21	38.0	542	625	25.8

Table 6. Seed size variation with site. Number of seeds per g.

	Elobeid	Dubeibat	Gedaref	Singa
	9.4	8.6	7.7	10.4
	6.7	10.4	8.1	10.9
	10.4	7.8	9.6	10.0
	7.7	10.5	9.9	9.7
	7.6	10.3	10.2	11.3
	7.5	9.7	7.6	9.6
	7.1	11.0	10.4	8.1
	8.2	11.9	8.8	9.8
	7.9	10.8	7.9	10.8
	8.3	9.2	8.6	8.4
Mean	8.08	10.02	8.88	9.90
S.E.	0.34	0.38	0.33	0.33

Table 7. Preliminary mean nitrogen concentrations in Acacia senegal leaves and gum.

Site	Material	Protein (%)	N (%)	Moisture(%)
Elobeid	Gum	0.49	0.08	8.67
	Leaves	22.55		
Dubeibat	Gum	0.51	0.09	8.61
	Leaves	20.71		
Singa	Gum	0.66	0.11	8.67
	Leaves	27.06		
Algedaref	Gum	0.59	0.09	8.44
	Leaves	24.19		

Table 8. Plant biomass and nodule formation in Acacia senegal seedlings from 4 seed sources in 4 different soils.

Soil Source	Seed Source			
	Elobeid	Gedaref	Singa	Dubeibat
		Nodules per plant		
Elobeid	6.3	9.8	6.2	10.4
Gedaref	14.0	11.8	13.5	7.1
Singa	13.6	7.4	10.8	10.5
Dubeibat	5.7	3.8	4.3	1.9
		Shoot mass (g/plant)		
Elobeid	.22	.13	.21	.19
Gedaref	.31	.39	.31	.32
Singa	.41	.33	.30	.43
Dubeibat	.21	.11	.22	.11
		Root mass (g/plant)		
Elobeid	.09	.09	.09	.11
Gedaref	.14	.20	.14	.13
Singa	.19	.15	.15	.19
Dubeibat	.11	.06	.11	.05
		Total mass (g/plant)		
Elobeid	.31	.22	.30	.30
Gedaref	.45	.59	.45	.45
Singa	.60	.48	.45	.62
Dubeibat	.32	.17	.33	.16

Table 9. The effect of soil type and testing time on nodule number and type. Seed used was from source E.

Soil Type	Total Nodule # 90 days		# of Nodules Per Plant 50 days		# of Nodules Per Plant 90 days		
	Fresh	Degenerate	Fresh	Degenerate	Fresh	Degenerate	Σ
Singa	26.0	54.7	13.6	---	1.9	4.0	5.9
Dubeibat	14.0	23.0	5.7	---	1.8	3.0	4.8
Elobeid	12.3	14.3	6.3	---	1.5	1.7	3.2

Table 10. Effect of plant competition on nodulation and biomass production.

Treatment	Average no. of Plants	Shoot mass (g/plant)	Root mass (g/plant)	Nodule no. per plant
High Competition	99.67	5.47	1.43	0
S.E.	4.30	0.26	0.06	
Moderate Competition	67.33	5.14	1.52	13.33
S.E.	1.45	0.04	0.03	1.20
Low Competition	6.33	3.76	1.63	47.67
S.E.	1.45	0.37	0.10	2.40

Table 11. Number of nodules on A. senegal from four sources inoculated with various Rhizobia strains. Units are avg. # nodules per pot. S = Singa, G = Gedaref, E = Elobeid, D = Dubeibat, T = soil, P = seed

		Seed Sources				
Code	Strains	Singa	Gedaref	Elobeid	Dubeibat	Mean
A.M.	A. mellifera	21.8	8.3	14.2	21.0	16.32
A.S.	A. seyal	4.7	6.5	6.4	5.7	5.82
4	ETDP	22.2	19.6	3.6	1.5	11.72
5	GTEP	8.0	12.4	10.4	3.0	8.45
6	GTGP	42.4	10.0	5.0	2.7	15.02
7	GTSP	10.4	9.6	5.6	4.4	7.50
9	STEP	11.8	3.5	10.5	3.6	7.35
11	STSP	7.0	3.0	9.6	15.8	8.85
	Control	11.0	21.8	18.8	3.2	13.70
	Mean	16.0	9.1	8.2	7.2	

Table 12. Effect of location of plants in pot on nodulation. Values are means per plant.

Treatment	Plant #	Shoot		Root		Nodule #
		Length (cm)	Dry wt (g)	Length (cm)	Dry wt (g)	
Edge	13	13.1	0.152	17.4	0.065	4.15
Middle	13	19.7	0.306	20.7	0.085	8.31