AGRICULTURAL RESEARCH CORPORATION

WESTERN SUDAN AGRICULTURAL RESEARCH PROJECT

SOIL AND WATER MANAGEMENT/CONSERVATION RESEARCH IN THE KORDOFAN REGION OF SUDAN: REPORT ON RESEARCH ACTIVITIES AND RESULTS FOR THE 1984-85 SEASON

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AGRICULTURAL RESEARCH CORPORATION

WESTERN SUDAN AGRICULTURAL RESEARCH PROJECT

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SOIL AND WATER MANAGEMENT/CONSERVATION RESEARCH IN THE KORDOFAN REGION OF SUDAN: REPORT ON RESEARCH ACTIVITIES AND RESULTS FOR THE 1984-85 SEASON

LALIT ARYA SOIL AND WATER SPEC'ALIST

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SOIL AND WATER MANAGEMENT/CONSERVATION RESEARCH IN THE KORDOFAN REGION OF SUDAN: REPORT ON RESEARCH ACTIVITIES AND RESULTS FOR THE 1984-85 SEASON.

LALIT M. ARYA[1]

A. SUMMARY

Western Sudan is an arid to semi-arid region. Shortage of water is the chief limitation to crop production and results from the combined effects of weather and soil conditions. The Western Sudan Agricultural Research Project (WSARP) is conducting field research to improve soil management and crop cultural practices with the objective of making the most efficient use of available rainfall.

Major agricultural soils in Western Sudan include stabilized sands (goz), noncracking low infiltration soils (gardud), and fine

1. Soil and Water Specialist, WSARP, El Obeid

textured clayey soils (cracking vertisols). Goz sands are the predominant soils in North Kordofan. These soils have very poor water and nutrient holding capacities. Gardud soils are very hard and difficult to cultivate with traditional hand tools. Water infiltration in these soils is very low. As a result, much of the rainwater on gardud lands is lost as runoff. Cracking vertisols dominate the lands in South Kordofan. These are potentially productive soils with high water and nutrient holding capacities. However, because of sever cracking on drying and surface sealing on wetting, losses of rainwater through evaporation and runoff are significant. Fixation on clay surfaces appears to cause a significant reduction in nutrient availability.

Several soil and water conservation practices were field tested during the 1984 cropping season. These included mulching and residue management, interrow surface tillage, soil amendments, ridge-furrow cultivation, planting in seed cradles, and depth of planting trials. Other efforts included studies of soil properties and dryland hydrologic processes, introduction of drip irrigation, and instrumentation for collection of weather data.

Despite an unusually poor rainy season, results have shown that crop yields can be increased with water conservation. Unavailability of resources did not permit monitoring of soil moisture during the cropping season. Only the biomass and grain yield data were taken as indicators of the effectiveness of the various moisutre conservations practices.

Mulching and residue management appeared to be most effective. Mulching on cracking vertisols increased sorghum biomass and grain yields by 53 and 138 percent, respectively. Increases of 56 and 63 percent in sorghum biomass and grain yields, respectively, were observed with naturally occurring residues left on the surface and planting without tillage. Yields were poorest in plots where residue was burnt. Weed growth was minimal in mulched plots and soil moisture remained significantly higher throughout the season. Mulching produced similar results on goz sands in North Kordofan. Millet biomass and grain yields were increased by 168 and 83 percent, respectively, when dry millet stalks were used as mulch.

Ridge-furrow cultivation did not prove to be beneficial in gardud soils and cracking vertisols, but increased millet biomass and grain yields by 18 and 65 percent, respectively, in goz sands. Depressed yields with ridge-furrow cultivation in cracking vertisols and crop failure in gardud soils appeared to be related to exposure of hard subsoil at the furrow bottoms where the seeds were planted. Ridges were difficult to maintain in goz sands because of unstable nature of the sand.

Frequent shallow cultivation of the surface in the interrow space in cracking vertisols was expected to conserve moisture through effective weed control and reduction of evaporation through soil mulching. Grain yield showed a positive effect (19 percent increase) but more effort was required to carry out the operation.

Seed cradles could not be maintained in goz sands and produced the poorest yields. They got filled up with loose sand soon after planting and only very few seedlings could emerge. In gardud soils, however, seed cradles were easy to maintain and showed a dramatically positive effect on emergence, seedling survival, and early growth. Soil moisture under the seed cradles was significantly higher than under the flat virgin surface.

Soil amendments were applied in goz sands to improve water retention and retard evaporation in the immediate vicinity of the seedlings. Ground clay soil appeared to be effective. A treatment with 100 g ground clay soil per hill produced increases of 37 and 67 percent in millet biomass and grain yields, respectively. Gum arabic was found to be an effective retardant of evaporation from goz sand in pot tests. Under field conditions, however, the results were poor and inconclusive. Similar results were found with mixtures of gum arabic and ground clay soil. General lack of moisture and crusting in goz sand are thought to have complicated the reaction of the amendments. Depth of planting observations in goz sands showed that millet emergence and seedling survival were better for a planting depth of 10 cm than for a planting depth of 5 cm. Emergence was poor for a planting depth of 15 cm and no emergence was observed for a planting depth of 20 cm.

Although increases in crop production were obtained with moisture conserving practices, yields were low. The rainfall for the 1984 season was critically low (the lowest recorded, perhaps). Under

critically low moisture supplies, crops perform poorly regardless of differences in moisture conditions due to conservation practices. Therefore, crop production data alone may not be an adequate indicator of the effectiveness of a practice. It would be desirable to carry out moisture conservation trials over several seasons. Additionally, soil moisture and crop water use must be monitored to evaluate field practices in a meaningful way. Such monitoring will also allow understanding of factors that can be manipulated.

Certain physical and moisture related characteristics of the goz sands were of particular interest. Studies were made of crusting problems, surface zone drying patterns, and moisture storage and conservation. Despite preponderance of sand, crusting occurs in goz sands. Crust strength was found to increase rapidly with drying and measured values appeared to be quite restrictive to seedling emergence and stem expansion. A high spatial variability exists due to randon occurence of crusted and noncrusted surfaces. Surface zone drying rates were quite high. In areas with loose sand on the surface, almost 75 percent of the moisture in the top 5 cm zone was lost within the first 24 hours after infiltration. The rate of loss of moisture decreased with depth. Crusted surfaces showed similar patterns but the rates were somewhat lower.

Data on surface zone drying rates and moisture distribution with depth suggest that planting seeds deeper than 5 cm may increase the chances of emergence and seedling survival. Depth of planting observations, in fact, showed that millet emergence and seedling survival were perceptibly better for a planting depth of 10 cm.

Moisture distribution in a 180 cm deep profile was measured as a function of depth and time. In irrigated plots, it was found that water moves downwared very rapidly and the soil cannot hold more than 50 percent of theoretical limit of maximum water content suggested by porosity values. In dry plots, data showed about 120 mm of water for most of March and April months. Most of the water was present in deeper layers and was held at very low tensions. Moisture distribution curves showed the tendency for the moisture content to increase with depth. It appears that a significant amount of moisture is present at great depths and moves upward into the root zone under appropriate circumstances.

These findings suggest that deep rooted crops have a better chance of survival in goz sands. The rate of water loss from the 180 cm deep soil profile was about 0.8 mm/week suggesting that the evaporative loss of water is minimal after the initial rapid drying of the surgace zone. It appears that a large amount of water is conserved from season to season. Estimates of the componenets of water balance suggest that a significant amount of water (150 to 200 mm) available during the 1984 season was actually conserved water from 1983 or the previous seasons. Fallowing from season to season would, therefore, appear to be an effective means of increasing profile moisture storage for crop production. An effective weed control and some residue cover will be most desirable for fallowing practice to succeed.

Thus, goz sands appear to have a natural potential for conserving water. Rapid percolation allows rainwater to be distributed over

great depths under the surface. Rapid drying of the surface provides a natural mulch which acts as a barrier against evaporation. The dry layer at the surface, thus, appears to be a desirable feature. However, this is also the zone where seeds are planted. Seed germination and seedling establishment are adversely affected by the surface zone moisture deficiencies. Seedling failure results in poor yields despite the fact that water is available in the lower depths of the soil profile. The management, therefore, has to focus on methods of seedling establishment on one hand and selection of deep rooted crops on the other.

Ridge-furrow system of cultivation appears to be a potentially effective method of improving water intake and physical condition in gardud soils. However, ridge-furrow beds are difficult to prepare the first time. But once prepared, they can be left undisturbed for several years. Only the furrows should be cultivated and planted to crops. Ridges in gardud soil are not damaged easily. Some maintenance may be required for portions that do get damaged. Furrows will act as catchment for water and ridges will prevent runoff and erosion. Cultivating furrows only will cut down considerably the amount of work, and the effort required should decrease with time as the soil improves with more and more water penetrating the soil each season.

Mulching and residue management should be considered seriously for soil and water conservation in cracking vertisols. 1984 results have demonstrated the beneficial effects of ground cover composed of

organic residues. Additionally, where possible, post rainy season tillage should also be considered. Clods and aggregates will act not only as a mulch but will also modify cracking patterns. Closure of wide cracks will certainly help conserve some of the subsoil moisture. The tilled layer will provide favorable conditions for infiltration of initial rains. Contour bunding should also be introduced as a means of capturing runoff.

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LALIT M. ARYA[1]

B. INTRODUCTION

The Western Sudan Agricultural Research Project (WSARP) has established research stations for crop and livestock research for traditional producers in the rainfed sector of Western Sudan (1,2,3). Figure 1 shows the locations of the WSARP research stations. One of the stations is located in El Obeid, in the southern part of the North Kordofan Province. WSARP Kadugli serves the South Kordofan (or Nuba Mountain Region). WSARP El Fasher and WSARP Ghazala Gawazat serve the Darfur Region. The aim of the WSARP research program is to achieve an improvement in the livelihood of the traditional producers.

Western Sudan is an arid to semi-arid region. Shortage of water is the most serious limitation to crop production. It is a result of the

1. Soil and Water Specialist, WSARP, El Obeid

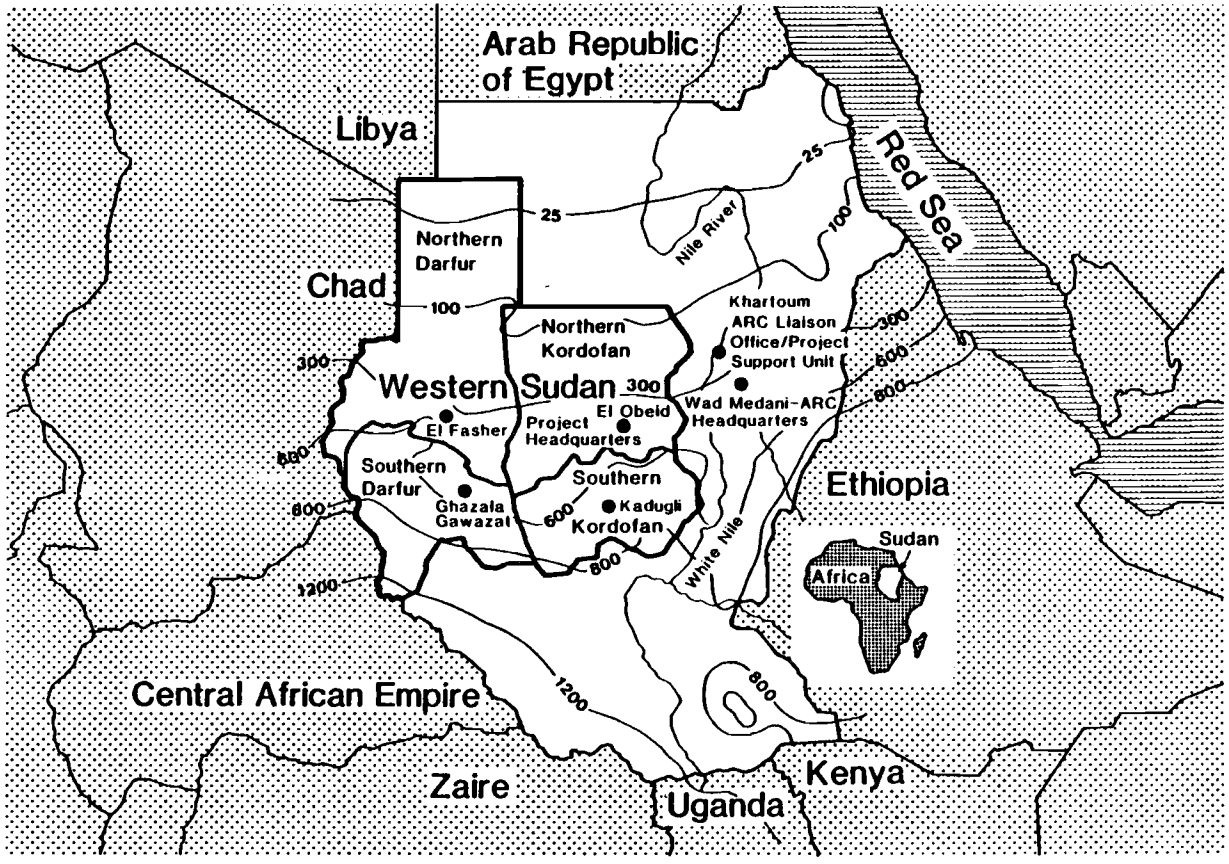


Figure 1. Locations of WASRP Research Stations in Sudan
Numbers Indicate Rainfall Isohyets.

combined effects of weather and soil conditions. Weatherwise, the region is characterized by low rainfall (Figure 1) and high atmospheric evaporativity (4). In recent years the annual rainfall has been signifcantly less than the long term averages indicated in Figure 1. For example, the 1984 rainfall for the region around El Obeid (North Kordofan) was only 132 mm compared with the long term average of 386 mm. Table 1 shows an example of the declining pattern of rainfall. Rainy season extends from June/July to September/October. However, the period between first and last useful rainfall is often limited to 70 to 90 days. This limits the choice of crop varieties to short maturing type and early planting is almost always necessary. Soils are poor in fertility and their physical conditions are conducive to excessive erosion, low water intake, and rapid losses of water through runoff, deep drainage, and evaporation. Through continued neglect and poor cultural practices, soil deterioration has progressed to a point that desired level of production cannot be sustained. Table 2 shows the declining yields of major field crops in North Kordofan. The decline in production appears to have paralleled the decline in rainfall.

There is urgent need to improve and stabilize food production in Western Sudan. However, since nothing can be done to change the weather, major emphasis has to be on soil management and crop cultural practices aimed at making the most efficient use of what rainfall is available.

Table 1. Declining pattern of annual rainfall in the region around El Obeid.

Year	Average rainfall, mm
1941 - 1970	386
1970 - 1977	350
1978 - 1984	280
1984 (9 locations)	132

Table 2. A comparison between yields (kg/ha) of major filed crops in North Kordofan (Sudan) and World estimates for the same crops for dryland areas.

Crop	Estimated[1] dryland yields	Maximum[2] achieved in North Kordofan (1960's)	Mean yields in North Kordofan, Sudan				
			1960's[2]	1974-78[3]	1979-83[3]	1983[3]	1984[3]
Sorghum	800	770	535	289	274	109	36
Millet	600	675	470	314	274	135	31
Sesame	500	440	305	180	173	97	24
Groundnuts	1300	1580	880	605	558	206	73

1. Reference 18
2. Reference 17
3. Statistics Office of the Regional Ministry of Agriculture, El Obeid, Sudan.

WSARP research activities in the area of soil and water management did not begin until late 1983. With the arrival of the soil and water specialist in late 1983, efforts were begun to assemble available information to develop a program of research. Early surveys revealed that negligible attention had been given to soil and water problems, although lack of water, low soil fertility, and erosion were widely recognized as constraints to productivity. However, since organized and sustained research had not been carried out in the region, there was a lack of factual information on specific limitations. Consequently, the initial program (5) was based on reconnaissance surveys, visual observations, and impressions gathered from discussions with professional agronomists, farmers, and administrators. Nevertheless, it was possible to identify the following as the major elements of the soil and water management problems in Western Sudan:

- Low and unreliable rainfall.
- Relatively short rainy season.
- High atmospheric evaporativity.
- Soil conditions conducive to low water intake and rapid losses of water through runoff, deep drainage, and evaporation.
- Excessive soil compaction.
- Soil erosion.
- Poor cultural practices.

- Weed competition for soil water and nutrients.
- Inefficient use of irrigation water.
- Lack of quantitative information on soil properties and processes, fertility status, crop/weather interactions, moisture balance and water loss patterns, and nature and magnitude of erosion problems.
- Lack of awareness of the severity of soil and water problems and potential conservation practices.

Although the program was ready by February/March 1984, little could be done until the rains began in early July. During the interim, efforts were made to gain an understanding of the soils and to identify potential solutions. But negligible progress was made due to lack of resources needed to carry out moisture related research during the dry season. Lack of equipment, personnel, space, water, and power greatly affected research that could be carried out in the laboratory.

During the cropping season, several moisture conserving practices were field tested at WSARP stations at El Obeid, Banou, and Kadugli. As the resources became available, efforts were made to obtain data on soil properties and processes relevant to making soil water management decisions. A weather station was also installed in El Obeid. Additionally, an introductory drip irrigation system was assembled to begin work towards improving irrigation efficiency in horticultural prodution in North Kordofan.

This report presents the soil and water management/conservation research carried out during the 1984-85 season. Significant results are presented and recommendations are made for a continuing future research.

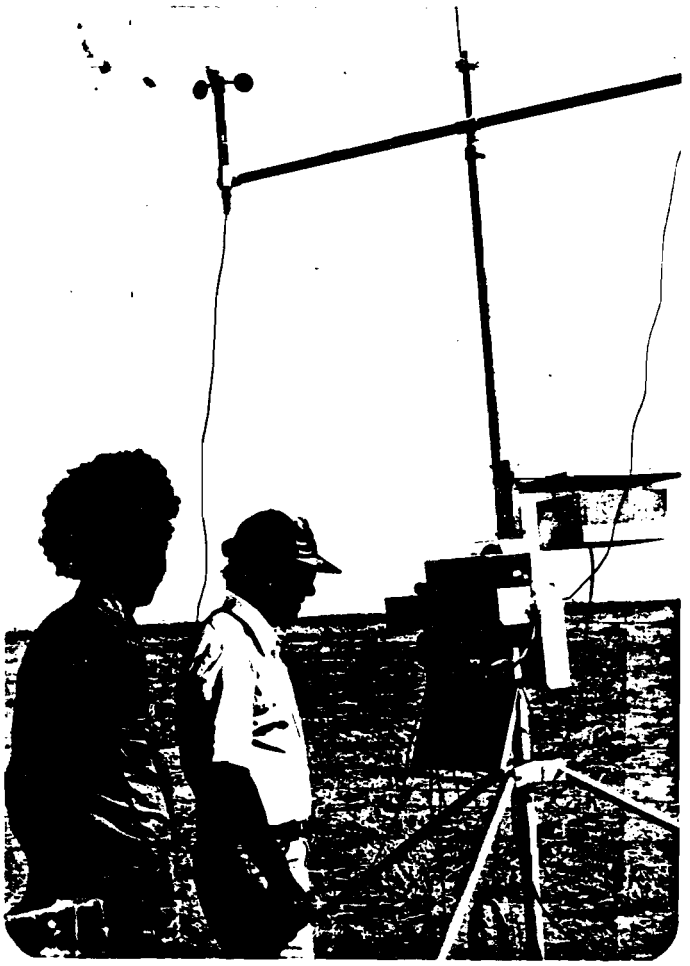
C. WEATHER DATA

Isohyets plotted in Figure 1 indicate the long term averages of rainfall for the various regions of Sudan. There is a gradual increase in rainfall from north to south. Table 1 shows the declining pattern of average annual rainfall in North Kordofan. The 1984 rainfall data for El Obeid, Banou, and Kadugli are shown in Table 3. The weather station at WSARP farm in El Obeid became operational on 29 August 1984. The recording unit is a CR-21 micrologger manufactured by Campbell Scientific of Logan, Utah (USA). The sensors connected to this unit include tipping bucket raingauge, anemometer, combined relative humidity and temperature probes, and a pyranometer. An evaporation pan (US Class A Pan) was also installed; however, because of lack of water and personnel problems, only partial evaporation data are available. Weekly averages of weather data recorded at the WSARP farm (El Obeid) are reported in Appendix 1.

Table 3. 1984 rainfall data for El Obeid, Banou*, and Kadugli.

Dates	Rainfall, mm		
	El Obeid	Banou	Kadugli
May 1 - 7			4.2
8 - 14			0.0
15 - 22			38.1
23 - 31			12.7
Jun 1 - 7		0.0	42.0
8 - 14		0.0	16.5
15 - 22		0.0	15.0
23 - 30		12.0	28.0
Jul 1 - 7	21.5	28.0	71.0
8 - 14	0.0	0.0	10.2
15 - 22	67 0	14.0	42.0
23 - 31	3.0	2.0	24.5
Aug 1 - 7	10.5	22.0	35.0
8 - 14	0.0	9.5	14.5
15 - 22	5.5	16.0	28.5
23 - 31	0.0	0.0	0.0
Sep 1 - 7	29.0	0.0	5.0
8 - 14	0.0	0.0	35.7
15 - 22	2.0	30.0	13.5
23 - 30	23 0	8.0	0.0
Oct 1 - 7		15.0	2.0
8 - 14			1.0
15 - 22			12.0
23 - 31			0.0
Total	161.5	156.5	451.4
Long term	386.0	-	732.0

* There was no raingauge at Banou site. Data are from nearby Bangdeed



Meteorological Station, WSARP Research Farm, El Obeid.

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An examination of the data in Figure 1, Tables 1 and 3, and Appendix 1 reveals the severity of weather in North Kordofan. Although the rainfall increases from north to south, the total amount and distribution remain unfavorable for successful crop production. The need is evident for management practices for making the most efficient use of available rainfall.

