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Interactions of Water, Nutrient, and Mulch on Sorghum Water Use in a Sahelian Agroecosystem

Christophe Guy Ludovic Zaongo

INTERACTIONS OF WATER, NUTRIENT, AND MULCH ON SORGHUM WATER USE IN A SAHELIAN AGROECOSYSTEM

A Dissertation

by

CHRISTOPHE GUY LUDOVIC ZAONGO

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 1993

Major Subject: Soil Science

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December 1993

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ABSTRACT

Interactions of Water, Nutrient, and Mulch on SorghumWater Use in a Sahelian Agroecosystem.

(August, 1993)

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In the Sahel region of Africa, grain sorghum (*Sorghum bicolor* (L.) Moench) is a major human food source. Due to scarce water resources and soil infertility efficient crop water use is a key challenge for sustainable crop production. The objectives of this study were to use supplemental irrigation, nutrient, and mulch to manipulate the system energy and soil water balance in order to improve crop water use efficiency and to integrate the soil-plant-atmosphere continuum water relationships into a mechanistic model capable of predicting soil evaporation and crop transpiration. The experiment site was located in Maradi, Niger. Soil physical, chemical, and hydrological properties were characterized, and water balance components (rainfall, soil evaporation, deep drainage, and changes of soil water storage), crop growth parameters (height, leaf area index, biomass production and root distribution), and relevant climatic parameters (temperatures, humidity, wind speed, and solar radiation) measured. Mulch reduced sensible flux between soil and air 3 to 5 times and soil long wave radiation emission 100 to 200 W m^{-2}. Soil net radiation balance was reduced 220 to 350 W m^{-2}, crop net radiation increased 60 to 100 W m^{-2}, and soil evaporation reduced 22%. Mulch caused significant ($P = 0.05$) WUE(ET) increase (18%), and WUE(T) 6%. Nutrient significantly increased biomass production, crop transpiration 12%, increased WUE(ET) 11%, and WUE(T) 9% Irrigation increased soil evaporation 24%, crop transpiration 5%, WUE(ET) 22% and WUE(T) 34%. It reduced the effect of mulch and nutrient on WUE(ET) and the effect of mulch on WUE(T) but improved the effect of nutrient on WUE(T). Interactions indicated that either irrigation or mulch significantly improved WUE(T) only with the other inputs. Grain water use efficiency was significantly improved by all factors. Results indicate that nutrient and soil evaporation control are required in water balance manipulation schemes for efficient crop water use in the Sahelian agroecosystem. The ENWATBAL model predicted soil evaporation of eight production systems with 5 to 15% error. This indicates that it can be a valuable tool for water balance studies in this region.

DEDICATION

To my mothers

and

To Dr. Jean Dider Zongo, a brother, an educator, a true leader, yet a modest giver.

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I. INTRODUCTION

Recurrent drought and poor soil resources are two causes of the low agricultural productivity of the Sahel. Annual rainfall in the Sahelian countries (Fig.1) ranges from less than 25 to more than 900 mm. Even though the rainy season lasts from the end of May to early October most of the rains fall as intense storms, causing severe runoff and erosion. Yearly amount and distribution are highly variable resulting in periodic soil moisture deficits referred to as "drought". Since 1968, drought has been chronic, with rainfall one standard deviation below the long term average (Sanders, 1988). A decline of national and per capita food production has occurred during the last two decades.

Soils in the region are predominantly sandy with laterite or ironstone occurring at shallow depths. Major upland soils are classified as Psamments, Kandiustalfs and Kandiustults (Wilding and Hossner, 1988). These soils are low in water holding capacity and organic matter, generally acid, and deficient in nutrients such as nitrogen (N), phosphorus (P), sulfur (S), and zinc (Zn) (TropSoils, 1991). Heavy textured soils (Vertisols and associated soils) occur in areas such as river valleys and inland depressions. Although such soils are relatively fertile and offer a great potential for grain production, they are often underutilized due to the high labor required to bring them into agricultural production.

Sorghum and millet are the two major staple food crops in the region. Crops are rainfed cultivated within the 300 to 800 mm rainfall zone under traditional farming systems using little or no purchased inputs. Crop yields are usually low due to declining soil fertility and uncertain rainfall. Under limited annual rainfall and a short growing season farmers in the Sahel generally grow sorghum in the lower portion of soil toposequences on alluvial soils along seasonal and perennial rivers.

Crop failure and its consequences are often blamed on poorly distributed rainfall. However, it is not appropriate to define drought only in terms of rainfall in the Sahelian farming systems since it may result from improper land resource use. Appropriate soil and water management techniques can reduce evaporation, runoff, and deep drainage, therefore improve plant nutrient and water use efficiency (Barrow, 1987). Different cultural practices and cropping strategies can be used under the same rainfall regimes. Inefficient water use is not limited to rainfall alone. Recent studies in this area have shown that in the rainfed agricultural areas rainfall is not necessarily the limiting factor to crop growth but rather the availability, preservation, depletion, replenishment, and efficient management of the soil water reservoir (Sivakumar and Wallace, 1991). The ultimate objective is to insure an efficient utilization of water by cultivated cereal crops. Due to problems in the Sahel this objective is seldomly attained.

This dissertation follows the style of the Soil Science Society of America Journal.

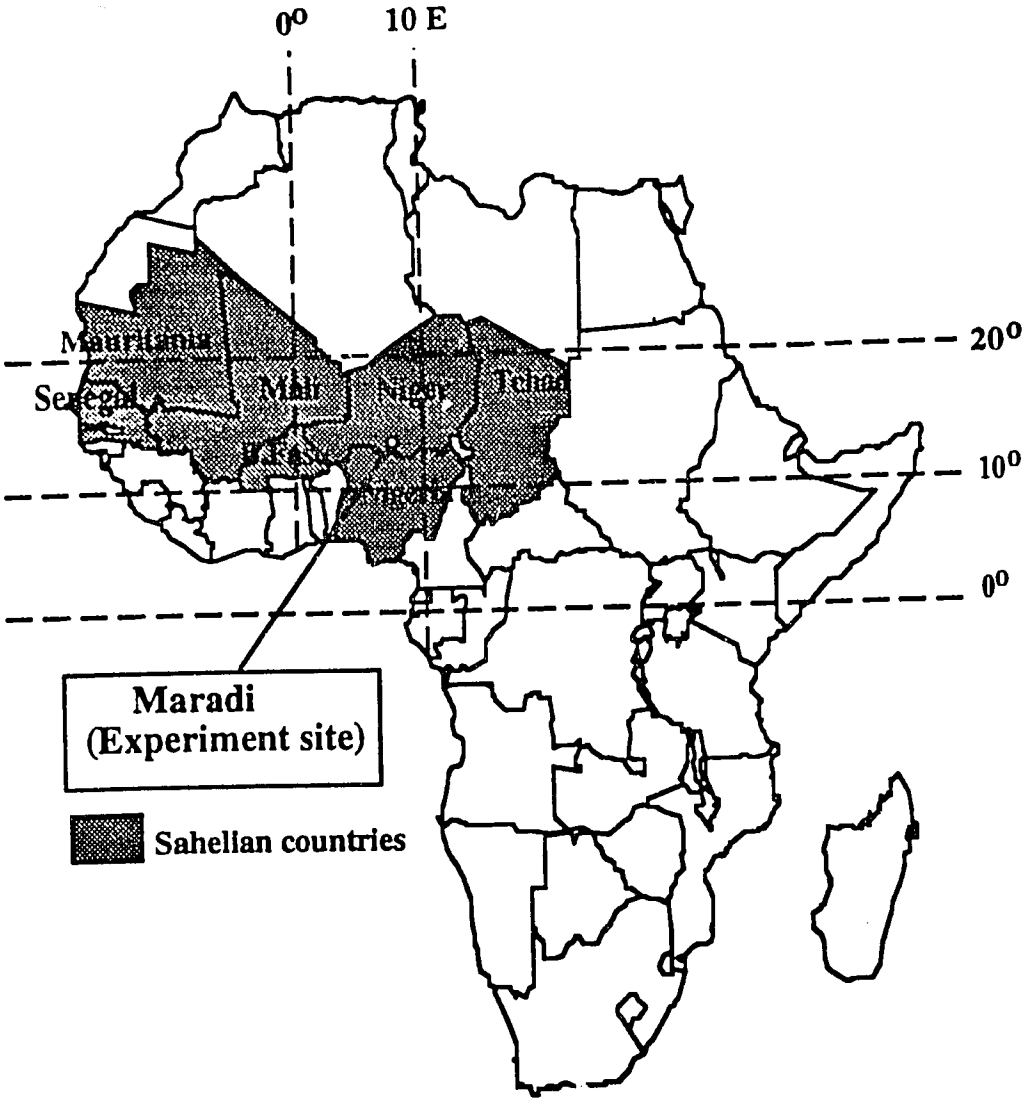

Figure 1. Location of the Sahelian countries and the experiment site (Maradi) on the African continent.