D. SOILS

Western Sudan soils have not been studied in detail. Data on physical properties, hydrologic processes, and fertility status are lacking. Reconnaissance surveys (6, 7) show three major soil types. These are:

Goz (or stabilized sands)
Gardud (or noncracking clayey soils)
Vertisols (or cracking clay soils)

Transitions between these major types have also been identified. According to the surveys, most of the soils are low in fertility and are drought-prone because of physical conditions conducive to low intake of water and rapid losses of water through runoff, evaporation, and deep drainage. Soil erosion is a serious problem in the region. Data on crop response to fertilizers confirm the low nutrient status of the soils (8).

Efforts were made during 1984 to have the soils on each of the WSARP research stations analysed for physical and chemical properties. Three soil profiles were sampled during the months from October to December 1984 at each of the WSARP farms, El Obeid, Banou, and Kadugli. Samples were obtained in 5, 10, or 15 cm depth increments down to a depth of about 150 cm or more. All samples were air dried, crushed, and passed through a 2-mm sieve. Since WSARP does not have facilities for analyses, samples had to be sent to the Agricultural Research Corporation (Wad Medani) for analyses. No results have been received till now. While sampling the soil profiles, observable features of the various layers were recorded. Bulk density data were obtained by core or clod (9) techniques.

D-1. GOZ SANDS:

Goz sands cover almost 70 percent of the land area in North Kordofan and North Darfur. These are deep soils and have very high infiltration capacity. However, their water and nutrient holding capacities are very low. Organic matter content appears to be negligible and there is no visible aggregation. Sand content appears to be in excess of 90 percent. There is some silt and little or no clay. These soils are most susceptible to wind erosion. Major crops grown on these soils are millet, groundnuts, sesame, and watermelon.

D-1-1. SOIL SAMPLING AND BULK DENSITY MEASUREMENTS:

Two soil profiles were sampled in varying depth increments down to a depth of 165 cm. Bulk samples were obtained from each layer for textural and chemical analyses. Bulk densities were measured using brass cores. Data for a soil profile at the WSARP farm, El Obeid are shown in Figure 2. For another profile, data are presented in Table 4. Except near the surface, there does not appear to be any compaction. The profile between the depths of 40 to 160 cm appears to be fairly uniform with an average bulk density value of about 1.47 g/cm^3.

D-1-2. CRUSTING AND SPATIAL VARIABILITY:

Two types of surfaces were observed on the goz land during the 1984 cropping season. One was with loose sand of variable thickness and the other was a smooth surface exhibiting a crusted appearance. Area under the two types of surfaces varies depending on the surface microrelief, and they occur, by and large, in a random manner. At first, this variability was not considered serious as the soil texture under the two surfaces appeared to be the same. Later on, however, it was noticed that seedling emergence in smooth areas was very poor with 100 percent failure in some plots. At this point, penetration resistances were measured using a proctor penetrometer. Data, presented in Figure 3, showed very high impedance under the smooth surfaces. Penetration resistance was quite low under the loose sand. Most of the strength under the smooth surface appeared to be confined

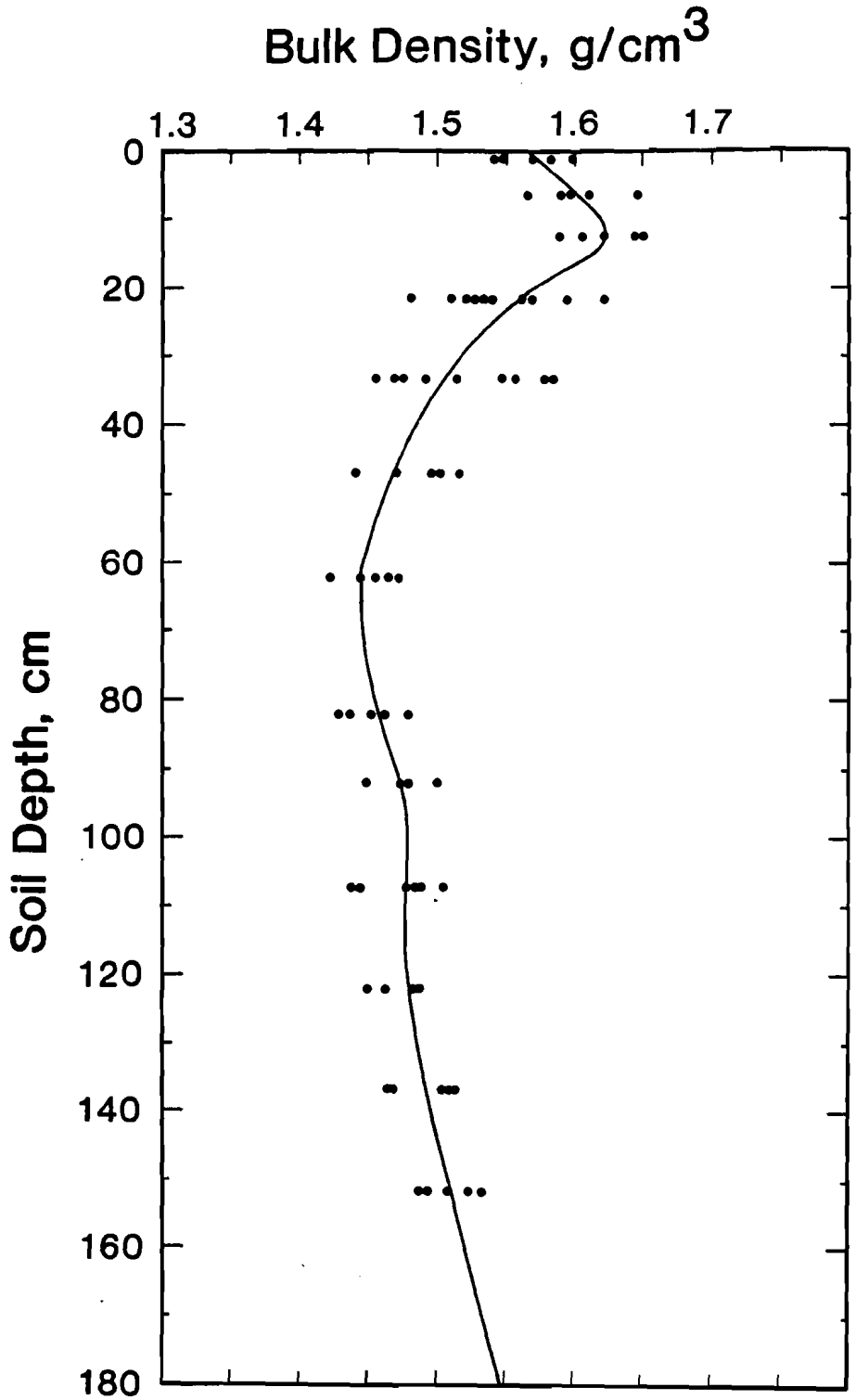


Figure 2. Bulk density profile for goz sand (profile 1), WSAP Farm, El Obeid.

Table 4. Variation in bulk density with depth in goz sand, profile 2, WSARP Farm, El Obeid. Each value is a mean of five samples.

Depth cm	Bulk density g/cm^3
0 - 5	1.544
5 - 10	1.589
10 - 15	1.573
15 - 20	1.590
20 - 30	1.584
30 - 45	1.532
45 - 60	1.520
60 - 75	1.552
75 - 90	1.556
90 - 105	1.550
105 - 120	1.564
120 - 135	1.620
135 - 150	1.634
150 - 165	1.647

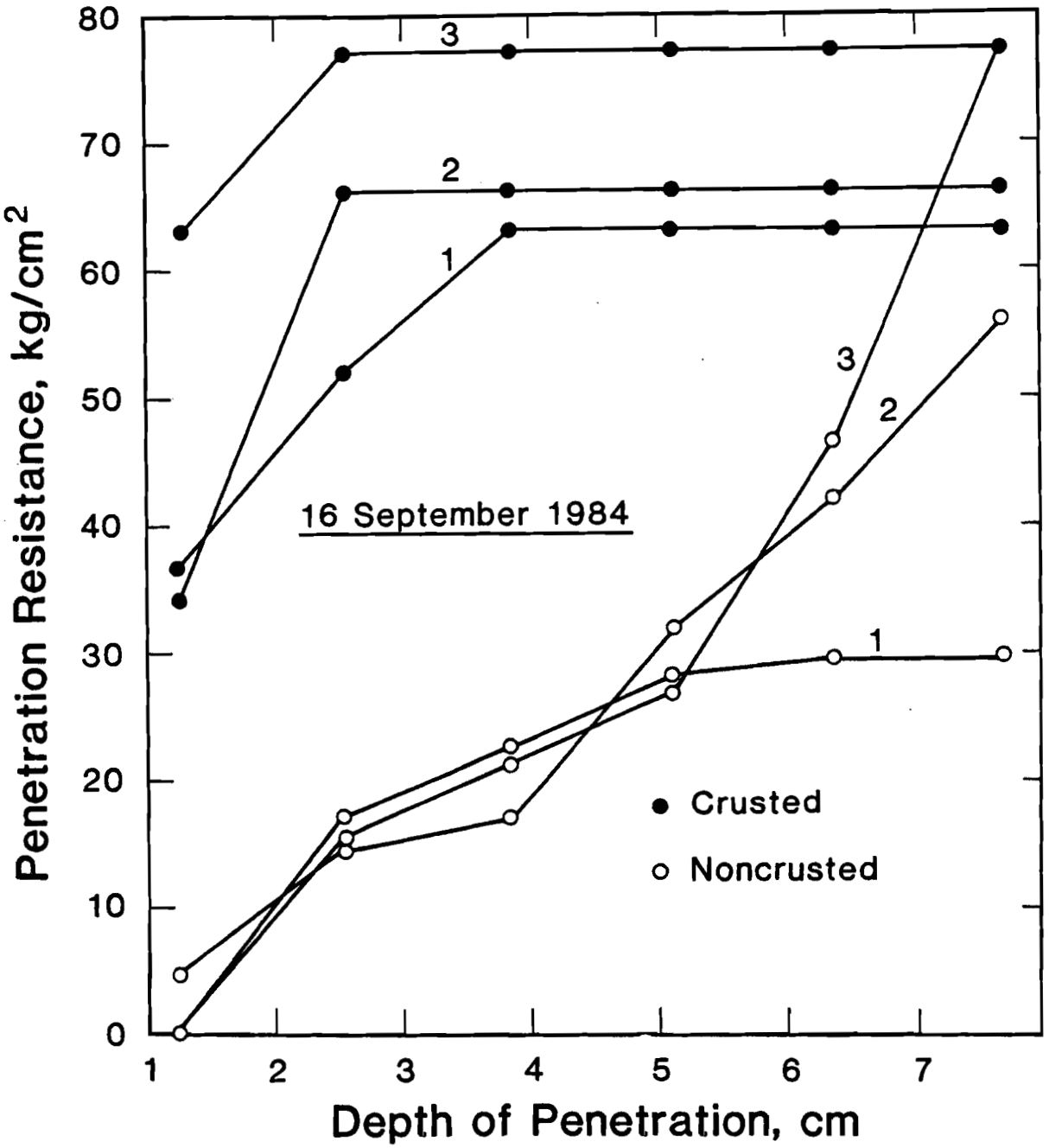


Figure 3. Penetration resistance in goz sand, as a function of depth. Numbers by the curves indicate locations on the farm.

to between the surface and 2.5 to 3.5 cm depths. Subsequently, we measured penetration resistance for a penetration depth of 5 cm, as a function of drying. Data are shown in Figure 4. Data show that penetration resistance under the crust increases rapidly as the drying progresses. It remains quite low under the loose sand. As will be seen later, drying of the surface zone in goz sand is very rapid (see Figures 5 and 6). It appears, therefore, that the combined effects of rapid drying and increasing mechanical impedance are responsible for poor emergence of seedlings. The pattern of the occurrence of these crusted surfaces also creates high spatial variability. Sensible field experiments cannot be carried out if this variability continues to exist. The land needs to be plowed in order to homogenize the soil but special measures will have to be taken to minimize the risk of wind erosion.

In addition to measurements of penetration resistance, 0 to 30 cm samples were taken from 24 spatially distributed locations to obtain data on variations in fertility and other important characteristics of the soil. Surface bulk densities for the 0 to 3 and 3 to 6 cm depths (Table 5) did not appear to be significantly different between the crusted and loose surfaces. Analyses for other soil properties have not been recieved from ARC (Wad Medani).

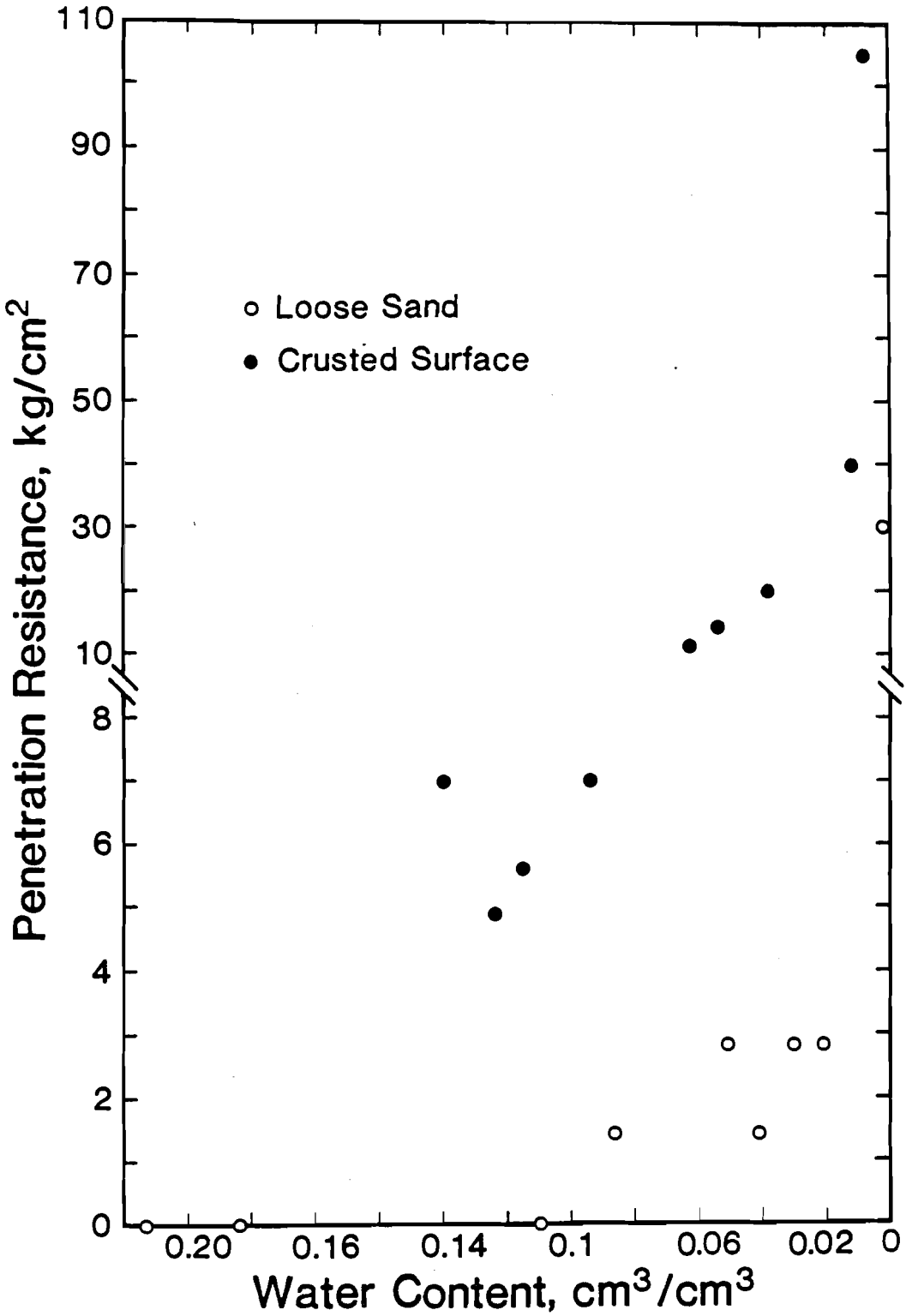


Figure 4. Penetration resistance for the 0-5 cm depth in goz sand as a function of drying.

Table 5. Variation in surface bulk densities under crusted and noncrusted surfaces in goz sand.

	Bulk density, g/cm^3			
	Crusted		Noncrusted	
Locations	0 - 3 cm	3 - 6 cm	0 - 3 cm	3 - 6 cm
1	1.595	1.689	1.586	1.569
2	1.620	1.591	1.588	1.444
3	1.576	1.481	1.642	1.557
4	1.596	1.610	1.543	1.466
5	1.629	1.617	1.590	1.567
6	1.544	1.662	1.645	1.572
7	1.585	1.654	1.596	1.614
8	1.580	1.650	1.599	1.646
9	1.583	1.599	1.618	1.647
10	1.593	1.715	1.676	1.618
11	1.596	1.581	1.627	1.641
12	1.620	1.596	1.645	1.622
Mean	1.593	1.620	1.613	1.580

D-1-3. MOISTURE MEASUREMENTS:

(a) Surface Zone Drying Patterns: Since surface zone moisture conditions are crucial to seed germination and seedling emergence, it was considered important to make an assesment of the surface drying patterns in the goz sands. Two plots were prepared, one in a crusted area and the other in an area with loose sand on the surface. Both plots were wetted with 30 mm of water. As soon as the free water disappeared from the surface, soil was sampled in 5 cm depth increments down to a depth of 20 cm. Sampling continued at short time intervals up to 70 hours after irrigation. Gravimetric water contents were determined by oven drying and converted to volume basis by multiplying the values with bulk densities for the respective depth increments. Volumetric water contents were converted to equivalent depth of free water for the various 5 cm depth increments. Drying pattern data are shown in Figures 5 and 6. Data show that surface zone moisture loss is, indeed, very rapid. The 0 to 5 cm zone under the loose sand lost almost 76 percent of the water within the first 24 hours. As expected, the rate of water loss decreased with depth but remained quite high for the top 10 cm zone. The water loss patterns under the crusted surface were similar; however, the values were somewhat smaller.

(b) Soil Moisture Characteristic: Soil moisture characteristic is the relationship between soil water content and the tension (or negative pressure) with which it is held in the soil pores

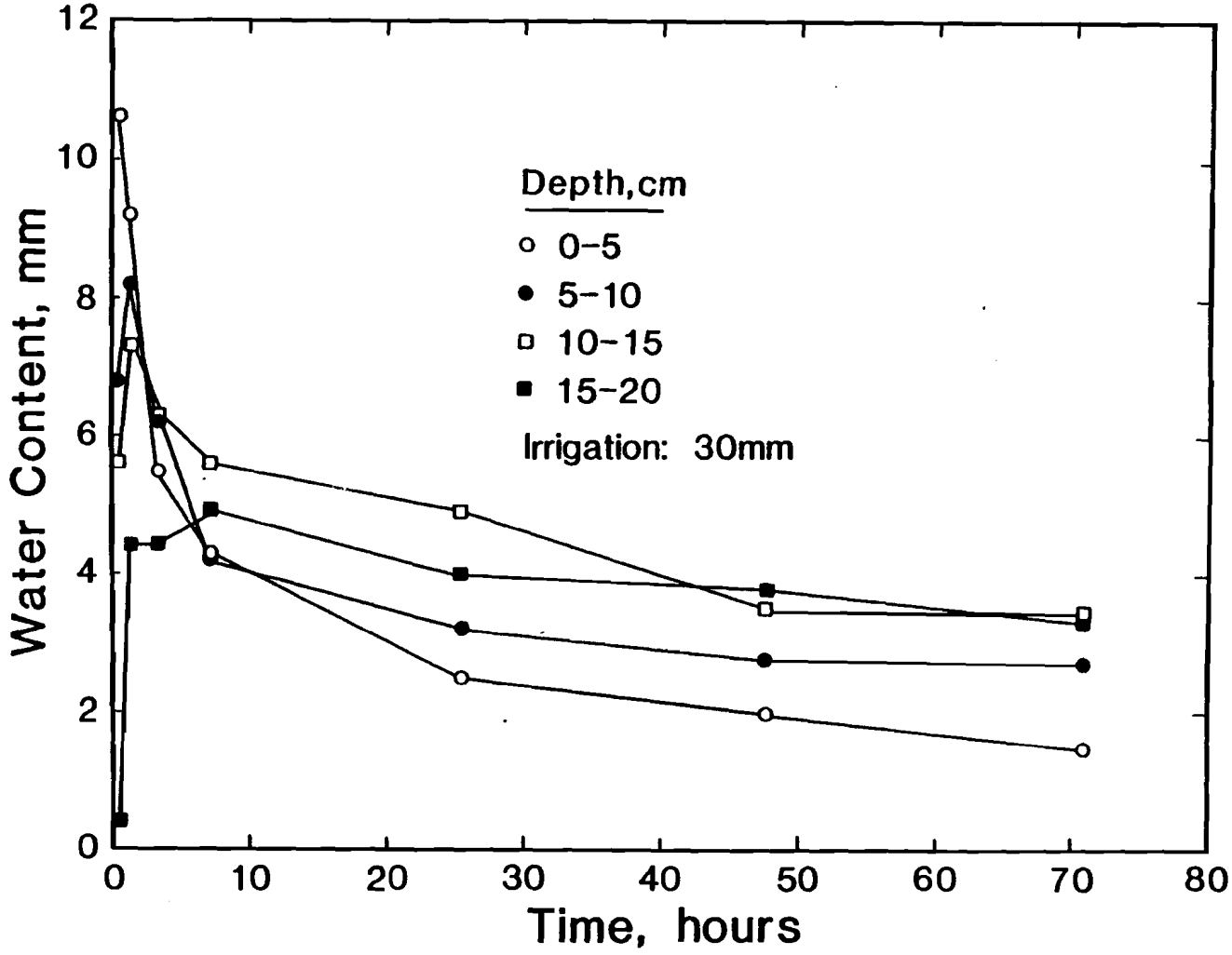


Figure 5. Surface zone drying patterns in goz sand. Noncrusted surface.

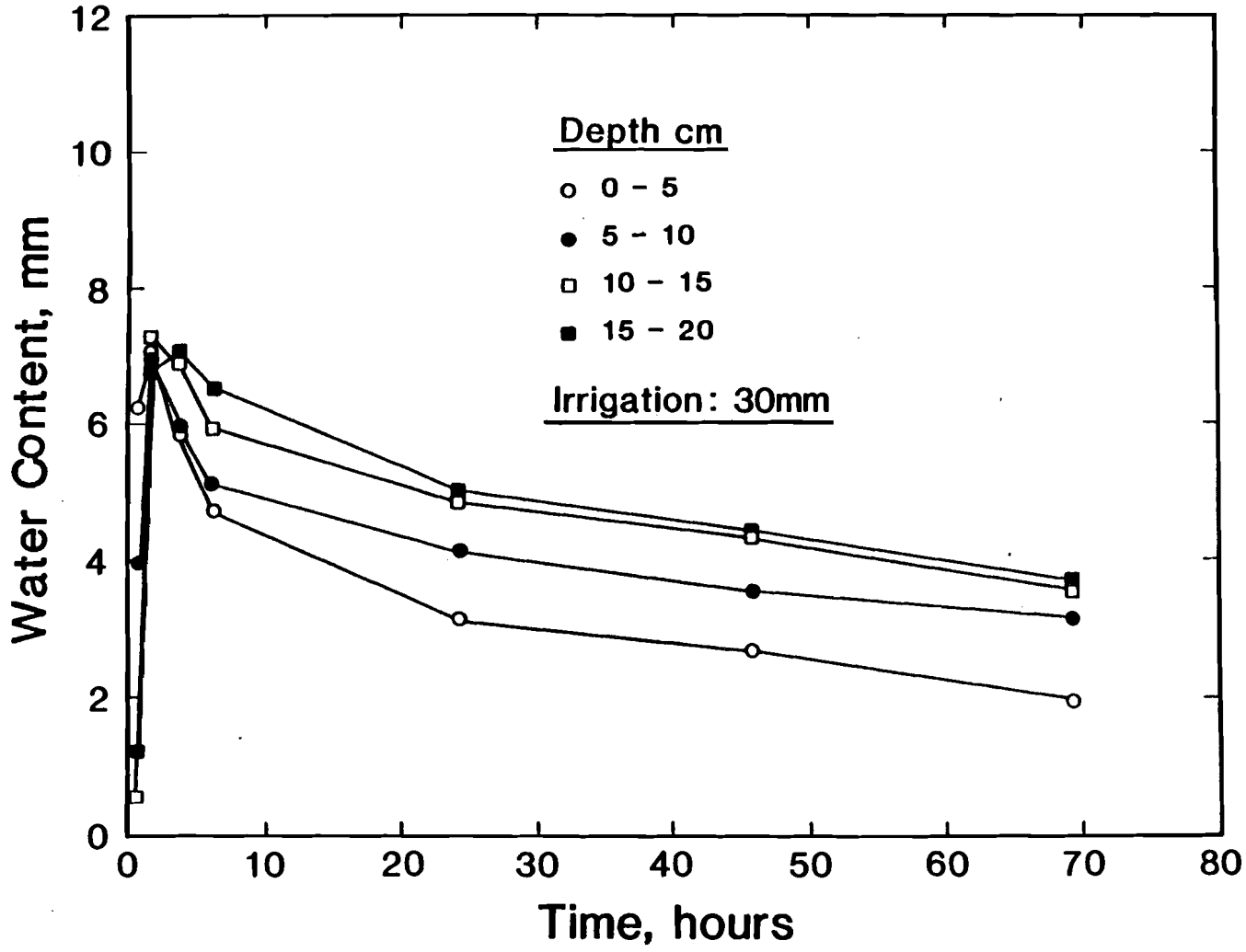


Figure 6. Surface zone drying patterns in goz sand. Crusted surface.

and on particle surfaces. This relationship for the goz sand is shown in Figure 7. Data show that most of the water is easily extractable. The traditional limit for wilting is considered to be a tension equivalent to -15000 cm of water. In goz sand, most of the water is released above a tension of -1000 cm of water. Data also indicate that most of the soil pores are large. The effect of large pores is to cause a rapid percolation of water. As will be seen later, goz sands do, in fact, allow a very rapid infiltration and percolation.

(c) Deep Percolation: Downward movement of water is rapid in goz sands. Moisture distribution in a 180 cm deep profile was measured at various times following a heavy flooding. Data are recorded in Appendix 3. Total water content of the profile 4.5 hours after flooding was 353 mm. It dropped down to 304 mm 21 hours after flooding (see Figure 8). A loss of 49 mm in 16.5 hours cannot be accounted for by evaporation alone. Pan evaporation was estimated to be around 7 mm for the elapsed time. The soil evaporation should be considerably less. Estimates suggest a water loss rate of about 12 mm/hour for the first 4.5 hours.

A further insight into the percolation characteristics of the soil is obtained from comparisons of porosity and measured water contents 4.5 hours after flooding. If we assume an average bulk density of 1.5 g/cm^3 and a particle density of 2.65 g/cm^3, a porosity value of 43 percent is obtained. Theoretically, when all pores are filled, the

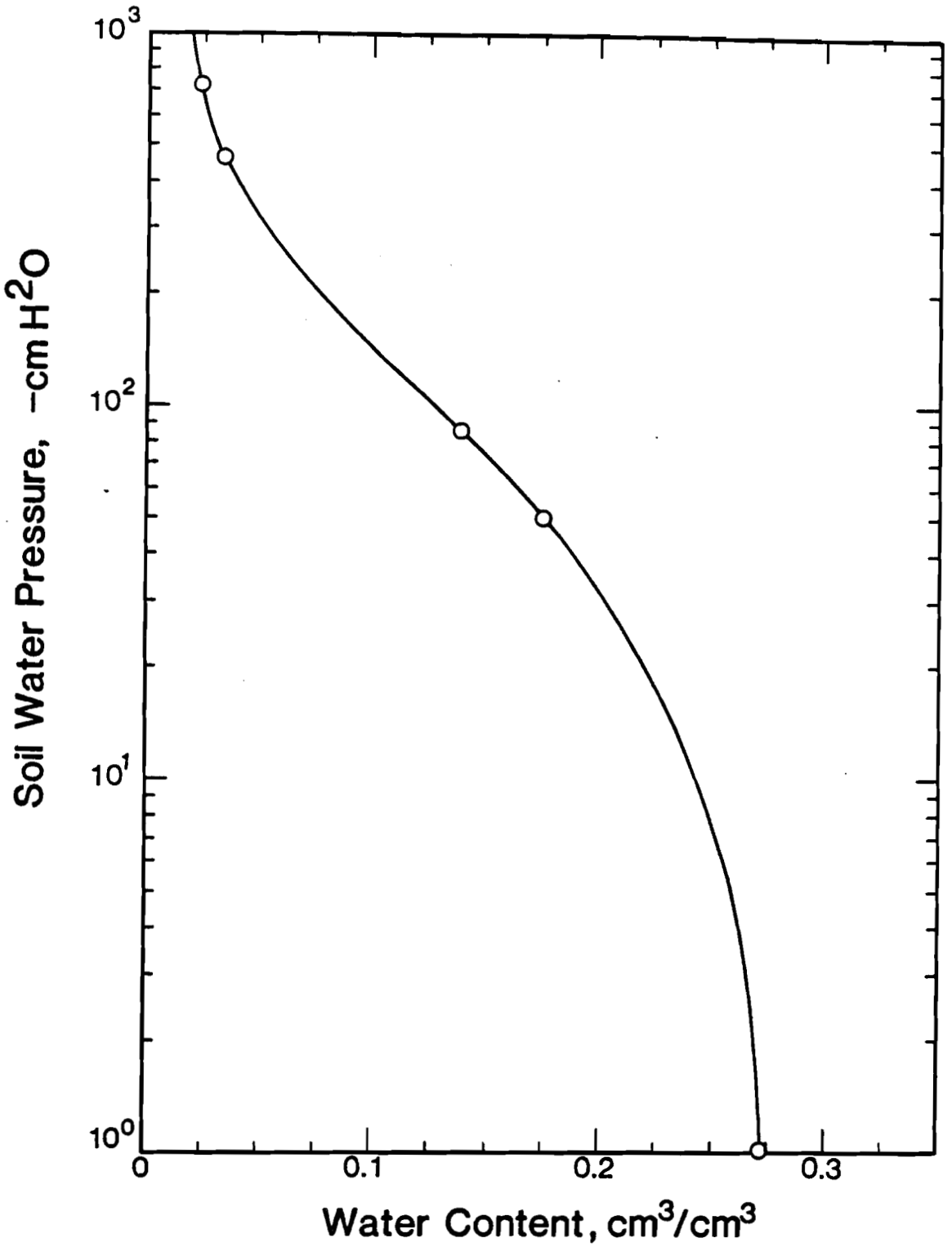


Figure 7. Moisture characteristic for goz sand.

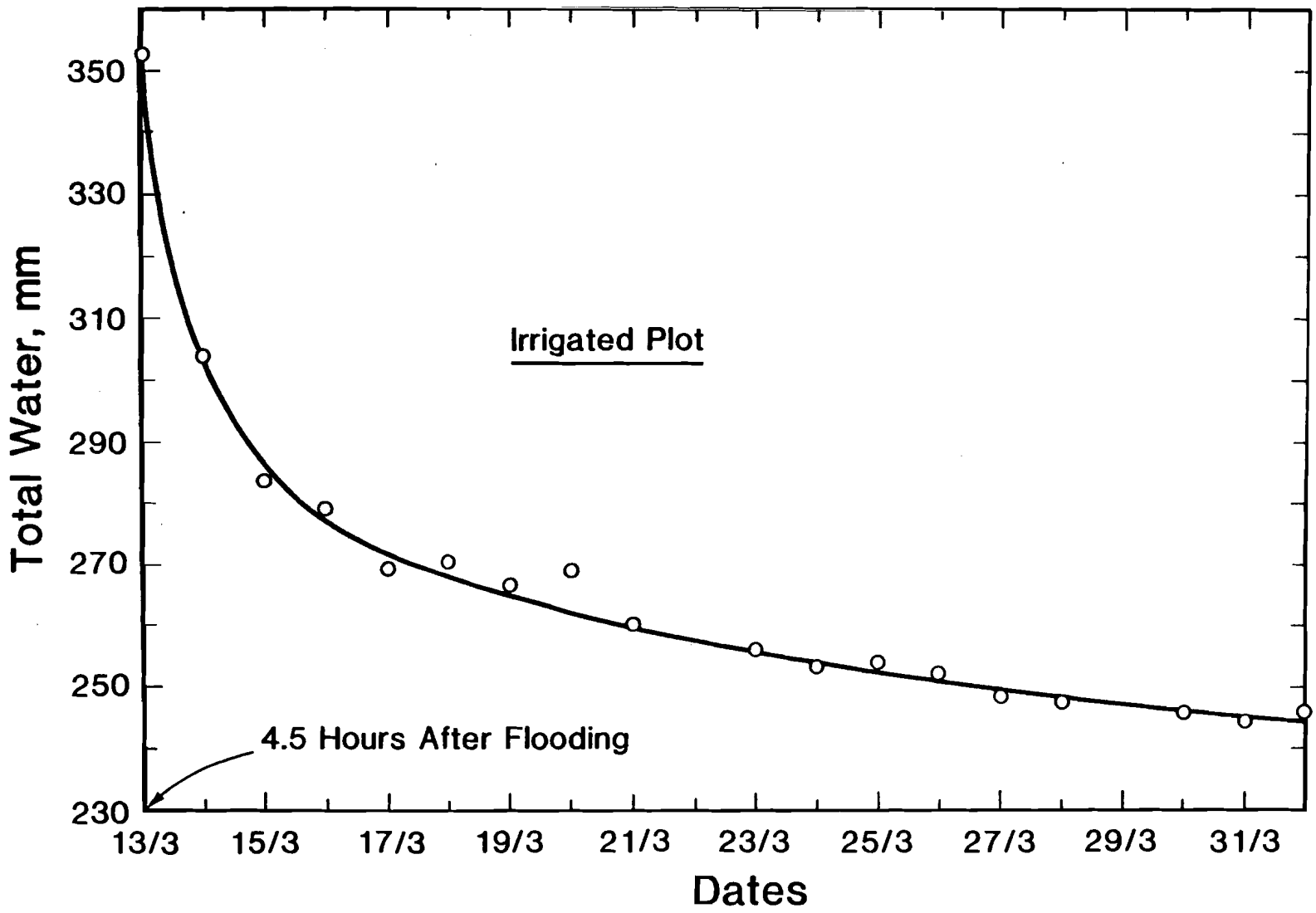


Figure 8. Post-flooding changes in the total water content of a 180 cm deep profile in goz sand.

volumetric water content should be 43 percent. Our measured values of water content 4.5 hours after flooding did not exceed 22 percent (Figure 9). Given that surface evaporation could account for only a small fraction of the applied water, it is concluded that a large portion of the water moved past the 180 cm depth in a very short time.

The implication of the results presented above is that, even if heavy rains are received, the root zone water content in goz sands will not rise above a certain maximum set by the drainage characteristics of the soil profile. Smaller applications at frequent intervals will, probably, be more effective for shallow rooted field crops.

The rapid infiltration and rapid drying of the surface zone have important consequences. A dry surface acts as a barrier to evaporation and appears to be a natural means of moisture conservation in goz sands. On the other hand, it is also the zone where seeds are sown. The rapid drying and the attendant increases in mechanical impedance create a hazardous environment for the emerging seeds. The result is a poor crop establishment. Because of large pores, the infiltrated water moves down to great depths. Although this water would appear to be relatively protected from evaporation, it cannot be effectively utilized by shallow root systems. Therefore, rapid establishment of seedlings and selection of deep rooted crops would appear to be the key to improving crop productivity in goz sands.

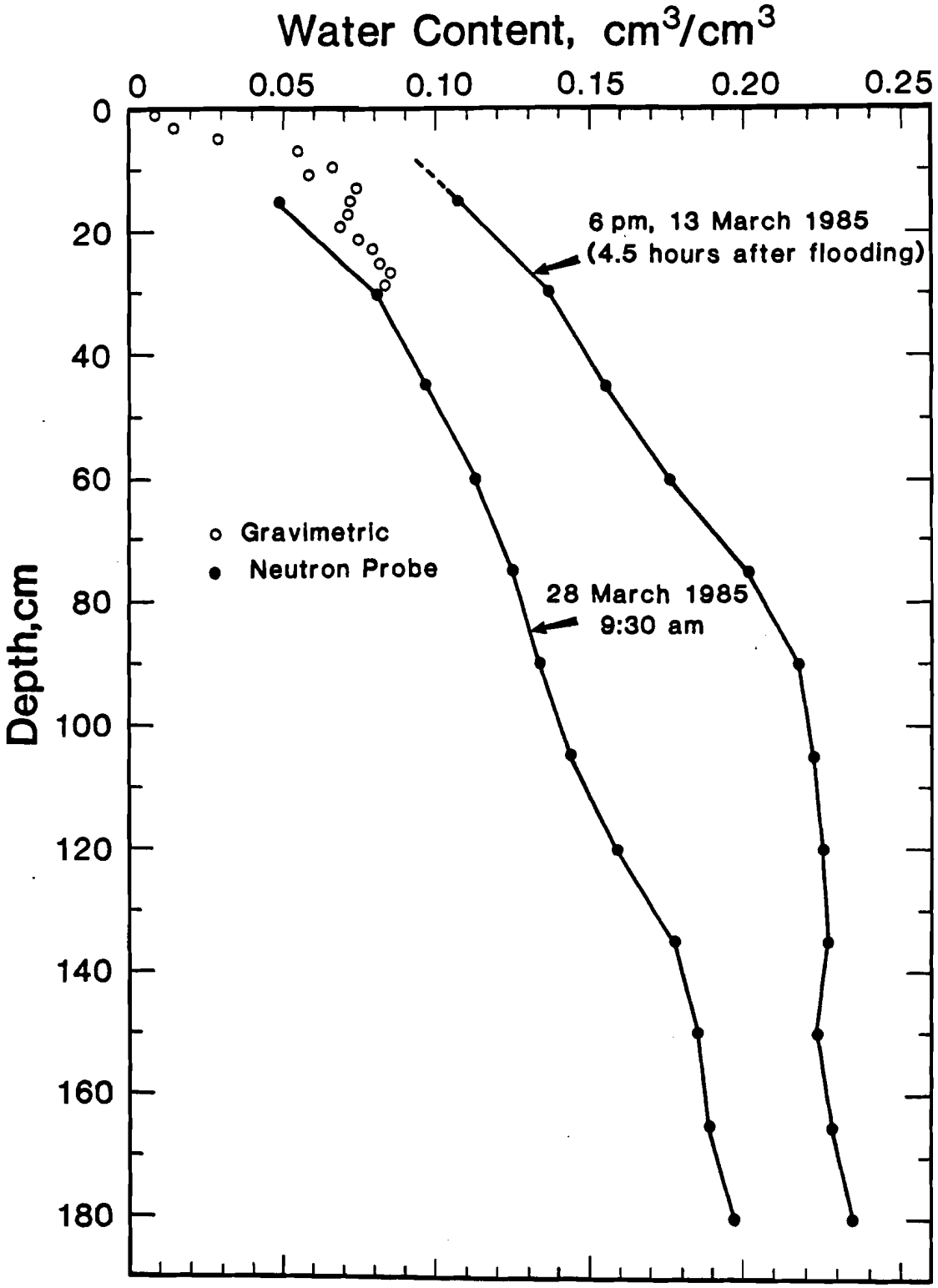
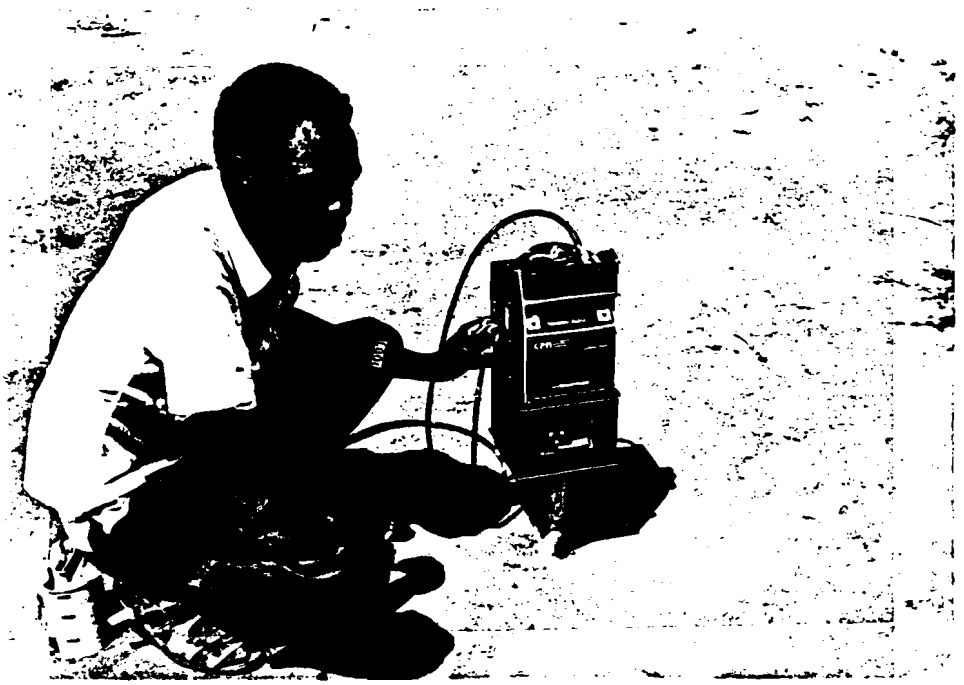


Figure 9. Moisture profiles in goz sand following a heavy irrigation.

(d) Profile Moisture Storage and Moisture Conservation: Measurements of profile moisture content as a function of depth and time began in early March 1985. All measurements were made by a neutron probe which was calibrated for the goz sand. The calibration curve along with the equation describing the curve is given in Figure 10. Weekly moisture data for four locations (2 for the crusted surfaces and 2 for the noncrusted surfaces) are presented in Appendix 2. Typical moisture profiles for the crusted and noncrusted locations are plotted in Figures 11 and 12. Data show extreme dryness near the surface, but an increasing moisture content with depth. The tendency for the moisture content is to continue to increase with depth, giving an impression that considerable moisture may be present at depths below 180 cm. Moisture characteristic of the soil (see Figure 7) indicates that water at lower depths is quite easily extractable. In fact, at the time of these observations, deep rooted plants such as sesame, pigeon peas, watermelon, and native bushes were found to be growing without apparent stress.

Comparisons of the moisture data for 7 March and 27 March (Figures 11 and 12) show that water loss from the profile is negligible. Total storage for the 180 cm profile is plotted as a function of time in Figure 13. These data show that more than 116 mm of water was present in the profile at all times during the dry season. The rate of water loss does not appear to be more than 1 mm/week for most of the dry months. These results are consistent with the self mulching effects suggested by surface zone drying patterns discussed earlier.



Neutron-Probe Measurement of Soil Moisture in Goz Sand.
WSARP Research Farm, El Obeid.

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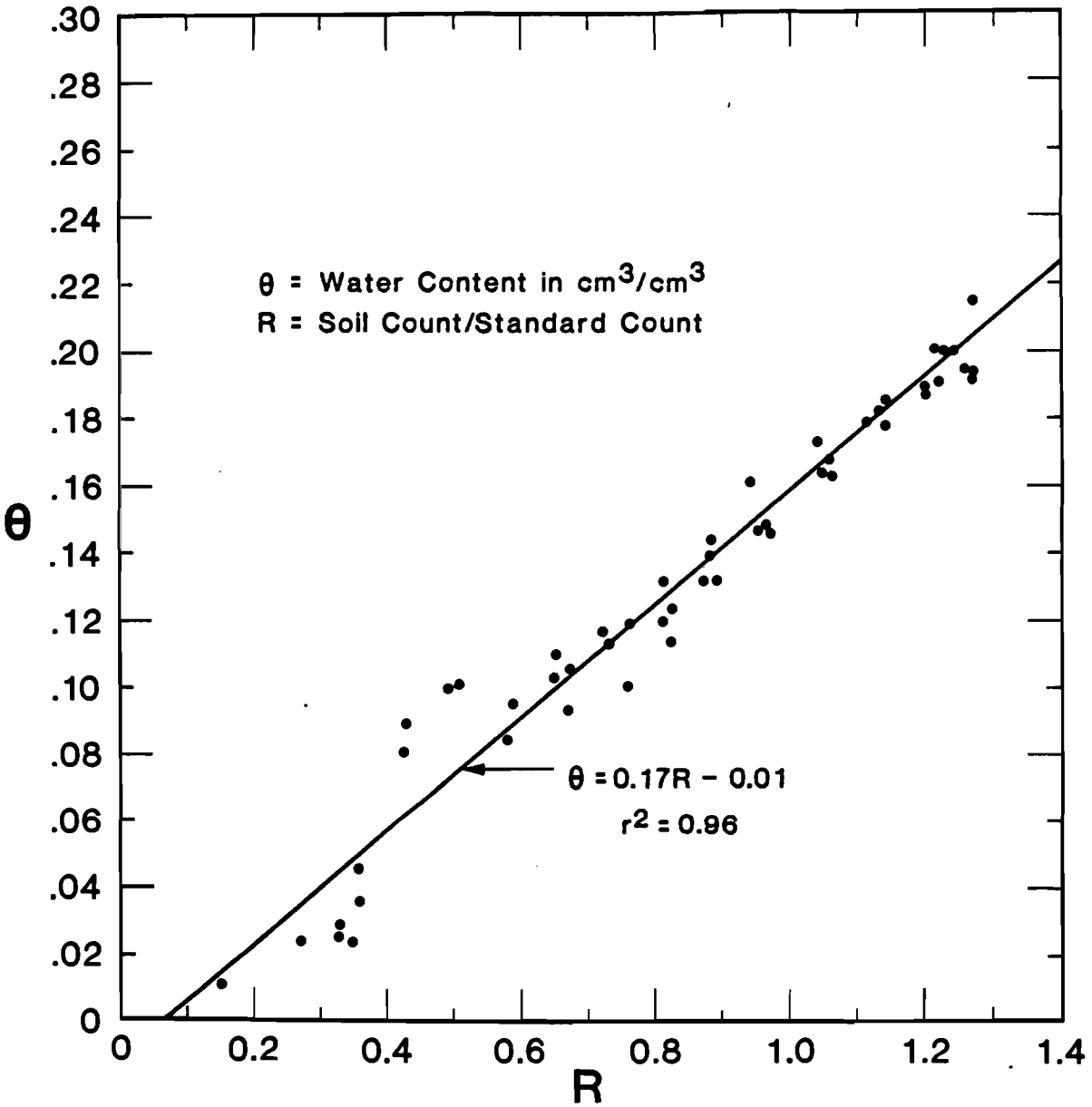

Figure 10. Neutron meter calibration for goz sand, WSARP, El Obeid.

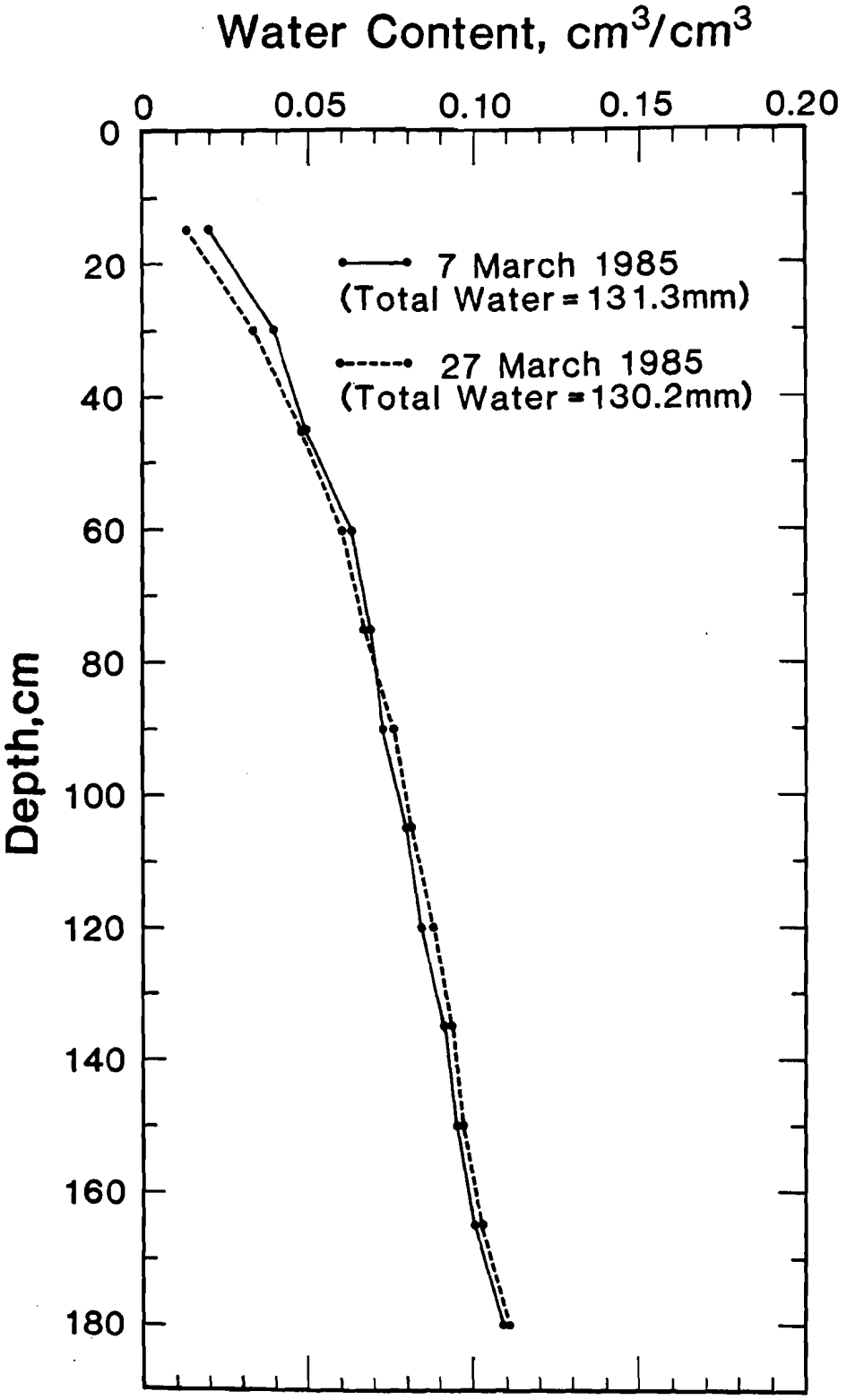

Figure 11. An example of dry season moisture profiles in goz sand. Crusted surface.

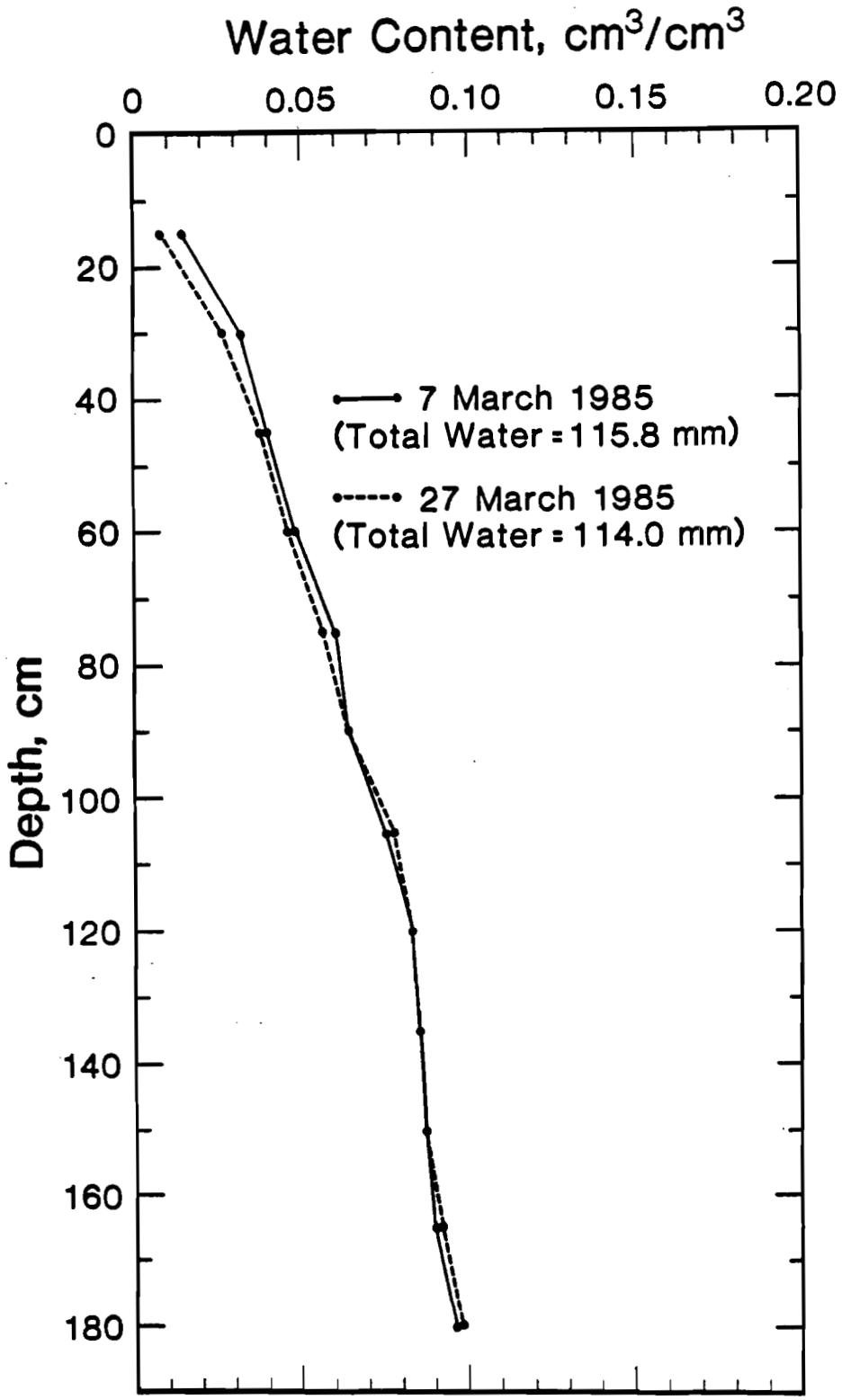

Figure 12. An example of dry season moisture profiles in goz sand. Noncrusted surface.

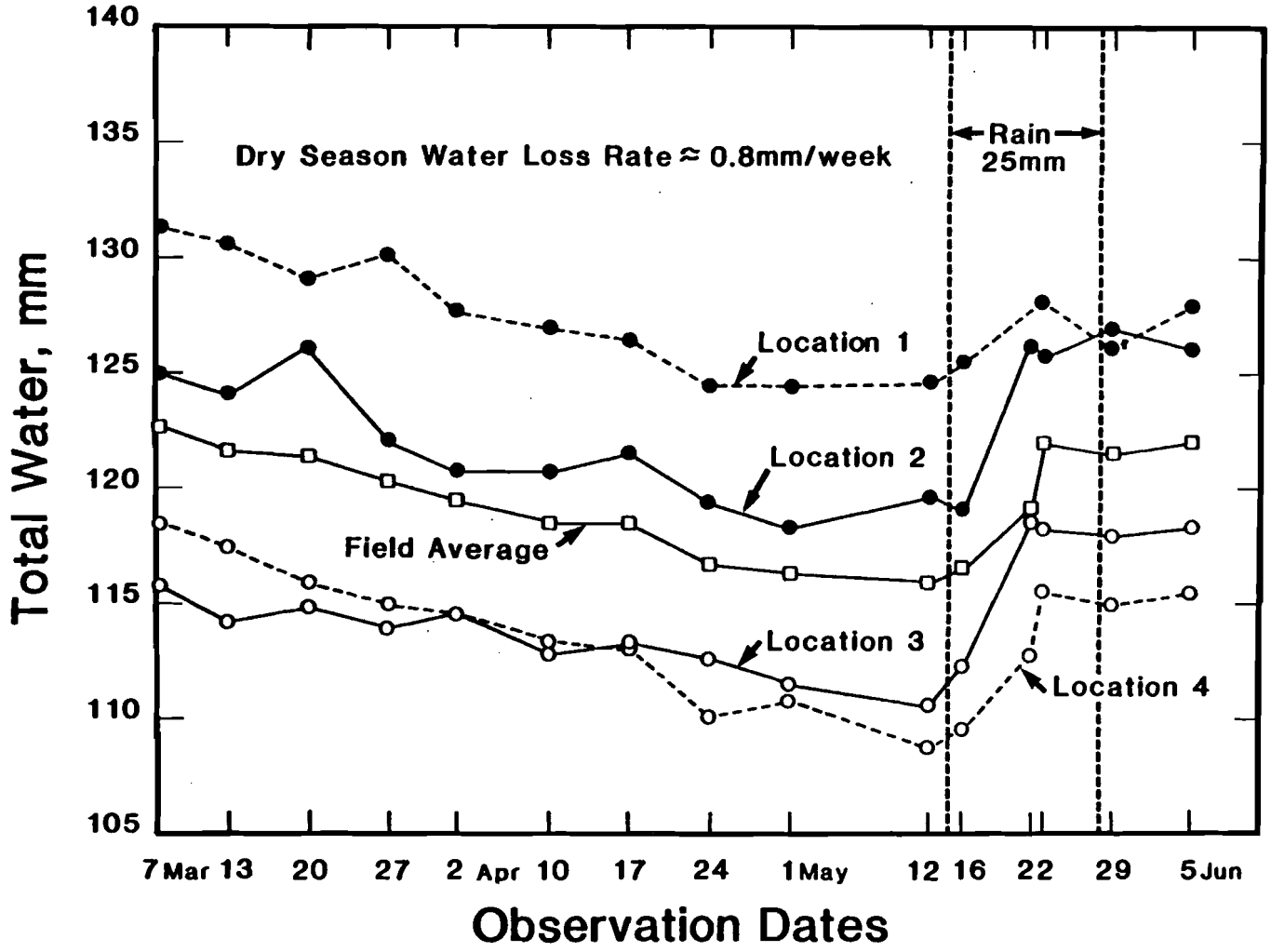

Figure 13. Dry season changes in the total water content of a 180 cm deep profile in goz sand. Locations 1 and 2: Crusted surface; Locations 3 and 4: loose sand on the surface.

An interesting fact emerges about water conservation in goz sands when we consider the balance between observed profile storage, 1984 rainfall, water loss rates during the dry season, and possible crop water use during the 1984 cropping season. The 1984 rainfall was only 160 mm. Water loss rates suggest that the profile will have 110 mm of stored water at the end of June 1985. If the rainfall was the only source of water, then the storage value at the end of June will suggest an accumulated loss of about 50 mm of water for the year. This is impossible given that dry season water loss rates are about 1 mm/week and crops were grown during the rainy season when evapotranspiration losses must have been considerably higher. It seems that a certain amount of moisture was conserved from the 1983 season and was available for crop use during the 1984 season. And quite possible, a certain amount of moisture might have moved into the root zone from depths below the 180 cm depth.

If we can make estimates of the various components of water balance, an idea of the amount of conserved water from the previous season can be obtained. We can use the following relationship:

$$S_1 + R - (ET)_c - (ET)_d = S_2$$

where S_1 is the conserved water from the 1983 season, R is the 1984 rainfall, $(ET)_c$ is the evapotranspiration during the 1984 cropping season (July to October), $(ET)_d$ is the evapotranspiration during the dry season (November to June), and S_2 is the stored water at the end of June 1985.

The rainfall, R, for the 1984 season was 160 mm. Values for the evapotranspiration during the cropping season, $(ET)_c$, are unavailable for El Obeid. In other similar localities (10, 11), millet water use has been reported to be about 300 to 400 mm. This would give an average value of 3.3 mm/day for growing seasons of 90 to 120 days. Given that 1984 millet stand in El Obeid was poor, we may assume a daily value of $(ET)_c$ only half as much. Then, for the period from July to October the total $(ET)_c$ will work out to be 203 mm. The dry season evapotranspiration, $(ET)_d$ can be estimated from water loss rates observed for the dry months. Since there were no crops and the surface was dry, a water loss rate of 1 mm/week should apply for the months from November to June (see Figure 13). Thus, $(ET)_d$ will work out to be 35 mm. The stored water at the end of June 1985, S_1 is 110 mm. Substituting all values in the water balance equation gives 188 mm as the value of S_1, the conserved water from 1983 season.

The analysis presented above is not rigorous because it is based on estimates and excludes water movement across the bottom boundary of the root zone. The amount of conserved water obtained in the above analysis also depends on the assumed value for $(ET)_c$. Our assumptions are conservative. Liberal values of $(ET)_c$ will increase the amount of conserved water. The results, nevertheless, suggest that a significant amount of water is, probably, conserved in goz soils. Results also suggest that fallowing can be an effective means of increasing profile water storage from one season to the next. Detailed measurements of the components of field water balance are needed to reveal the full potential of goz sands.

D-2. GARDUD SOILS:

Major areas under gardud soils are in the south of El Obeid extending to khor Abu Habl in the south and from Er Rahad in the east to Umm Jamala in the west. Surface characteristics and vegetation density are quite variable. Our experiment site was at Banou, approximately 25 km south of El Obeid. This site is being developed as a horticultural research station for WSARP.

Gardud soils have finer texture. The clay content varies from about 10 percent to 30 percent, according to some reports (12). Thus, they are believed to have a better potential for water and nutrient retention and, therefore, a potential productivity higher than that for the goz sands. In their present condition, however, the gardud soils are very hard and difficult to cultivate with traditional hand tools and human power. The infiltration rate is very low. As a result, much of the rainwater is lost as runoff. The surface appears to be highly eroded and stoney in many instances. Because of lack of moisture and high mechanical impedance, vegetative growth is sparse and consists mainly of scrub type vegetation. The lack of moisture and organic matter is reflected in hard and massive structure. Detailed analyses of the soil are unavailable. Available reports suggest that most of the soil profile is slightly alkaline to alkaline and nitrogen and phosphorus contents are low.

The rationale for rehabilitating gardud soils emerges from the realization of the need to shift pressure from the more fragile goz soils. At the present time, much of the cultivation in North Kordofan is concentrated on goz lands. The reason appears to be the ease with

which the sands can be cultivated with hand tools. The cultivation practices, however, expose the land to wind erosion and accelerate the process of desertification. Since crop yields are very low on goz lands, cultivating them does not appear to be rational. Expert opinions suggest that the best use of goz lands would be to preserve them under forest and natural vegetation. However, an alternative must be developed. If gardud soils can be made more cultivable, and if their productivity is increased, then the pressure from goz lands might shift.

Our work on the gardud soil was limited during the 1984 season, mainly because of distance to the site, transportation difficulties, and lack of personnel and equipment.

D-2-1. SOIL SAMPLING AND BULK DENSITY MEASUREMENTS:

Three soil profiles were sampled at the WSARP farm at Banou. Pits were dug during the dry season but the soil was so hard that sampling for bulk density was found to be impossible. Sampling was, therefore, carried out at the end of the rainy season. Samples were obtained in 5, 10, or 15 cm depth increments down to parent rock, and the soil profile was described as it appeared to visual observations. Soil depth was found to vary from about 70 cm to about 120 cm. White streaks were observed throughout the soil profile suggesting presence of carbonate and bicarbonate salts. Stones were present in all the layers and appeared to be significant at some locations.

Bulk samples were obtained for textural and chemical analyses. These samples were air dried, ground, and passed through a 2-mm sieve. Stone content was measured in all samples. The processed samples were sent to ARC (Wad Medani) for analyses. As yet, no results are available. Bulk density measurements were made on cores and clods. In many instances it was difficult to obtain well defined cores because of hardness and presence of stones. Therefore, clod samples were taken to measure bulk density in the laboratory by a liquid displacement technique (9). A 10 percent solution of gum arabic was used to coat the clods.

Stone content and bulk density data for gardud soil are presented in Table 6. Stone content varies with depth as well as with location. Bulk densities are generally high to very high in some cases. They reflect the hardness of the soil and impedance to root penetration. Bulk densities for profiles 1 and 3 appear to be somewhat lower than those for profile number two. The difference appears to be associated with wetness of the soil. It had been observed that pits 1 and 3 had accumulated rainwater during the rainy season while the pit number two remained dry because of unfavorable surface microrelief around it. Observations suggest that hardness of the soil can decrease provided it can be wetted.

D-2-2. MOISTURE MEASUREMENTS:

Neutron access tubes could not be installed in the gardud soil. The only means of moisture measurements was the gravimetric sampling. A great amount of effort was needed to drill the soil with a sampling

auger. Because of the dryness of the soil, rotary action of the auger produced powdery soil which could not be lifted out. Partial success was obtained when sampling tubes were hammered vertically downward into the soil. However, the depth to which these tubes could be hammered in was very limited.

Rainfall data for Banou site are unavailable. Data recorded in nearby Bangdeed were assumed to apply to Banou (see Table 2). The last rainfall of the season fell on 7 October. Soil moisture data obtained during the last 10 days of October are shown in Figures 14 and 15.

Figure 14 shows the data obtained from the walls of the dug out pits. Data show substantially higher moisture contents in the pits that had accumulated rainwater. Moisture content was very low where no rainwater had accumulated. Figure 15 shows the data obtained by sampling on a flat natural surface and in a seed cradle. Under the flat surface, moisture content did not exceed 4.5 percent between the depths of 0 and 60 cm. Moisture content in the seed cradles, on the other hand, appeared to be significantly higher between the depths of 10 and 40 cm. Very low moisture content under the flat surface, three weeks after the rains, indicates that water intake in gardud soil is very low. Therefore, rainfall data alone may not be adequate to assess the production potential for the gardud lands. Higher moisture contents in the seed cradles and pits suggest that soil can wet provided catchments and barriers to surface flow are created on the land.

Table 6. Bulk density and stone content (gravel larger than 2-mm) in gardud soil at Banou.

Depth	Profile 1		Profile 2		Profile 3	
	Bulk density	Stone	Bulk density	Stone	Bulk density	Stone
cm	g/cm^3	%	g/cm^3	%	g/cm^3	%
0 - 5	1.677	7.5	-	-	-	-
5 - 10	1.599	15.2	-	-	-	-
0 - 10	1.590	11.0	1.907	10.1	1.821	1.3
10 - 20	1.505	8.7	1.905	8.8	1.756	1.5
20 - 30	1.698	15.2	1.967	6.6	1.822	1.7
30 - 45	1.715	16.5	1.932	3.4	1.875	1.3
45 - 60	1.716	11.6	1.896	2.0	1.609	1.9
60 - 75	1.732	10.5	1.897	3.2	1.691	20.2
75 - 90	1.710	7.7	1.873	4.9	2.065	61.3
90 -105	1.667	18.9	1.872	7.9	-	-
105 -120	-		1.868	8.4	-	-

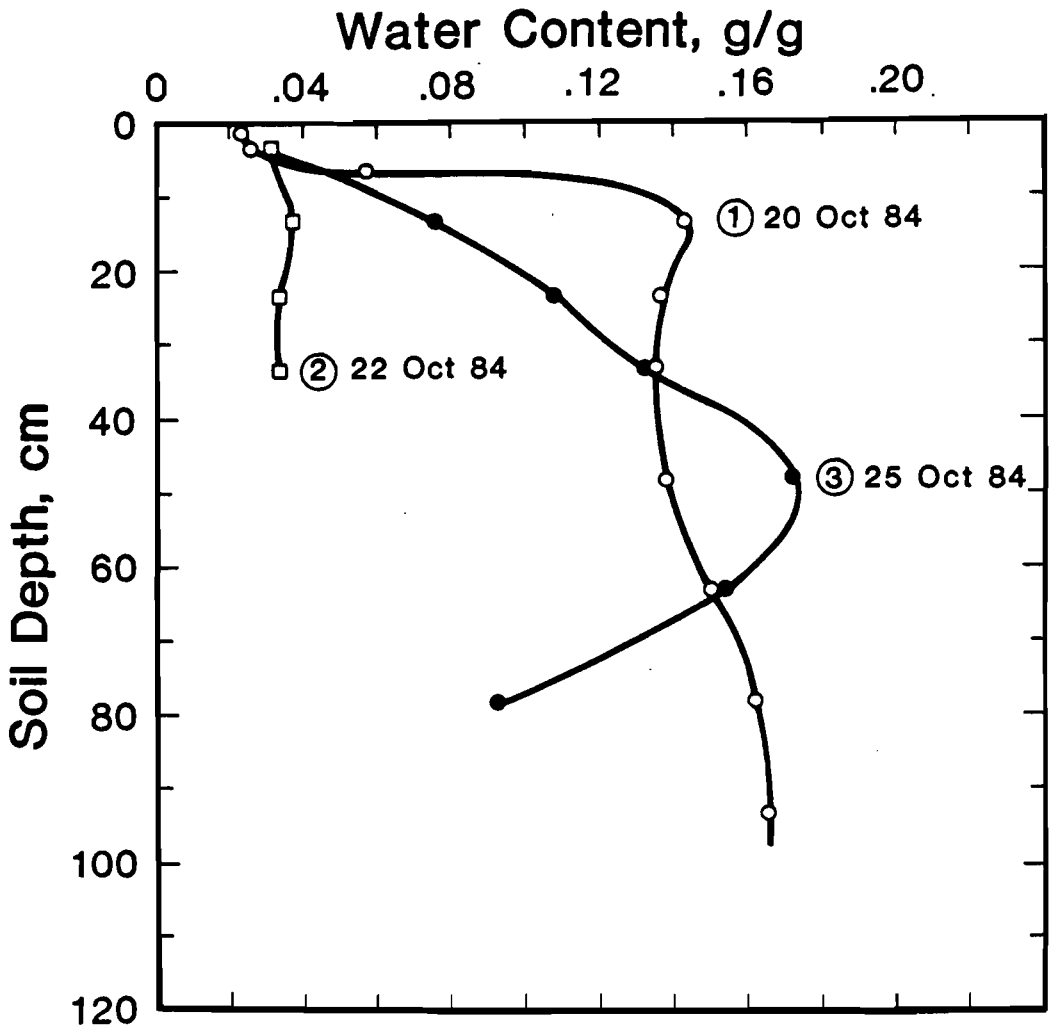

Figure 14. Moisture profiles in gardud soil at Banou. Moisture samples were obtained from walls of the pits opened for soil sampling. Pits 1 and 3 were filled with runoff water during the rainy season.

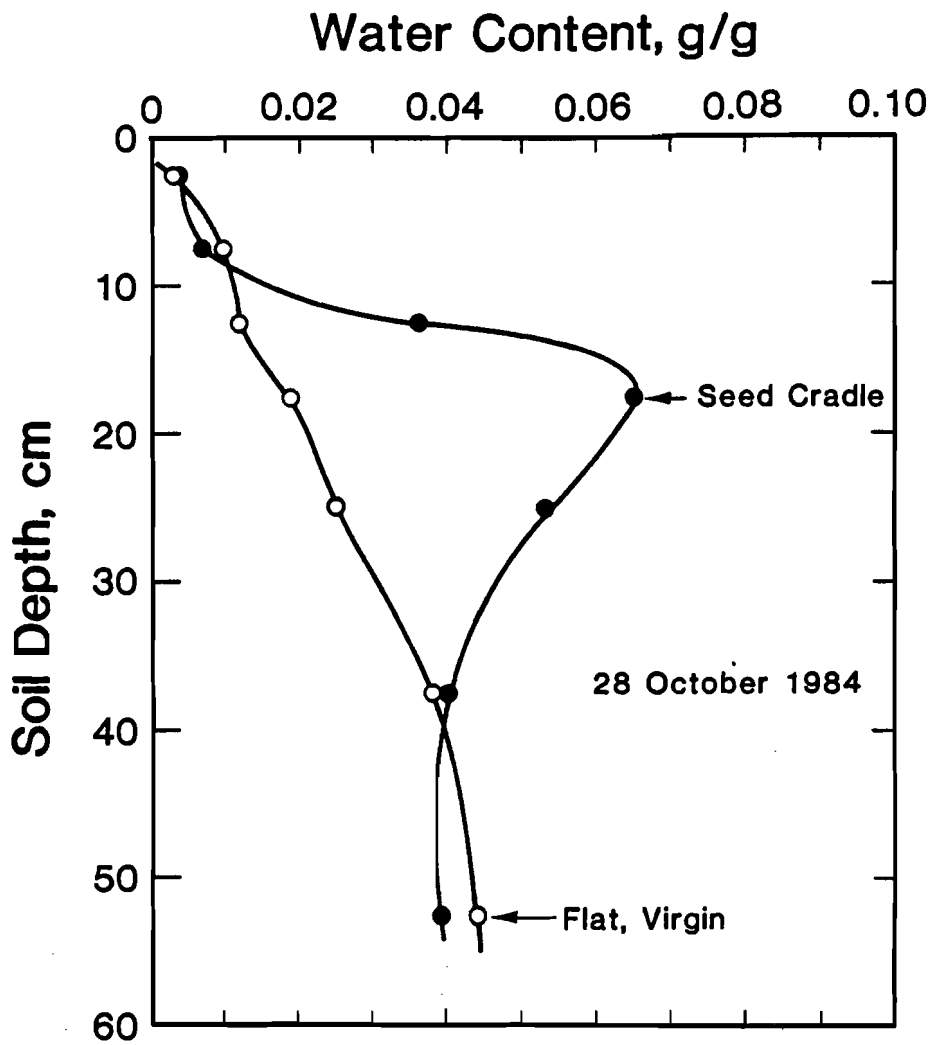

Figure 15. Comparison of moisture profiles under seed cradles vs. flat surface in gardud soil, WSARP (Banou). Last rain : 15 mm on 7 October 1984.

D-3. CRACKING VERTISOLS:

Cracking vertisols are the most important agricultural soils in South Kordofan. Available reports suggest clay contents in excess of 60 percent. Thus, their water and nutrient holding capacities are expected to be high. However, under natural conditions these soils crack extensively, sometimes to depths in excess of 60 cm. Crack widths of 10 to 15 cm are most common during the dry season. This exposes a large internal surface area to external atmosphere. As a result, a rather large amount of subsoil moisture is lost to direct evaporation. Cracking begins as the drying process sets in following a rain. As the soil continues to dry, it shrinks. Shrinkage results in an increased mechanical impedance which limits root growth and plant's ability to utilize soil moisture that might otherwise be available in deeper layers. On the other hand, in the event of a continuing rain, cracks close and the surface gets sealed up, particularly when rainfall intensity is high. Surface sealing leads to reduced intake of water. The result is runoff and soil erosion. The rainwater that could be stored in the soil profile is lost. Thus, cracking vertisols remain drought-prone despite their high water holding capacity. Crops suffer from water shortage even though the average annual rainfall in the region is over 700 mm.

Detailed analyses of soil fertility have not been carried out. Available reports suggest high cation exchange capacity (about 57 me/100g) but low nutrient availability. Adsorption on clay surfaces appears to be too strong. Data on crop response to fertilizers in

experiments carried out by WSARP and GTZ* indicate that both nitrogen and phosphorus are low. Soil reaction is slightly acidic to slightly above neutral. Organic carbon varies from about 0.3 to about 0.7 percent. Data on soil physical and moisture related properties and processes are unavailable.

D-3-1. SOIL SAMPLING AND BULK DENSITY MEASUREMENTS:

Three soil profiles were sampled at the WSARP farm at Kadugli in December 1984. Bulk samples were collected in 5, 10, or 15 cm depth increments to a depth of 150 cm. These samples, after air drying, crushing, and passing through a 2-mm sieve, were bagged and sent to ARC (Wad Medani) for analyses. As yet, no results have come back.

Because of severe cracking, it was impossible to extract well defined cores for measuring bulk density. Therefore, all bulk density measurements were made on clod samples. Bulk density data for the three soil profiles are presented in Table 7. Data show very high bulk densities and reflect the extent of shrinkage at the moisture contents prevailing at the time of sampling. Swelling upon rewetting causes a reduction in the bulk density. Thus, the usefulness of these data is limited because of dependence of bulk density on moisture content. Data, nevertheless, suggest that conditions restrictive to root growth exist in cracking vertisols, i.e., poor aeration under wet

* Sudanese/German Pilot Project for Agricultural Development in the Nuba Mountain Region, Kadugli, South Kordofan Province.

Table 7. Bulk density profiles in cracking vertisols at Kadugli. Measurements were made by clod method. Soil was dry at the time of sampling.

Depth	Bulk density, g/cm^3		
cm	Profile 1	Profile 2	Profile 3
0 - 5	1.956	1.877	1.563
5 - 10	1.998	1.909	1.897
10 - 20	1.921	1.889	1.911
20 - 30	1.953	1.893	1.934
30 - 45	1.939	1.893	1.943
45 - 60	1.944	1.900	1.932
60 - 75	1.956	1.871	1.959
75 - 90	1.949	1.863	1.956
90 -105	1.949	1.903	1.963
105 -120	1.929	1.922	1.970
120 -135	1.886	1.826	1.958
135 -150	1.853	1.837	-

conditions and high mechanical impedance under dry conditions. A detailed study of soil physical behavior and its effect on soil moisture processes and crop production would be useful in formulating management strategies.

E. SOIL MOISTURE CONSERVATION TRIALS:

Soil moisture conservation trials were conducted at El Obeid on goz sands, at Banou on gardud soils, and at Kadugli on cracking vertixols. Practices that were selected for field testing were based on general impressions of soil limitations and weather conditions at each location. The main objectives were to maximize soil water storage and minimize evaporative losses of soil water. Unavailability of resources did not permit adequate monitoring of soil moisture. Only the biomass and grain yield data were taken as indicators of the effectiveness of the moisture conserving practices.

The following trials were conducted:

E-1. GOZ SANDS, EL OBEID:

E-1-1. SOIL AMENDMENTS TO IMPROVE SEED ZONE MOISTURE SUPPLY IN GOZ SANDS: Rapid loss of soil moisture from the surface zone appeared to be the major cause of seedling failure in goz sands. Addition of materials that have the property of improving soil moisture retention and/or reducing evaporation was considered as a potential management practice. Synthetic polymers in use in western countries were considered inappropriate for Western Sudan. An effort was made to

identify locally available materials. Gum arabic, which is produced locally and clayey soils, which occur in fulas (ponds) were considered. Adding fine textured materials to sandy soils has been suggested as a means of improving moisture retention (13).

(a) Gum Arabic: First, a pot test was conducted to observe the effect of gum arabic on evaporative loss of water and sorghum seedling growth in goz sands. Powdered gum arabic was applied at the rate of 0, 5, 10, 15, and 20 g per pot. Results (Figure 16) showed decreasing evaporation from the soil surface with increasing amounts of gum arabic. At the end of two days of drying, the ratios of cumulative evaporation from the treated soil to that from the untreated soil were 0.81, 0.66, 0.53, and 0.50 for the 5, 10, 15, and 20 g treatments, respectively. Sorghum dry matter production (see Figure 17) increased with time for all treatments but remained perceptibly lower for the untreated soil. After about a month of growth, the amount of dry matter produced was 0.32, 0.42, 0.60, 0.82, and 0.87 g per pot for the 0, 5, 10, 15, and 20 g treatments, respectively. Observations also indicated that only small concentrations of the gum were beneficial to plant growth. Amounts in excess of 20 g per pot, though very effective in retarding evaporation, produced crusts of high mechanical impedance which adversely affected water infiltration, emergence, and stem expansion.

Details of the above experiment and results are available in WSARP publication No. 26 (14).

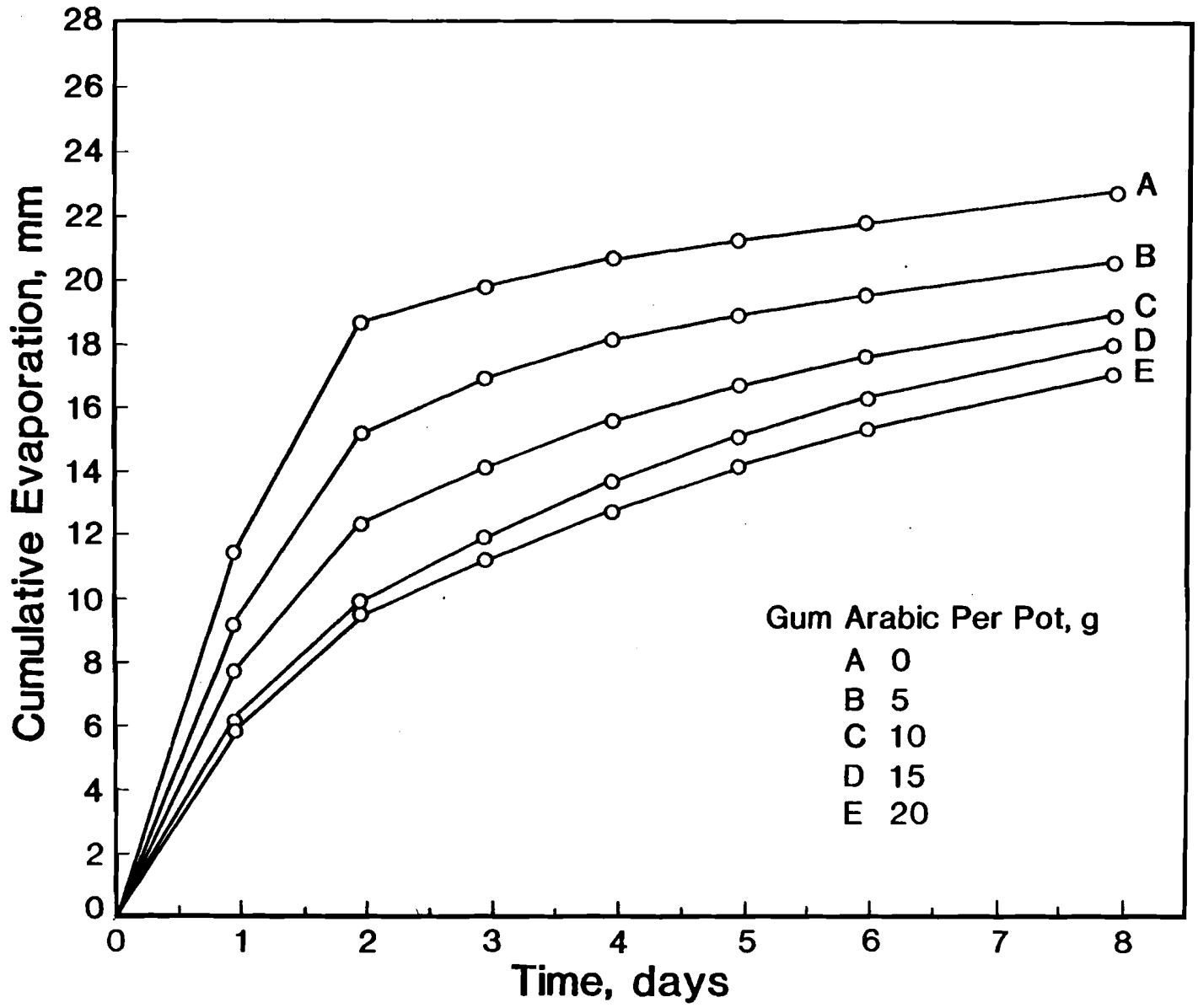

Figure 16. Effect of gum arabic on evaporative loss of water from potted goz sand.

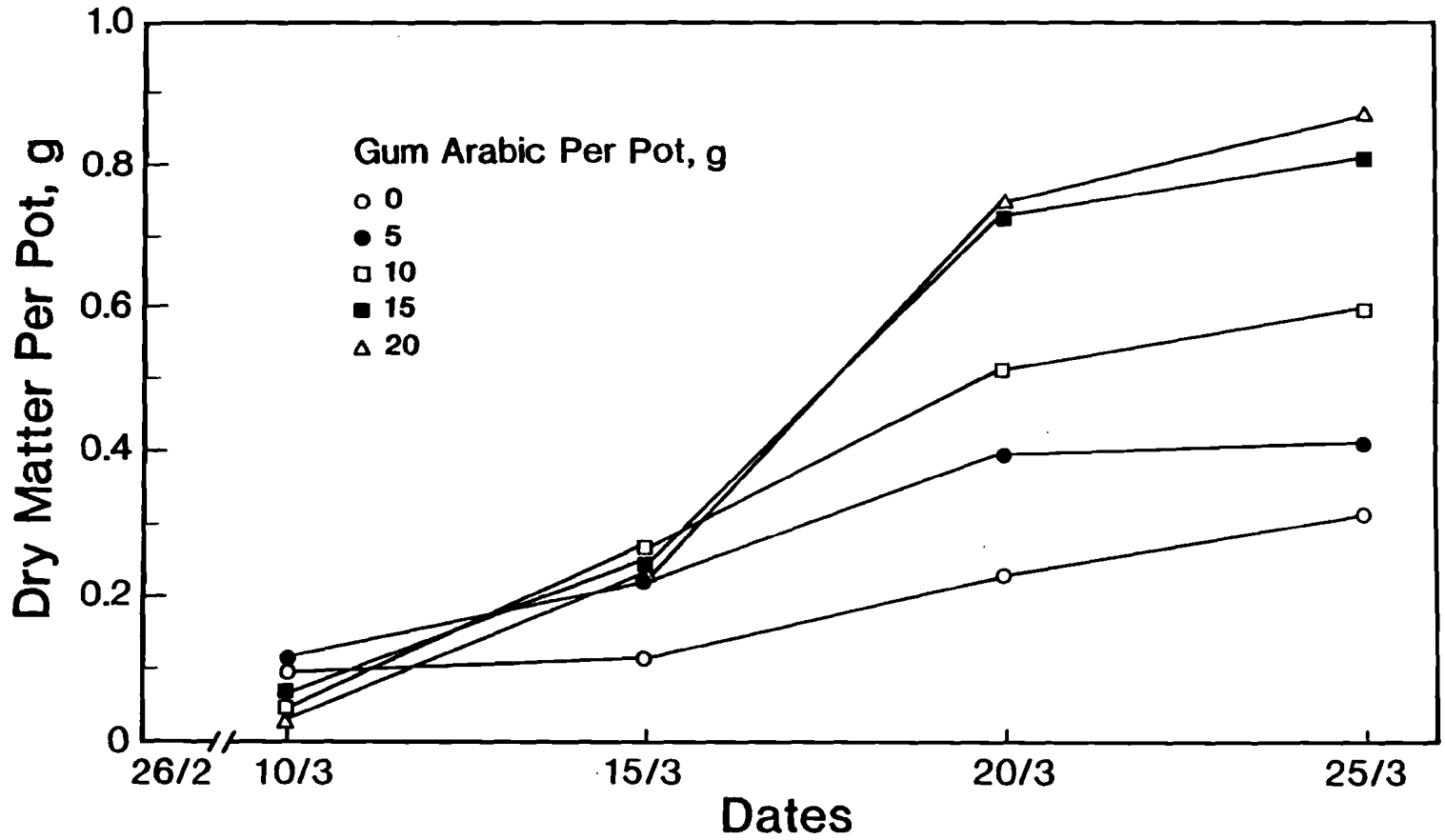

Figure 17. Sorghum seedling dry matter production in potted goz sand, as affected by gum arabic treatment of the soil.

Field tests of gum arabic were carried out at the WSARP farm at El Obeid using pearl millet as a test crop. Powdered gum arabic was applied at the rate of 0, 5, 10, 15, and 20 g per hill. The gum was mixed in the soil in a 20 cm diameter circle. Seeds were planted in the center of the circle at a depth of 5 cm and covered. The soil was then firmed by hand. The experiment was laid out in a randomized complete block design with four replications. The crop was planted in rows 75 cm apart with 50 cm spacing between hills. Plots were 8M x 3.75M in size.

Planting was carried out on 6 July. Preplanting rains were received on 1 July (16mm) and 2 July (7.5mm). Although the soil appeared moist at the time of planting, a considerable amount of moisture must have been lost between the rain and the planting time (see discussion on surface drying patterns). This was confirmed, as no emergence took place until the next rain on 21 July (67mm). The lack of moisture must have also resulted in a poor dissolution of the gum.

The emergence was very poor. The experiment was located in an area with a crusted surface. Initially, the area was selected for its smoothness and apparent surfacial uniformity. It wasn't until late September that crusting was recognized and its effects realized. It is also possible that gum increased the crust strength. General lack of rains (see rainfall data in Table 2), perhaps, aggravated the effect of crusting.

Measurements of soil moisture were not possible due to lack of resources. Data on crop growth and yield are reported in Table 8. Data show very poor yields. The variability among plots was very high and there were several missing plots. Observations in plots with loose sand on the surface showed good emergence. It is, therefore, concluded that failure of emergence in this trial was due to crusting, caused either by inherent nature of the soil, or gum arabic, or both.

There is no doubt that the film produced by dissolved gum arabic should retard evaporation, but lack of moisture can keep the film strength high enough to be detrimental to seedling emergence. No research has been carried out to determine the best method of application and timing etc. Perhaps, post emergence spraying of the soil surface with gum arabic solution would be more preferable. Since the gum binds the sand grains, it can also be useful in controlling wind erosion.

(b) Clayey Soil: This trial was identical to the one where gum arabic was used as an amendment except that the amendment in this case was a ground clayey soil. The clayey soil was obtained from a pond 3 km north of El Obeid. The air dry soil was ground and passed through a 2-mm sieve. The application rate was 0, 50, 100, 150, and 200 g clayey soil per hill. The powdered clay soil was applied in a 20 cm diameter circle and mixed with the sand. Millet seeds were planted in the center of the circle and covered. The hill was then firmed by hand.

Table 8. Gum arabic as a soil amendment and its effect[1] on millet growth and yield in goz sand.

Treatment g/hill	Plants No/ha	Tillers No/ha	Heads No/ha	Biomass, kg/ha Fresh	Biomass, kg/ha Dry	Grain kg/ha
0	7599	29859	16495	542	302	22
5	11398	42164	18626	870	416	19
10	9174	42477	23769	826	432	24
15	11676	35028	21128	528	275	16
20	7784	26799	10008	512	268	12

Number of hills planted: 26667/ha

1. Because of several missing plots and high spatial variability, no statistical analysis was carried out.

Data on crop growth and yield are presented in Table 9. Planting was completed on 8 July, 6 days after the previous significant rain. In this case also, no emergence was observed until after the next rain on 21 July. Observations showed good emergence and early growth. The land surface was not as crusted as in the case of gum arabic. This may explain the better emergence. Or, the clay soil mixed with the sand created a better physical environment. Since measurements of soil properties and moisture conditions were not possible, it is difficult to say as to how clayey soil affected crop growth. The results, however, do show a positive trend. Although differences between the treatments were not significant, biomass and grain yields increased with the increasing amounts of the amendment up to 100 g/hill. A decrease in the yield was noticed for the 150 and 200 g treatments. From these data it appears that clayey soil as an amendment did create better moisture conditions in the immediate vicinity of the seedlings. The depression in yield for treatments higher than 100 g/hill could have resulted from crusting and higher mechanical impedance. Data on number of plants/ha at harvest do not suggest that emergence was affected by higher clay amounts. It is quite possible that delayed emergence or competition caused by too good an emergence may have depressed the biomass and grain yields. Adverse effects of higher plant population were observed throughout the farm.

(c) Mixture of Gum Arabic and Clayey Soil: This trial was also identical to the one with gum arabic as an amendment. Here, the

Table 9. Ground clayey soil as a soil amendment and its effect on millet growth and yield in goz sand.

Treatment	Plants	Tillers	Heads	Biomass, kg/ha		Grain[2]
g/hill	No/ha	No/ha	No/ha	Fresh	Dry[1]	kg/ha
0	17088	56048	27089	977	742	70
50	20838	76809	33617	1153	910	84
100	19449	76681	36255	1281	1019	117
150	22639	81312	31111	1099	880	67
200	21818	66784	29602	946	635	65

Number of hills planted: 26667/ha

1. F-test showed no significant difference at 5% level, CV = 46.5%
2. F-test showed no significant difference at 5% level, CV = 55.7%

amendment was a mixture of 1 part gum arabic and 4 part ground clayey soil on a volume basis. The treatments were 0, 25, 50, 75 and 100 g mixture per hill replicated four times in a randomized complete block design. The experiment was planted on 7 July, 5 days after the previous significant rain.

Data on crop growth and yield are presented in Table 10. Results show very poor plant population and yields. Land surface under this experiment was also smooth and crusted. It is quite possible that crusting effect was aggravated by addition of gum arabic and clay soil. Variability among the plots was very high and no sensible conclusions could be drawn from the results.

E-1-2. MULCHING: Mulching is effective in soil and water conservation. It controls erosion, improves soil structure, increases infiltration, reduces evaporation, and suppresses weed growth. Unger (15) has reviewed the literature and concludes that where effective soil cover is used, substantial yield increases often result.

Our trial consisted of two treatments, mulch and no mulch, replicated four times in a randomized complete block design. Plots were 12M x 6M in size. Millet was used as a test crop. Plant spacing was 75 cm between rows and 50 cm between hills in each row. The experiment was planted on 9 July. The mulched plots were covered with a single layer of dry millet stalks. The rate of application of mulch was not

Table 10. A mixture of gum arabic and ground clayey soil as a soil amendment and its effect[1] on millet growth and yield in goz sand.

Treatment g/hill	Plants No/ha	Tillers No/ha	Heads No/ha	Biomass, kg/ha Fresh	Biomass, kg/ha Dry	Grain kg/ha
0	10564	46910	21128	655	398	28
25	9823	47796	25020	1128	684	26
50	7376	27078	10842	300	150	9
75	7089	24455	9452	328	175	7
100	7784	42562	22240	907	379	40

Number of hills planted: 26667/ha

1. Because of several missing plots and high spatial variability, no statistical analysis was carried out.

determined but the amount spread on the ground was enough to completely cover the soil surface. The rows to be planted were exposed by opening the millet stalks to about 10 cm width.

Data on crop growth and yield are reported in Table 11. Although the yields were low, the differences between mulched and unmulched plots were highly significant.

Emergence occurred after the rain on 21 July. Mulched plots showed very good emergence and the early growth was quite robust. Early growth in unmulched plots was very poor. The land surface under this trial was also smooth and crusted. However, as the season progressed, an accumulation of loose sand was observed in the mulched plots, particularly around the edges. It appeared as though the mulch was acting as a trap for the wind blown sand. The effect was a beneficial one as the accumulated sand kept the crust from getting hard. Emergence and early growth in unmulched plots elsewhere on the farm, where only loose sand existed on the surface, appeared to be similar to those in the mulched plots. It appeared as though the loose sand on the surface had an effect similar to mulching. If loose sand is beneficial as a mulch, it would be necessary to keep it from blowing away. It would appear that sand entrapment can be achieved with much less residue than was used for mulch. This might prove to be a useful modification in mulching stategy, since mulching material in North Kordofan is limited.

Table 11. Effect of mulching on millet growth and yield in goz sand.

Treatment	Plants	Tillers	Heads	Biomass, kg/ha		Grain[2]
	No/ha	No/ha	No/ha	Fresh	Dry[1]	kg/ha
Mulch	18839	79770	54306	2216	1662	108
No Mulch	17847	48072	24653	765	620	59

Number of hills planted: 26667/ha

1. F-test showed significant difference at 5% level, CV = 25.0%

2. F-test showed significant difference at 5% level, CV = 14.0%

A drastic depression in growth was observed later in the season in all plots which showed high population and healthy growth early in the season. It seems that most of the available water was used up early in the season. With rainfall limited to only 160 mm, yields were drastically affected.

The effect of mulching on crop production in goz sands needs to be evaluated further. The amount of mulch applied during the 1984 season was probably excessive. Also, the critically low rainfall did not allow the full benefits to be realized. Since there is a demand for crop residue for various types of uses, it is important to determine the optimum amounts in relation to variations in rainfall, plant population, and other cultural practices. It is quite possible that the benefits of sand entrapment associated with presence of surface barriers is what is needed. And that can be achieved with a very small amount of residue. Because of aridity of the climate, rate of decomposition is very low. Hence, crop residue applied once may last over a period of time.

E-1-3. SEED CRADLES AND RIDGE-FURROW BEDS: This trial was conducted to observe the effects of planting in seed cradles and ridge-furrow beds. Seed cradles are holes about 10 to 15 cm in depth and 10 to 15 cm in diameter. These holes accumulate water and provide a protective environment by partial shading and by reducing the advective effects of the wind. Thus, the chances of emergence and seedling survival can be improved if seeds are planted in the bottom of the holes. Benefits

are similar in a ridge-furrow cultivation. Furrows capture water and ridges provide partial shading from sun as well as protection against the effects of wind. Ridges are also an effective means of controlling erosion, (16).

The treatments consisted of seed cradles, ridge-furrow beds, and traditional method of planting, replicated four times in a randomized complete block design. Seed cradles were prepared in rows 75 cm apart with 50 cm between seed cradles in each row. Ridge-furrow beds were prepared by hand. Ridge to ridge spacing was kept at 75 cm and ridge height measured from the furrow bottom was about 25 cm.

The trial was planted on 10 July. Emergence in seed cradles and ridge-furrow beds began early (unlike other trials in which emergence occurred after the rain on 21 July). This was, obviously, a result of better moisture conditions. During the period after planting, it was observed that dry sand had begun to fall into the seed cradles. Ridges remained intact. The rainfall on 21 July was 67 mm and was received with a high intensity. As a result, all of the seed cradles got filled with sand and ridges were washed into the furrows. A large number of the emerged seedlings were destroyed. Subsequent efforts to restore the trial were unsuccessful. Reshaping the ridges meant destroying the seedlings that had survived. Reseeding was attempted but new seedlings did not catch up with those that had emerged earlier.

In seed cradles, very few of the seeds that got buried under the sand could emerge.

Results of crop growth and yield are presented in Table 12. As expected, differences among the treatments were insignificant. However, a trend existed despite damage to the seed cradles and ridge-furrow beds. Ridge-furrow beds produced the highest biomass and grain yields. Observations showed a low plant population but the plants were much healthier in the ridge-furrow beds. Number of plants at harvest suggest that competition might have been minimum. However, when comparisons are made with similar plant populations in other trials, production in ridge-furrow beds appears quite a bit superior. It would appear that moisture conditions in ridge-furrow beds were more favorable. Also, the effect of crusting was eliminated in ridge-furrow beds.

From the experience gained during the 1984 season, unstable nature of the sand appears to be a serious problem in goz sands. Seed cradles are unlikely to be successful. Even if a high intensity rain is not expected every season, wind blown sand is enough to fill the seed cradles. Ridge-furrow beds appear to have a better chance of succeeding, particularly if they are prepared early in the season and reshaped after a rain or two, but before planting. From the crop production point of view, it is the initial establishment of seedlings that is critical. Once the crop has established, damage to ridges should not matter as water intake in goz sands is naturally efficient.

Table 12. Effect of seedbed preparation and planting technique on millet growth and yield in goz sand.

Treatment	Plants	Tillers	Heads	Biomass, kg/ha		Grain[2]
	No/ha	No/ha	No/ha	Fresh	Dry[1]	kg/ha
Traditional	17963	67078	31296	1224	812	62
Seed Cradle	4259	29022	14630	854	506	50
Ridge-Furrow	8241	49211	37685	1588	962	102

Number of hills planted: 26667/ha

1. F-test showed no significant difference at 5% level, CV = 57.4%

2. F-test showed no significant difference at 5% level, CV = 68.0%

Ridges are also effective in controlling erosion. As a measure against wind erosion, large areas should be brought under ridge-furrow system and maintained. Spraying with soil binding substances can help in maintaining the ridges.

E-1-4. DEPTH OF PLANTING: Because of rapid loss of moisture from the surface zone, seeds planted near the surface often fail to germinate. Lack of moisture also causes emerged seedlings to wither. Drying patterns in goz sands show that rate of loss of moisture decreases with depth. Therefore, if seeds are planted deeper, their chances of germinating should be better. However, emergence can be affected if seeds are placed too deep. This is particularly true for small seeds as food supply is limited and emerging plumules are too weak to provide the required force against the overlying soil.

An unreplicated trial was conducted on the goz sand to observe the effect of depth of planting on millet seedling emergence and survival. Seeds were planted at depths of 5, 10, 15, and 20 cm. A wooden stake was driven into the soil to desired depths and rotated several times to form a stable hole. Seeds were placed at the bottom and the hole was filled with soil. The surface of the planted hill was firmed by pressing with hand. Five rows, each 10 M in length, were planted for each depth of planting. Row to row spacing was 75 cm and hill to hill spacing was 50 cm.

The trial was planted on 25 July. Observations of emerged hills and number of hills with surviving seedlings were made at regular intervals till 7 August. Data are reported in Table 13. First count made on 28 July showed that percent of emerged hills were 46, 66, 5, and 0 for the 5, 10, 15, and 20 cm depths of planting, respectively. Number of emerged hills increased with time for the 5, 10, and 15 cm depths. No emergence was observed for the 20 cm depth. The maximum emergence (80 percent) for the 5 cm depth was observed on 30 July. On this day the emergence was 91.4 percent for the 10 cm depth and 11 percent for the 15 cm depth. Emergence for the 10 cm depth continued to increase and reached 94 percent on 4 August. The 15 cm depth showed a maximum emergence of 31 percent, also on 4 August. The decline in the percentage of surviving hills was observed on 31 July for the 5 cm depth, and on 7 August for the 10 and 15 cm depths. On 7 August, the percent of surviving hills were 59, 89, 30, and 0 for the 5, 10, 15, and 20 cm depths of planting, respectively.

Data show that germination, emergence, and seedling survivability are affected by the depth at which seeds are planted. Planting at 10 cm depth appeared to be most successful for millet planted in goz sands. 15 cm depth was too deep for millet seeds. Moisture deficiency appears to be the chief limitation to germination and seedling survival.

Since this trial was planted late and there were little rains after planting, emerged seedlings did poorly and no harvest was obtained.

Table 13. Effect of depth of planting on millet seedling emergence and survival in goz sand.

(Unreplicated Trial)

Planting depth cm	Observation dates						
	25 Jul*	28 Jul	30 Jul	31 Jul	1 Aug	4 Aug	7 Aug
	Emerged and surviving hills, %						
5	0	45.7	80.0	77.1	78.1	69.5	59.0
10	0	65.7	91.4	91.4	92.4	94.3	88.6
15	0	4.8	10.5	19.0	27.6	30.5	29.5
20	0	0	0	0	0	0	0

* Date of planting

E-2. GARDUD SOIL, BANOU:

E-2-1. PLOWING AND RIDGE-FURROW CULTIVATION: Surface of a virgin gardud land is very hard and stoney in many instances. The hardness is a result of a long period of dryness. Seasonal rains make little difference with the soil moisture because of extremely poor intake. The appraoch taken, therefore, was to begin a treatment of the soil that might induce better intake of water. Experiments conducted by Doxiadis Associates (17) showed that plowing was effective in improving water intake; however, a plowed layer settled back to its original density after a few rains. We decided to compare the effects of simple plowing and ridge-furrow beds imposed on a plowed surface. The approach was based on the thinking that whereas a plowed surface, lacking in stable aggregates, can be recompacted by the puddling action of rain, furrows should be more permanent and might continue to act as a catchment for rainwater.

Land preparation was carried out from 12 to 15 July. No rain had fallen until this time. A piece of gardud land was plowed with a disc plow. The depth of penetration varied from 5 to 15 cm with no penetration at some spots. Three diskings were applied in order to achieve uniformity in the depth of plowing but the result remained unsatisfactory. After the third disking the land was planked several times in order to achieve a level surface. Half of the plowed land was then turned into a ridge-furrow bed using a tractor-drawn ridger. It was observed that the ridger simply pulled the loose soil together to form a ridge leaving the furrow bottoms quite hard. In places

using a tractor-drawn ridger. It was observed that the ridger simply pulled the loose soil together to form a ridge leaving the furrow bottoms quite hard. In places where plow discs were unable to cut the soil, no ridge could be formed. In such places, soil was worked with a pic after the first rain. Ridge to ridge spacing was 80 cm and ridge height, measured from the furrow bottom, varied from 5 to 25 cm depending on the penetration of discs at the time of plowing.

First significant rain was received on 10 August. Crops were planted on 12 and 13 August. Four crops (millet, sorghum, sesame, and watermelon) and a bare treatment were included with three replications in a randomized complete block design. Both the ridge-furrow and the flat beds existed side by side and received the identical cropping treatments. Individual plots were 15M x 8M in size. Seeds were planted in the furrow bottoms. Row to row spacing was 80 cm but plant to plant spacing varied depending on the crop.

First observations showed that plowed land did, in fact, wet and appeared moist for several days after the rain. The unplowed land, on the other hand, looked dry the very next day after the rain. Free water had accumulated in the furrows whereas plowed flat bed appeared only wet. Crops did extremely poorly as there was very little emergence, so little that it wasn't worth counting. It appears that the hard subsoil exposed in the furrow bottoms was too hard for the seedling roots to develop. Similar situation existed in the flat beds but, perhaps, for other reasons. It is possible that soil had puddled and its mechanical strength increased rapidly. No records of the

rainfall were kept, but looking at the rainfall data in nearby Bangdeed, it appears that very little rain was received after the first heavy shower on 10 August.

No data on crop growth were obtained. Nor was it possible to make measurements of soil properties or moisture conditions. Reasons for this have been indicated earlier.

It is pertinent to point out that effort devoted to land preparation was too large and it will not be possible for small farmers to adapt the practice of plowing. The soil improvement is a slow process and no measurable gains can be expected in terms of crop production the first year. Who can afford to wait for several years just watching the improvement in soil condition?

Yet the idea of ridge-furrow beds does look attractive as a means of rehabilitating gardud soils. Furrows act as catchment for water and ridges act as a barrier against run off and erosion. Ridges in gardud soil are not easily damaged by rain or wind. If they can be prepared once, they may be left undisturbed for several years. Some maintenance may be required to reshape portions that do get damaged. Soil exposed in the furrow bottoms can be cultivated and planted to crops. Thus, the amount of tilling required will be reduced by more than half and a permanent catchment will remain in place. Tilling of furrows can be accomplished by hand tools. The effort required should decrease with time as soil improves with more and more water penetrating the soil each season. It may be possible that a group of farmers hire the needed machinery for the initial installation of

ridge-furrow system. This service could also be provided by the soil conservation department. Mechanized schemes and government owned farms can easily adapt the practice suggested here.

E-2-2. PLANTING IN SEED CRADLES: In our search for ideas for simpler methods to establish crops on gardud soil, we looked into seed cradles as a possibility. Seed cradles, as described for the goz sand in section E-1-3, were prepared on a piece of virgin gardud land. Holes were dug around 20 July in rows 1 M apart with 1 M between holes in each row. Rows were 20 M in length.

After the rain on 10 August, it was observed that the seed cradles had accumulated water and fine dust brought in by runoff and settled in the bottom. Soil physical condition appeared quite good to the feel. Seven rows, each of mesquite, acacia, watermelon, sorghum, millet, sesame, clitoria, and pigeon peas were planted on 12 August. Mesquite and acacia were planted as seedlings. Same crops were planted in the traditional manner on an adjacent piece of land. Traditional practice consisted of digging a hole, placing the seed, and covering it with the soil.

Observations of emergence and seedling survival are presented in Tables 14 and 15. Each crop had a total of 147 hills except pigeon peas which had 168 hills. Observations on 30 August showed that almost all of the seed cradles had healthy, dark green, and turgid plants. Number of hills with seedlings were much less in the

Table 14. Observations of plant growth in seed cradle vs. traditional planting methods in gardud soil at WSARP (Banou).

Planting date: 12 August 1984 Observation: 30 August 1984

CROP	SEED CRADLE		TRADITIONAL	
	n/N*	Observation	n/N*	Observation
Mesquite	118/147	Plants healthy; turgid leaves.	99/147	Most plants dry but stem appeared alive.
Watermelon	144/147	Healthy seedlings; several plants per hill.	95/147	Poor seedlings, shriveled leaves, stressed.
Sorghum	144/147	Very green, healthy, turgid leaves; several plants per hill.	86/147	Very poor, only partially green. Most hills had only one seedling.
Clitoria	0/147	No emergence; poor seeds.	0/147	No emergence; poor seeds.
Acacia	143/147	Leaves yellowed but plants alive.	142/147	No leaves, stem alive but partially dry.
Millet	147/147	Very green, healthy, turgid leaves; several plants per hill.	140/147	Very poor, partially dry; mostly one seedling per hill.
Sesame	133/147	Appeared somewhat stressed, through the leaves were green.	30/147	Seedlings very small, stressed, nearly dead.
Pigeon Peas	159/168	Appeared green but slightly stressed.	122/168	Very stressed; nearly dead.

* n = number of hills with surviving seedlings.

N = total number of hills planted.

Table 15. Observations of plant growth in seed cradle vs. traditional planting methods in gardud soil at WSARP (Banou).

Planting date: 12 August 1984 Observation: 23 September 1984

CROP	SEED CRADLE		TRADITIONAL	
	n/N*	Observation	n/N*	Observation
Mesquite	93/147	Plants healthy, green; some stress visible.	61/147	Very few leaves; stems appeared live.
Watermelon	115/147	Most seedlings healthy and green. Some stress.	51/147	Very poor, most leaves shriveled and dry.
Sorghum	131/147	Healthy, green, turgid; nearly 25 cm height.	44/147	Very poor, stunted, stressed; generally dry.
Clitoria	0/147	No emergence; poor seeds.	0/147	No emergence; poor seeds.
Acacia	101/147	Few leaves per plant; stem supple and live.	86/147	Plants appeared quite bare; stem live.
Millet	127/147	Seedlings healthy, green, slightly stressed, 20 cm height.	57/147	Very poor, stunted, dry to partially dry; severe stress.
Sesame	112/147	Stunted, green, stressed.	9/147	Generally dry, appearing dead; stems broke when moved.
Pigeon Peas	137/168	Some plants appeared dry, though retaining green color, generally stressed.	73/147	Generally dry, appearing dead; stems broke when moved.

*n = number of hills with surviving seedlings.

N = number of hills planted.

traditional planting method. Also, the seedlings in the traditional planting method were stunted, pale, and stressed. On 23 September, the number of surviving plants had dropped in both cases (see Table 15) but the drop was more drastic in the case of the traditional planting. There was only slight stress in the plants in seed cradles whereas plants in the traditional planting were severely stressed, pale, and partially dry.

All plants died eventually because of lack of rain. No method of conservation can succeed in periods of extreme drought. No harvest was obtained because the crops were grazed by animals.

One observation of soil moisture was made on 28 October. Data are given in Figure 15. There was a clear evidence that soil under the seed cradle had gained significantly higher amount of moisture in the 10 to 40 cm zone.

Unless detailed measurements of moisture conditions, soil properties, and crop growth are made, the benefits of seed cradles can be expressed only in qualitative terms. The soil volume influenced by seed cradles is an important factor for the plant growing in the seed cradles. Also, the crop moisture supply would depend on the amount and frequency of rains. Had the rains not failed, crops planted in the seed cradles could have produced some yield. Size of the individual seed cradles and spacing need to be determined in relation to rainfall.

Despite limited observations, seed cradles can be recommended as a means of establishing crop on gardud land. The most attractive aspect of seed cradles is that they are easy to make and require only simple hand tools.

E-2-3. DRIP IRRIGATION: Horticultural production in Western Sudan depends on the availability of irrigation water. Critically low supplies and wasteful methods of irrigation make it necessary that efforts begin to educate farmers in new technologies of irrigation. Drip system is the most efficient method of water application. There is almost 50 percent reduction in water usage. Pumping cost is reduced accordingly. Labor requirement to construct and maintain open earthen channels is eliminated. Water is delivered to individual plants via drip outlets. Between row spaces are always dry so that weed growth is minimal and farm operations such as weeding, staking, picking, and pruning continue uninterrupted. Earth work to move water from one end of the field to another is completely eliminated.

Drip irrigation equipment were imported from the United States. These included twin wall hoses with varying outlet spacings, supply tubes, anchors, insertion tools, water filters, and flow meters. Mains, submains, and fittings were purchased in El Obeid market. It needs mentioning that except for the twin wall hoses, all other components can be obtained from within Sudan. Only some improvisations may be necessary.

A small demonstration system consisting of 25 drip lines (each 20 M in length) was installed on a horticultural farm in Khor El Abyad between 15 and 17 April 1985. The system was tested on the bare field. It worked beautifully. The problem was encountered in regulating the pump pressure. Unless a bleeder was provided, increased pressure in the system caused stoppage of the pump. A pressure regulator was unavailable. Supplying water from an overhead tank appeared to be the only alternative. It is also a simpler alternative. The farmer was contacted and he agreed to build a tank. While we waited for the tank, the city of El Obeid ran out of drinking water. All the wells in the area were taken over by the Army to supply water to the city. This crisis halted further work on the drip irrigation. It is hoped that WSARP horticulturist will resume the work after the situation returns to normal.

E-3. CRACKING VERTISOLS, KADUGLI*:

E-3-1. MULCHING, SURFACE TILLAGE, AND RIDGE-FURROW BEDS: The discussion in section D-3 would suggest that in cracking vertisols, management practices should aim at minimizing large cracks on one hand and surface puddling and sealing on the other. Mulches protect the soil surface from raindrop impact and keep the surface porosity at the maximum. They suppress weed growth and reduce evaporative loss of water. Cracking is a result of drying and the rate of cracking depends on the drying rate. Therefore, reduction of drying rate should be the goal. Frequent surface tillage breaks up the capillary connections, obliterates
the cracks, and creates a dry surface layer which acts as a mulch of some sort. It is also effective in weed control. Ridge-furrow beds are also useful because furrows dry at a slower rate than the flat surfaces. Additionally, furrows act as a catchment for rainwater and help increase profile water storage by preventing runoff.

The field trial carried out at the WSARP station (Kadugli) consisted of traditional methods of cultivation, mulching, shallow surface

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* Moisture conservation trials on cracking vertisols were carried out in collaboration with Kadugli Research Station. Dr. T. Woldetatios, Agronomist and his assistants carried out and supervised all the field work.

tillage between rows, and ridge-furrow system of planting as treatments replicated four times in a randomized complete block design. Individual plots were 12M x 12M in size. Naturally growing grasses were cut and collected as a mulching material several months before the season. Plots receiving mulching treatment were covered with dry grass just before planting. Since this was a preliminary experiment, it was considered necessary to provide a complete ground cover. An application rate of 1 kg/m^2 was suggested. However, no determination of the actual applied rate was made. The grass was very dry and light. Later observations of the mulched plots indicated that mulching rate was probably much less than the initially suggested rate. Plots with ridge-furrow beds had ridges 80 cm apart and the ridge height was about 20 cm. The trial was planted on 5 July. Sorghum variety Gadam El Hammam was planted in rows 80 cm apart with 20 cm between hills. In mulched plots, planting was carried out by opening the mulch just enough to prepare the hill and drop the seeds. In ridge-furrow beds, seeds were planted on the ridge slope about 5 cm above the furrow bottom. Five seeds per hill were planted and thinned to 2 plants per hill after seedling establishment. Post emergence weeding was carried out as and when necessary. Plots receiving surface tillage as treatment were tilled to a depth of about 5 cm with a hand hoe. Hoeing frequency was based on observations of surface condition and cracking patterns. Our intention was to create a tilled layer in the surface after every rain but the schedule could not be followed strictly. Plots with traditional method of planting were only weeded.

Gravimetric soil moisture measurements for the top 30 cm of the soil were made on 29 August, 24 September, and 30 October.

Data on crop growth and yield, soil moisture condition, and tissue moisture at harvest are reported in Table 16. Mulching produced the highest amount of biomass and grain yield. Surface cultivation was next. Yields in ridge-furrow beds were depressed and were poorer than those for the traditional practice. It was observed that ridges were not prepared as desired. Also, the exposure of the hard subsoil may have affected the crop establishment and early growth. Moisture contents in plots with traditional practice were lowest throughout the season. Mulched plots showed the highest soil moisture content and minimal weed growth.

Visual observations showed that early growth in plots receiving surface tillage was superior. Mulched plots had depressed growth and the number of plants appeared to be less than in other plots. It was discovered that seeds had been planted under the mulch and a number of plants died because of smothering effect of the grass mulch on them. The mulch on the rows was opened and missing hills were reseeded. Opening the mulch helped existed seedlings but reseeded hills did not succeed. The overall effect of this inadvertent error was that mulched plots had a lower plant population to start with. moisture in plots with high plant population and better early growth was used up at a faster rate. When rains failed late in the season, plots with high plant population were most seriously affected. It now appears important to determine optimum plant population in relation to moisture regimes.

Table 16. Effects of mulching, ridge-furrow cultivation, and interrow surface tillage on soil moisture conservation and Sorghum Production in cracking verticols.

Treatments	Biomass, kg/ha		Grain** kg/ha	%Soil Moisture, 30cm			Tisue Moisture, %
	Fresh	Dry*		29/8	24/9	30/10	(Harvest)
Traditional	1491	1370	175	18.1	17.4	9.8	24.0
Ridge-Furrow	1073	824	116	23.3	21.0	9.2	36.8
Surface Cultivation	1551	1423	208	20.9	19.9	10.5	28.0
Mulch	3133	2098	417	28.8	29.3	19.0	45.2

* F-test shows that differences are significant at 5 and 1% levels. CV = 18.4%

** F-test shows that differences are significant at 5 and 1% levels. CV = 35.7%

E-3-2. RESIDUE MANAGEMENT: Even before mulching trials were carried out, it was obvious that some sort of a cover on the ground surface would be the most effective soil and water conservation practice on vertisols. It was also observed that natural grasses grow in abundance in fields around Kadugli. By about March/April these grasses dry out. Farmers, generally, collect and burn them before planting. It was reasoned that leaving these residues on the surface or incorporating them into the soil should have effects similar to mulching and a beneficial effect on soil structure.

An unreplicated trial consisting of large plots was carried out at the WSARP farm, Kadugli. Treatments included chopped residue left on the surface, residue incorporated into the soil by plowing, and residue burnt. Plots were 50M x 42M in size. Sorghum variety Gadam El Hammam was the test crop, planted in rows 80 cm apart with 20 cm between hills.

Results of crop growth and yield, moisture condition, and tissue moisture at harvest are reported in Table 17. Data show that production was highest in the plot where residue was left on the surface and was quite superior to that where residue was burnt.

Table 17. Effects of residue management on sorghum growth and yield in cracking vertisols .

Treatments	Biomass, kg/ha		Grain kg/ha	%Soil Moisture, 30cm			Tissue Moisture, %
	Fresh	Dry		29/8	24/9	30/10	(Harvest)
Chopped Residue	---	1496	235	24.1	25.8	13.5	43.7
Residue Incorp.	---	1154	198	28.7	22.7	11.0	6.1
Residue Burnt	---	958	144	15.3	24.5	12.3	47.1

Production in the plot where residue was incorporated into the soil was intermediate. Moisture content during the early part of the season was much higher in the plots with residue on the surface and residue incorporated. During the mid season, the moisture content in the plot where residue was burnt was comparable to those in the other two plots. This was probably due to reduced utilization of stored soil moisture, which might have resulted from low plant population and poor growth.

Results of the two trials reported here show the effectiveness of ground cover in conserving moisture. Further trials should be conducted to determine optimum rates, method of application, and residual effects. In addition, a cropping system in which ground cover is naturally produced should be investigated. Mulching, as was carried out at the WSARP farm, is probably not a feasible practice under traditional producers' conditions. However, it is not the word mulching per se which is of significance. Any form of ground cover composed of dead residue should be beneficial. Residue existing in the field at the time of planting can be utilized. Additional residue may be brought in, if available. Weeds may be left in place after cutting them at the time of weeding. Part of the crop residue may also be left in the field. It is also important to realize that a farmer does not have to start with the optimum amount of ground cover. It can be built over a period of time. A complete mulching would appear to be feasible in small plots such as kitchen gardens around the houses.

Where possible, post rainy season plowing may be considered as a means of conserving residual moisture. Clods and aggregates will act not only as a mulch but will also modify cracking patterns. Closure of wide cracks will certainly help conserve some of the subsoil moisture. The tilled layer will provide favorable conditions for infiltration of initial rains.

A significant portion of available rainfall runs off the land as a result of surface sealing. Efforts should be devoted to evolve practices to minimize runoff on vertisols. Contour bunding appears to have a potential. This practice is in use in India and a number of Southeast Asian countries.

F. RECOMMENDATIONS

Soil and water conservation research program for the 1984-85 season was exploratory to a large extent. The results have demonstrated the potential for increasing crop productivity through water conservation. A better understanding has also been gained of the soil-water problems for the three major soil types. It is now possible to focus field trials on specific problems that have been identified. Following is a list of recommended field trials for the major soil types in Western Sudan. A brief discussion of the background information is included to justify each trial.

It is also time to begin to collect information for economic evaluation of the practices that are being proposed for field testing.

F-1. GOZ SANDS:

Water is normally conserved in these soils but is available at deeper depths. The rapid drying of the surface zone is most limiting to seed emergence and seedling establishment. Therefore, the major emphasis has to be on improving seedling environment and selection of deep rooted crops and genotypes. In addition, optimum plant density in relation to prevailing moisture regimes must be determined. Management practices must also be developed to combat wind erosion.

The following trials are proposed for consideration:

1. Mulching and Residue Management: Mulching and residue are effective in reducing evaporation, weed control, and erosion control. 1984 trials showed that mulching caused a significant increase in millet biomass and yields. Reduction in evaporation implies more drainage and an increased storage of water at deeper depths.

2. Ridge-Furrow Cultivation: Ridges are effective in controlling wind erosion as well as reducing evaporation. Furrows capture more water and provide a shelter to young seedlings. In sands, however, it is difficult to maintain the ridge height because of unstable nature of the sand. During the 1984 season, ridges collapsed when a heavy rain was received. It damaged the emerged seedlings and prevented seeds from germinating. it is proposed that ridges be prepared before the

rains begin and reshaped and compacted before planting. A periodic maintenance may be necessary during the growing season. Research should continue to explore ridge desings and methods of stabilizing them if they are to remain in place for the purpose of controlling erosion. As for a crop, once the crop has established, ridge damage may not be of much effect.

3. Plant Population and Water Use Trial: Crop growth and yield and water use must be determined for several planting densities. The limited water supply can support crop growth only for a given number of plants. When number of plants increases, competition for available water also increases. During the 1984 season, plots with high population density and early vigorous growth failed later on in the season. Data showed that per plant biomass production increased as the number of plants decreased. This also raises the question as to whether the millet should be tillering or non-tillering type under the conditions in North Kordofan.

4. Selection of Crop Genotypes and New Crops Based on Water Extraction Patterns: Moisture profile data for goz sands reveal that a substantial amount of water stays at lower depths and is easily extractable. This implies that deep rooted crops have a better chance of survival and production. Genotypes of the presently grown crops must, therefore, be selected based on their root growth. However, since the net effect of root growth is on the moisture uptake, selections should be carried out based on water extraction patterns. Those genotypes that are able to extract water from deeper layers must

be selected. An alternative would be to change crops. Millet is not a very deep rooted crop. Sesame, watermelon, pigeonpeas, and kerkedi are known to be deep rooted. These crops are, probably, better suited to conditions in goz sands. Sesame and pigeonpeas were found to be growing at the WSARP farm during the March/April months, without much apparent stress. A corroborative evidence also comes from healthy growth of scrub vegetation species which are also known to be deep rooted.

5. Large Seeds, Seed Soaking, and Deep Planting: Data on surface drying patterns have shown that more than 60 percent of the moisture in the top 10 cm layer of the soil is lost during the first 24 hours of the rain. This indicates that emergence and early root growth will be severely affected unless the first rain is followed by other rains at short intervals. Data also show that rate of moisture loss decreases with depth. Therefore, if seeds are planted deep, chances of seedling survival will be better. During the 1984 cropping season, millet seeds planted at 10 cm depth showed better emergence and survival than those planted at 5 cm depth. Seeds planted at 15 cm depth did not emerge as well. Since moisture loss is rapid, a faster emergence and root growth should be most useful. Dry millet seeds take 4 to 5 days to emerge under optimum moisture conditions. If this period is reduced, there may be a better chance of survival. Seed soaking appears to be an effective means of effecting a rapid germination and emergence. Trials should be carried out to determine the best soaking time. A combination of seed soaking and deep planting in conjunction with other methods of reducing surface soil evaporation may prove to be the ultimate solution to the problem of crop establishment in goz sands.

6. Fallowing: Moisture distribution to a depth of 180 cm indicates that a substantial amount of water is present in deeper layers. Measurements made during the month of March indicated a total of 122 mm of water and a rate of loss of about 0.8 mm per week.

Estimates based on present water content, last season's rainfall, and estimated crop water use suggest availability of water conserved from the previous seasons. Fallowing, therefore, may be quite beneficial in augmenting profile moisture supply for the subsequent season. Large plots should be established to begin monitoring effects of fallowing on moisture conservation. An effective weed control and some residue cover to minimize wind erosion should be part of the fallowing practice.

7. Establishment of Windbreaks: Rapid moisture loss and wind erosion are serious problems in goz sands. Windbreaks have long been proposed as one of the solutions. However, since moisture is limited, windbreak plants planted in the required density and geometry fail to establish. Observations show that there are certain species (names unknown to the author) of the scrub vegetation which remain green and grow without stress even during the driest months. These plants must be very deep rooted and must be physiologically adapted to the drought conditions. At present these plants are growing at random. It is proposed that seeds from these species be collected and planted in the desired density and geometry. Methods of moisture conservation must be applied to help in the initial establishment. It may also be useful to investigate the means of rapid propagation of natural desert species.

F-2. GARDUD SOILS:

These soils are excessively compact and have very low infiltration. Major emphasis should be on increasing water intake. Hardness of the soil is related to dryness. Once the water can get in, the hardness should decrease. It is quite possible that the effect or a treatment is not significant at the first attempt. But continued improvement in infiltration should bring about a more lasting change in the physical condition of the soil.

The following trials are proposed for consideration:

1. Seed Cradle Planting: Seed cradles are holes 10 to 15 cm in diameter and 10 to 15 cm deep. They capture water and provide a shelter for seedlings. 1984 plantings in seed cradles showed extremely healthy growth of seedlings. This effort should continue. Research should be extended to explore the effects of the size and frequency of seed cradles.

2. Bunding and Runoff Capture: Much of the water on gardud lands is lost to runoff. Infiltration would increase if water could be impounded on the surface. Bunding can provide means of retaining water on the land. Bunds will have to be made on contour lines and emergency spillways provided to handle the excess water.

3. Ridge-Furrow Cultivation: Furrows are effective in capturing and impounding water. A trial was initiated at WSARP farm at Banou during the 1984 cropping season. Observations showed that furrows did, indeed, impound water. However, the crops showed very poor emergence.

It is believed that formation of ridge exposed the hardest subsoil in which the seeds were planted. It seems important to loosen the furrow bottoms after some rain has been received. Ridges remain in place for a long time. Only a periodic maintenance may be necessary. It is proposed that crop growth, soil moisture status, and soil physical condition be monitored in the existing ridge-furrow beds. A system of cultivation in which crops are planted in furrow bottoms, season after season, without disturbing the ridges seems quite feasible.

F-3. CRACKING VERTISOLS:

Despite high water holding capacity, these soils remain drought-prone. Surface sealing upon wetting and cracking upon drying lead to significant losses of rainwater. Major emphasis, therefore, should be on the protection of soil surface with mulch and residue cover. It is also important to determine optimum plant population and crop water use.

The following trials are proposed for consideration:

1. Mulching and Residue Management: Mulching and residue with no-till planting showed significant increases in soil moisture and sorghum yield during the 1984 cropping season. Research in this area should continue. Now there is a need to determine the optimum rates of mulching and its effect on crops in addition to sorghum. The persistence of the effect of mulching should also be studied. It is

quite probable that mulch, once applied, needs to be replenished only by a small amount in the subsequent year. Large plots should be established to study the effects over a long period on the same location. Similar studies should continue with naturally produced residue.

2. Plant Population and Water Use Trial: Same as for goz sands.

3. Ridge-Furrow Cultivation: Same as for gardud soils. Here also the results were poor during the 1984 cropping season. Effects of the exposure of subsoil is suspected. It is recommended that furrows be made a little deeper and wider and be tilled before planting. Since the furrow bottoms are expected to improve with time, there should be no need to change the plot location from one season to the next.

4. Bunding and Runoff Capture: Same as for gardud soils. Bunds should be prepared before the rains and spillways should be provided.

5. Post Rainy Season Plowing: Soil moisture from the deeper layers is lost to direct evaporation via large cracks that develop after the rains. Conserving the residual moisture is important as it will add to the total profile storage in the subsequent season. Post rainy season plowing of land appears to have a potential. Clods and aggregates will act not only as a mulch but will also modify cracking patterns. Closure of wide cracks will certainly help conserve some of the subsoil moisture. The tilled layer will provide favorable

conditions for infiltration of initial rains. Research should focus on quantifying the moisture loss patterns and benefits from plowing. The type of tillage and best time to plow are also subjects for research.

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APPENDICES

Appendix 1. Seven-day averages of weather data, 1984-85 season. WSARP Farm, El Obeid, Sudan.

Dates	Air Temperature, °C			Relative Humidity, %			Rainfall	Solar Radiation	Wind	Pan Evap
	Mean	Max	Min	Mean	Max	Min	mm*	kj/m^2/day	km/day	mm/day
29 Aug-4 Sep 84	30.0	37.5	24.4	59.5	81.6	37.5	29.0	22,189	363	12.9
5 Sep-11 Sep	30.3	38.0	24.1	50.5	77.7	28.7	00.0	25,923	265	12.1
12 Sep-18 Sep	29.5	37.9	23.8	57.9	80.5	37.6	00.0	21,074	358	11.8
19 Sep-25 Sep	29.4	38.3	22.8	61.2	88.4	35.9	25.0	18,483	292	10.8
26 Sep- 2 Oct	31.1	39.4	24.5	48.1	73.6	28.5	00.0	16,917	295	12.5
3 Oct- 9 Oct	31.3	40.4	24.8	46.8	68.7	27.8	00.0	11,085	275	11.5
10 Oct-16 Oct	30.9	39.7	22.3	31.2	56.2	21.9	00.0	15,070	212	11.5
17 Oct-23 Oct	30.6	38.6	22.8	23.5	27.2	22.1	00.0	13,514	303	14.1
24 Oct-30 Oct	29.9	37.2	22.9	25.5	29.9	23.1	00.0	18,600	358	13.4
31 Oct- 6 Nov	28.7	37.0	19.8	24.7	28.6	22.8	00.0	20,961	306	12.5
7 Nov-13 Nov	25.0	33.4	16.9	24.0	27.4	22.5	00.0	22,254	324	11.8
14 Nov-20 Nov	23.7	33.5	14.3	22.5	23.7	21.8	00.0	22,810	287	-
21 Nov-27 Nov	22.1	30.7	13.6	26.4	33.6	22.6	00.0	20,877	342	8.6
28 Nov- 4 Dec	22.0	31.2	13.3	26.1	31.7	22.7	00.0	20,729	265	9.4
5 Dec-11 Dec	19.1	28.0	10.6	24.8	29.8	22.4	00.0	20,830	342	10.1
12 Dec-18 Dec	18.2	26.2	10.6	27.5	32.8	23.7	00.0	19,461	383	9.8
19 Dec-25 Dec	24.3	33.6	15.5	31.5	40.5	24.7	00.0	14,403	278	9.6
26 Dec- 1 Jan 85	24.6	33.4	16.2	30.3	36.6	25.1	00.0	7,246	317	10.2

* Total for the week

Appendix 1. Seven-day averages of weather data, 1984-85 season. WSARP Farm, El Obeid, Sudan

Dates	Air Temperature, °C			Relative Humidity, %			Rainfall	Solar Radiation	Wind	Pan Evap
	Mean	Max	Min	Mean	Max	Min	mm*	$kj/m^2/day$	km/day	mm/day
2 Jan- 8 Jan	23.1	32.6	14.4	22.2	23.6	21.5	00.0	8,745	344	12.1
9 Jan-15 Jan	25.6	35.0	16.7	31.7	41.9	24.6	00.0	20,663	263	10.0
16 Jan-22 Jan	24.6	33.3	16.7	24.3	29.4	22.0	00.0	15,492	345	12.3
23 Jan-29 Jan	21.9	31.8	12.6	22.6	24.7	21.5	00.0	9,391	294	13.2
30 Jan- 5 Feb	19.9	28.1	11.9	21.9	22.8	21.4	00.0	11,958	382	-
6 Feb-12 Feb	20.1	29.5	10.8	21.7	22.6	21.3	00.0	9,839	357	12.5
13 Feb-19 Feb	20.5	29.3	10.9	21.7	22.6	21.3	00.0	7,558	386	13.7
20 Feb-26 Feb	23.3	32.0	14.8	22.0	23.4	21.3	00.0	5,556	394	14.4
27 Feb- 5 Mar	20.4	29.0	11.7	21.8	22.6	21.4	00.0	9,146	297	13.7
6 Mar-12 Mar	26.0	35.6	16.1	21.9	22.7	21.5	00.0	9,726	334	15.3
13 Mar-19 Mar	32.1	42.1	22.3	21.8	22.3	21.4	00.0	17,968	242	15.1
20 Mar-26 Mar	31.1	38.9	24.3	28.7	39.7	23.0	00.0	3,704	234	14.4
27 Mar- 2 Apr	29.6	39.9	19.9	22.4	26.7	21.1	00.0	9,256	187	17.8
3 Apr- 9 Apr	28.8	35.4	22.7	25.4	31.8	22.6	00.0	19,047	376	-
10 Apr-16 Apr	28.5	38.8	18.0	21.3	21.4	21.2	00.0	18,927	164	-
17 Apr-23 Apr	31.2	40.4	22.1	21.3	21.4	21.2	00.0	17,877	281	-
24 Apr-30 Apr	29.3	39.6	18.9	21.3	21.4	21.2	00.0	23,613	242	-
1 May- 7 May	32.2	40.6	24.4	28.9	46.7	21.4	00.0	14,579	196	-

* Total for the week

Appendix 1. Seven-day averages of weather data, 1984-85 season. WSARP Farm, El Obeid, Sudan.

Dates	Air Temperature, °C			Relative Humidity, %			Rainfall	Solar Radiation	Wind	Pan Evap
	Mean	Max	Min	Mean	Max	Min	mm*	kj/m^2/day	km/day	mm/day
8 May-14 May	33.5	42.1	26.3	26.8	38.9	21.7	00.0	10,678	106	-
15 May-21 May	30.8	38.7	25.0	46.2	71.3	27.1	19.0	13,459	156	-
22 May-28 May	30.3	39.3	24.4	53.5	79.4	28.6	6.0	9,742	301	-
29 May- 4 Jun	32.9	41.5	25.6	32.3	50.9	21.5	00.0	8,792	292	-

* Total for the week

Appendix 2. Dry season moisture profiles in goz sand, El Obeid, Sudan

Date: 7 March 1985

Depth cm	Water content, cm^3/cm^3			
	Location 1	Location 2	Location 3	Location 4
15	0.020	0.018	0.014	0.020
30	0.040	0.043	0.032	0.042
45	0.049	0.057	0.040	0.052
60	0.063	0.059	0.048	0.062
75	0.069	0.064	0.060	0.062
90	0.073	0.072	0.064	0.069
105	0.080	0.076	0.075	0.071
120	0.085	0.078	0.083	0.076
135	0.092	0.084	0.085	0.082
150	0.095	0.089	0.087	0.081
165	0.101	0.093	0.090	0.085
180	0.109	0.102	0.096	0.090
Total, mm	131.3	125.0	115.8	118.5

Locations 1 and 2 crusted Field average = 122.7 mm

Locations 3 and 4 noncrusted

Appendix 2. Dry season moisture profiles in goz sand, El Obeid, Sudan

Date: 13 March 1985

Depth cm	Water content, cm^3/cm^3			
	Location 1	Location 2	Location 3	Location 4
15	0.017	0.015	0.010	0.017
30	0.038	0.041	0.031	0.041
45	0.050	0.054	0.038	0.051
60	0.062	0.059	0.047	0.061
75	0.069	0.064	0.058	0.067
90	0.073	0.071	0.065	0.068
105	0.080	0.076	0.075	0.070
120	0.086	0.080	0.082	0.076
135	0.092	0.083	0.085	0.080
150	0.096	0.088	0.086	0.080
165	0.101	0.093	0.090	0.085
180	0.108	0.103	0.096	0.090
Total, mm	130.7	124.1	114.2	117.6

Locations 1 and 2 crusted Field average = 121.7 mm

Locations 3 and 4 noncrusted

Appendix 2. Dry season moisture profiles in goz sand, El Obeid, Sudan

Date: 20 March 1985

Depth cm	Water content, cm^3/cm^3			
	Location 1	Location 2	Location 3	Location 4
15	0.013	0.032	0.009	0.014
30	0.034	0.036	0.028	0.037
45	0.048	0.053	0.038	0.049
60	0.060	0.060	0.046	0.058
75	0.068	0.065	0.057	0.066
90	0.072	0.071	0.067	0.068
105	0.080	0.075	0.076	0.070
120	0.087	0.080	0.083	0.075
135	0.092	0.085	0.086	0.079
150	0.096	0.088	0.087	0.080
165	0.102	0.093	0.092	0.087
180	0.108	0.103	0.097	0.090
Total, mm	129.1	126.1	114.9	115.9

Locations 1 and 2 crusted Field average = 121.5

Locations 3 and 4 noncrusted

Appendix 2. Dry season moisture profiles in goz sand, El Obeid, Sudan

Date: 27 March 1985

Depth cm	Water content, cm^3/cm^3			
	Location 1	Location 2	Location 3	Location 4
15	0.013	0.011	0.008	0.012
30	0.033	0.033	0.026	0.034
45	0.048	0.050	0.038	0.048
60	0.060	0.058	0.046	0.059
75	0.067	0.066	0.056	0.064
90	0.076	0.072	0.065	0.068
105	0.081	0.077	0.077	0.070
120	0.088	0.079	0.083	0.075
135	0.093	0.083	0.085	0.078
150	0.097	0.089	0.087	0.081
165	0.103	0.093	0.092	0.087
180	0.111	0.103	0.098	0.092
Total, mm	130.2	122.1	114.0	115.0

Locations 1 and 2 crusted Field average = 120.3 mm

Locations 3 and 4 noncrusted

Appendix 2. Dry season moisture profiles in goz sand, El Obeid, Sudan

Date: 2 April 1985

Depth cm	Water content, cm^3/cm^3			
	Location 1	Location 2	Location 3	Location 4
15	0.013	0.010	0.007	0.012
30	0.032	0.031	0.026	0.034
45	0.047	0.048	0.037	0.048
60	0.059	0.058	0.046	0.057
75	0.066	0.065	0.057	0.065
90	0.073	0.072	0.067	0.066
105	0.080	0.074	0.077	0.070
120	0.087	0.081	0.084	0.075
135	0.090	0.084	0.087	0.078
150	0.095	0.087	0.087	0.082
165	0.101	0.094	0.092	0.086
180	0.110	0.103	0.098	0.093
Total, mm	127.8	120.8	114.7	114.7

Locations 1 and 2 crusted

Locations 3 and 4 noncrusted

Field average = 119.5 mm

Appendix 2. Dry season moisture profiles in goz sand, El Obeid, Sudan

Date: 10 April 1985

Depth cm	Water content, cm^3/cm^3			
	Location 1	Location 2	Location 3	Location 4
15	0.014	0.009	0.008	0.013
30	0.031	0.030	0.024	0.033
45	0.045	0.046	0.035	0.048
60	0.057	0.058	0.044	0.057
75	0.066	0.066	0.055	0.063
90	0.073	0.071	0.065	0.066
105	0.080	0.076	0.077	0.070
120	0.086	0.080	0.083	0.073
135	0.090	0.085	0.085	0.078
150	0.095	0.090	0.087	0.080
165	0.101	0.094	0.092	0.086
180	0.110	0.101	0.097	0.090
Total, mm	127.0	120.7	122.8	113.4

Locations 1 and 2 crusted

Locations 3 and 4 noncrusted

Field average = 118.5

Appendix 2. Dry season moisture profiles in goz sand, El Obeid, Sudan

Date: 17 April 1985

Depth cm	Water content, cm^3/cm^3			
	Location 1	Location 2	Location 3	Location 4
15	0.012	0.009	0.007	0.011
30	0.031	0.030	0.024	0.032
45	0.044	0.045	0.037	0.046
60	0.057	0.058	0.045	0.057
75	0.067	0.065	0.055	0.063
90	0.074	0.073	0.066	0.067
105	0.082	0.078	0.077	0.069
120	0.085	0.080	0.085	0.074
135	0.090	0.084	0.087	0.077
150	0.095	0.091	0.087	0.081
165	0.099	0.095	0.091	0.088
180	0.108	0.104	0.096	0.090
Total, mm	126.5	121.6	113.4	113.1

Locations 1 and 2 crusted

Locations 3 and 4 noncrusted

Field average = 118.7 mm

Appendix 2. Dry season moisture profiles in goz sand, El Obeid, Sudan

Date: 24 April 1985

Depth cm	Water content, cm^3/cm^3			
	Location 1	Location 2	Location 3	Location 4
15	0.012	0.009	0.007	0.010
30	0.030	0.028	0.024	0.029
45	0.043	0.043	0.035	0.044
60	0.055	0.056	0.043	0.055
75	0.063	0.065	0.056	0.061
90	0.074	0.071	0.065	0.066
105	0.079	0.076	0.077	0.069
120	0.085	0.079	0.083	0.072
135	0.087	0.084	0.085	0.076
150	0.094	0.090	0.088	0.079
165	0.100	0.093	0.092	0.085
180	0.110	0.102	0.097	0.089
Total, mm	124.5	119.4	112.7	110.1

Locations 1 and 2 crusted

Locations 3 and 4 noncrusted

Field average = 116.7 mm

Appendix 2. Dry season moisture profiles in goz sand, El Obeid, Sudan

Date: 1 May 1985

Depth cm	Water content, cm^3/cm^3			
	Location 1	Location 2	Location 3	Location 4
15	0.012	0.009	0.007	0.010
30	0.029	0.017	0.023	0.030
45	0.042	0.043	0.034	0.044
60	0.055	0.056	0.042	0.054
75	0.065	0.064	0.054	0.061
90	0.073	0.072	0.064	0.065
105	0.079	0.076	0.077	0.069
120	0.084	0.081	0.084	0.074
135	0.089	0.084	0.084	0.076
150	0.093	0.089	0.087	0.080
165	0.101	0.096	0.091	0.085
180	0.109	0.105	0.098	0.091
Total, mm	124.5	118.4	111.6	110.9

Locations 1 and 2 crusted

Locations 3 and 4 noncrusted

Filed average = 116.4 mm

Appendix 2. Dry season moisture profiles in goz sand, El Obeid, Sudan

Date: 12 May 1985

Depth cm	Water content, cm^3/cm^3			
	Location 1	Location 2	Location 3	Location 4
15	0.012	0.010	0.006	0.010
30	0.030	0.028	0.023	0.029
45	0.043	0.042	0.033	0.042
60	0.054	0.055	0.041	0.052
75	0.062	0.065	0.054	0.060
90	0.073	0.072	0.066	0.065
105	0.080	0.076	0.075	0.068
120	0.086	0.082	0.082	0.072
135	0.090	0.085	0.085	0.075
150	0.095	0.087	0.087	0.079
165	0.100	0.095	0.091	0.086
180	0.108	0.103	0.096	0.089
Total, mm	124.7	119.7	110.7	108.8

Locations 1 and 2 crusted

Locations 3 and 4 noncrusted

Field average = 116.0 mm

Appendix 2. Dry season moisture profiles in goz sand, El Obeid, Sudan

Date: 16 May 1985

Depth cm	Water content, cm^3/cm^3			
	Location 1	Location 2	Location 3	Location 4
15	0.013	0.010	0.007	0.011
30	0.029	0.028	0.023	0.029
45	0.043	0.042	0.034	0.042
60	0.052	0.054	0.041	0.052
75	0.063	0.064	0.053	0.060
90	0.074	0.071	0.065	0.064
105	0.081	0.077	0.077	0.067
120	0.086	0.079	0.083	0.073
135	0.090	0.083	0.087	0.076
150	0.095	0.088	0.088	0.080
165	0.102	0.094	0.093	0.087
180	0.109	0.105	0.098	0.090
Total, mm	125.5	119.0	112.3	109.7

Locations 1 and 2 crusted Field average = 116.6 mm

Locations 3 and 4 noncrusted

Appendix 2. Dry season moisture profiles in goz sand, El Obeid, Sudan

Date: 22 May 1985

Depth cm	Water content, cm^3/cm^3			
	Location 1	Location 2	Location 3	Location 4
15		0.045	0.037	0.033
30		0.044	0.038	0.038
45		0.043	0.035	0.042
60		0.053	0.041	0.050
75		0.062	0.054	0.059
90		0.072	0.064	0.064
105		0.075	0.077	0.067
120		0.080	0.083	0.072
135		0.083	0.087	0.075
150		0.087	0.087	0.078
165		0.093	0.092	0.085
180		0.105	0.097	0.089
Total, mm		126.3	118.6	112.8

Locations 1 and 2 crusted

Locations 3 and 4 noncrusted

Field average = 119.2 mm

Appendix 2. Dry season moisture profiles in goz sand, El Obeid, Sudan

Date: 23 May 1985

Depth cm	Water content, cm^3/cm^3			
	Location 1	Location 2	Location 3	Location 4
15	0.025	0.040	0.035	0.033
30	0.034	0.044	0.040	0.039
45	0.042	0.044	0.035	0.043
60	0.052	0.052	0.041	0.052
75	0.062	0.064	0.053	0.061
90	0.073	0.072	0.064	0.065
105	0.082	0.076	0.077	0.070
120	0.086	0.080	0.083	0.073
135	0.090	0.084	0.087	0.077
150	0.096	0.088	0.086	0.081
165	0.103	0.093	0.092	0.087
180	0.110	0.102	0.096	0.090
Total, mm	128.2	125.8	118.4	115.6

Locations 1 and 2 crusted

Locations 3 and 4 noncrusted

Field average = 122.0 mm

Appendix 2. Dry season moisture profiles in goz sand, El Obeid, Sudan

Date: 29 May 1985

Depth cm	Water content, cm^3/cm^3			
	Location 1	Location 2	Location 3	Location 4
15	0.024	0.036	0.031	0.030
30	0.035	0.046	0.042	0.041
45	0.044	0.050	0.037	0.045
60	0.051	0.053	0.044	0.052
75	0.062	0.064	0.052	0.058
90	0.071	0.072	0.064	0.065
105	0.080	0.075	0.076	0.069
120	0.086	0.079	0.083	0.073
135	0.089	0.084	0.085	0.076
150	0.093	0.087	0.087	0.081
165	0.099	0.095	0.091	0.087
180	0.108	0.105	0.098	0.090
Total, mm	126.2	127.0	118.0	115.0

Locations 1 and 2 crusted

Locations 3 and 4 noncrusted

Field average = 121.6 mm

Appendix 2. Dry season moisture profiles in goz sand, El Obeid, Sudan

Date: 5 June 1985

Depth cm	Water content, cm^3/cm^3			
	Location 1	Location 2	Location 3	Location 4
15	0.019	0.027	0.023	0.024
30	0.034	0.045	0.041	0.041
45	0.045	0.046	0.039	0.046
60	0.053	0.053	0.041	0.052
75	0.064	0.062	0.052	0.060
90	0.072	0.074	0.065	0.066
105	0.082	0.077	0.078	0.070
120	0.086	0.081	0.084	0.074
135	0.091	0.086	0.088	0.077
150	0.096	0.090	0.088	0.081
165	0.101	0.096	0.093	0.088
180	0.112	0.104	0.099	0.092
Total, mm	128.0	126.1	118.4	115.6

Locations 1 and 2 crusted

Locations 3 and 4 noncrusted

Field average = 122.0 mm

Appendix 3. Post-irrigation moisture profiles in goz sand, El Obeid, Sudan.

Depth	Water content, cm^3/cm^3					
cm	13 Mar* 6:00 pm	14 Mar 10:40 am	15 Mar 10:15 am	16 Mar 9:31 am	17 Mar 9:40 am	18 Mar 9:49 am
15	0.107	0.080	0.069	0.068	0.065	0.061
30	0.136	0.109	0.099	0.099	0.094	0.095
45	0.155	0.123	0.113	0.111	0.108	0.106
60	0.176	0.138	0.129	0.128	0.126	0.123
75	0.201	0.153	0.141	0.141	0.137	0.138
90	0.217	0.164	0.154	0.151	0.145	0.146
105	0.222	0.182	0.167	0.163	0.156	0.157
120	0.225	0.203	0.183	0.179	0.172	0.173
135	0.227	0.214	0.197	0.194	0.187	0.190
150	0.223	0.217	0.208	0.204	0.194	0.198
165	0.228	0.219	0.210	0.207	0.202	0.204
180	0.235	0.226	0.222	0.216	0.211	0.213
Total, mm	352.8	304.0	283.7	279.4	269.5	270.5

* Irrigation ended 1:30 pm

Appendix 3. Post-irrigation moisture profiles in goz sand, El Obeid, Sudan.

Depth	Water content, cm^3/cm^3					
cm	19 Mar 9:33 am	29 Mar 10:03 am	21 Mar 9:32 am	23 Mar 11:12 am	24 Mar 9:10 am	25 Mar 10:10 am
15	0.062	0.061	0.057	0.055	0.052	0.052
30	0.093	0.093	0.088	0.086	0.085	0.084
45	0.105	0.106	0.103	0.100	0.100	0.100
60	0.121	0.123	0.119	0.115	0.117	0.116
75	0.134	0.136	0.132	0.130	0.127	0.126
90	0.144	0.145	0.140	0.138	0.136	0.137
105	0.155	0.158	0.150	0.149	0.147	0.149
120	0.171	0.174	0.168	0.165	0.165	0.165
135	0.187	0.187	0.184	0.180	0.178	0.181
150	0.197	0.198	0.192	0.191	0.190	0.190
165	0.202	0.204	0.200	0.194	0.193	0.193
180	0.209	0.211	0.203	0.205	0.200	0.201
Total, mm	266.9	269.2	260.2	256.1	253.5	254.2

Appendix 3. Post-irrigation moisture profiles in goz sand, El Obeid, Sudan.

Depth cm	Water content, cm^3/cm^3					
	26 Mar 10:45 am	27 Mar 10:05 am	28 Mar 9:30 am	30 Mar 10:05 am	31 Mar 9:22 am	1 Apr 10:15 am
15	0.050	0.050	0.049	0.048	0.047	0.048
30	0.086	0.082	0.081	0.082	0.081	0.081
45	0.098	0.097	0.097	0.095	0.095	0.095
60	0.115	0.114	0.113	0.112	0.113	0.112
75	0.127	0.125	0.125	0.123	0.123	0.123
90	0.133	0.133	0.134	0.134	0.132	0.132
105	0.146	0.145	0.144	0.143	0.142	0.142
120	0.163	0.163	0.159	0.159	0.158	0.160
135	0.178	0.175	0.178	0.175	0.175	0.175
150	0.191	0.187	0.185	0.185	0.183	0.185
165	0.195	0.191	0.189	0.189	0.189	0.189
180	0.203	0.195	0.197	0.195	0.194	0.197
Total, mm	252.2	248.5	247.7	246.0	244.6	245.8

Appendix 3. Post-irrigation moisture profiles in goz sand, El Obeid, Sudan.

Depth	Water content, cm^3/cm^3					
cm	2 Apr 11:15 am	10 Apr 11:35 am	17 Apr 9:00 -	24 Apr -	1 May -	12 May -
15	0.046	0.044	0.040	0.037	0.034	0.032
30	0.081	0.077	0.075	0.072	0.072	0.067
45	0.097	0.094	0.091	0.090	0.091	0.089
60	0.114	0.111	0.107	0.106	0.108	0.105
75	0.124	0.120	0.120	0.121	0.116	0.113
90	0.134	0.129	0.127	0.124	0.125	0.122
105	0.142	0.138	0.135	0.136	0.133	0.130
120	0.159	0.157	0.150	0.153	0.151	0.145
135	0.174	0.169	0.167	0.166	0.166	0.161
150	0.186	0.180	0.177	0.177	0.175	0.170
165	0.190	0.182	0.181	0.179	0.178	0.176
180	0.196	0.191	0.187	0.186	0.186	0.184
Total, mm	246.4	238.7	233.7	232.1	230.4	224.0

Appendix 3. Post-irrigation moisture profiles in goz sand, El Obeid, Sudan.

Depth cm	Water content, cm^3/cm^3					
	16 May -	22 May -	23 May -	29 May -	5 Jun -	
15	0.031	0.062	0.058	0.052	0.046	
30	0.067	0.077	0.077	0.079	0.077	
45	0.088	0.087	0.0 87	0.0 88	0.0 90	
60	0.104	0.104	0.103	0.103	0.105	
75	0.133	0.116	0.115	0.113	0.115	
90	0.120	0.122	0.122	0.121	0.123	
105	0.132	0.132	0.131	0.129	0.132	
120	0.148	0.147	0.146	0.143	0.145	
135	0.160	0.160	0.160	0.158	0.159	
150	0.169	0.171	0.169	0.165	0.169	
165	0.173	0.173	0.172	0.172	0.173	
180	0.183	0.183	0.181	0.182	0.183	
Total, mm	223.2	230.7	227.9	226.3	227.3	

25 mm rain between 15 May and 28 May.