II. PROBLEM STATEMENT

Water use efficiency (WUE) can be defined as the ratio between yield (grain or dry matter) to evapotranspired or transpired water. Achieving efficient crop water use involves manipulating the soil water balance. Soil water balance is a fundamental parameter that provides valuable quantification of the fate of rainfall. The soil serves as a reservoir for water to meet plant evapotranspirational demand. Losses from this reservoir are also encountered through vapor and liquid (deep drainage) phase movements. Payne et al. (1990) attributed low WUE to deep drainage and evaporative losses. Zaongo (1988) attributed poor millet and sorghum growth to soil acidity, and aluminum and manganese toxicity. Rainfall distribution probabilities in the Sahel are reported by Konate (1984) to have a coefficient of variation (CV) as high as 45% during the growing season. However, in most cases, crop failure in many Sahelian regions has been reported by the same author to be caused by poor rainfall distribution. The lack of agreement on the causes of crop failure indicate that factors affecting crop water use efficiency are site specific. A common problem of most cereal crop production systems in the Sahel is inefficient water use. To improve WUE and its effect on nutrient uptake by crops a better understanding of water dynamics and balance of Sahelian agroecosystems is needed. General scientific principles and agronomic innovations from temperate regions that are often derived from single factor-based research may be applied to the Sahelian crop production systems. However, failure to consider the total environmental conditions and interactions may lead to further misuse of limited resources in the search for solutions to the severe constraint of plant moisture deficit in the Sahel.

When the water balance of a soil is considered along relevant soil, crop and weather characteristics a good understanding of the ecosystem function can be provided. From the water balance knowledge base appropriate attempts can be made to systematically manipulate the soil-plant-atmosphere water relationships in order to improve crop WUE. One problem is the fact that this knowledge base is not available for the Sahelian agroecosystem.

Recent cereal crop studies in the Sahel have focused on increasing crop yields by solving specific yield-limiting problems such as developing high yielding cultivars (INRAN, 1986), nitrogen (N) and phosphorus (P) nutrients (INRAN, 1988; Bationo et al., 1988), improvement of soil moisture availability with techniques such as surface catchments and mulches with crop residues (Zaongo, 1988; TropSoils, 1991). Many crop water related studies evaluate and report crop performance in terms of WUE without mentioning the water budget allocated to the crop. Rainfall or irrigation water applied need to be included to provide an accurate description of water use in field crop production systems. To date, no study has attempted to characterize the agroecosystem in terms of (1) integrating the variables that operate and regulate the ecosystem, and (2) evaluating the total productivity as it relates to the sustainability of the farming system in question. For a given water budget, improved WUE may be only

achieved by manipulating the soil water balance. The soil water balance may in turn be manipulated via the energy balance. For example if the energy balance is known and since heat is required for water evaporation at the soil surface, soil evaporation can be reduced by decreasing heat transfer from the air to the soil. The efficiency of such attempt in terms of water conservation can be quantified thereafter. Such a manipulation may require deliberate alterations of the system energy and water balance via interferences such as mulch application and supplemental irrigation. Manipulation is site specific and may also be done through assuring plants have adequate nutrients.

Characterization of the water relationships mentioned earlier are only limited in space and time when it is uniquely based on experimental data. The scope of the global system analysis and experimental data interpretation may be considerably improved over time and space by the use of a predictive and analytical tool such as modeling. Modeling can provide short and long term insights that may not be available otherwise or from field experiments. For this stand point the problem is the fact that even though such avenues are appropriate and can lead researchers more quickly to positive solutions they have been neglected, yet need to be developed for the Sahelian agroecosystems.

Before formulating hypothesis and research objectives to the problems discussed above it is appropriate to present the Sahelian agriculture and cereal crop production agroecosystem. The soil-plant-atmosphere water relationships, cereal crop water use efficiency, and soil water balance are also reviewed.

III. LITERATURE REVIEW

A. Agriculture in the Sahel

The Sahel region in Africa is defined on the basis of the long-term annual rainfall (Konate, 1984). A summarized definition of the Sahel is the semi-arid tropical region that extends from the Atlantic to the Sudan, between 8 and 16° N (Fig. 1). Between 80 to 90% of the Sahel inhabitants are subsistence farmers who produce rainfed millet and sorghum. Agriculture accounts for 44% of gross national product and 90% of the national work force (Bairs, 1987). Most of the rainfed production occurs south of the 300 mm rainfall isohyet. For example, in Niger only one third of the total 1,267,000 km^2 is arable; the remainder is desert. Farming remains a life style with technology levels ranging from manual to animal traction. All production systems are based on low or no purchased input.

Most of the Sahelian agricultural production relies on rainfall and is therefore subject to the risk of failure associated with drought. The need to reach self-sufficient grain production in the Sahel requires alternative production systems that broaden the current Sahelian agricultural frontier FAO, 1981; Fisher et al. 1978). To stabilize production in this region requires identification and characterization of the predominant rainfall-soil-crop relationships in each system. Therefore, to understand the scope of that challenge the entire soil-plant-atmosphere of the agroecosystem needs to be examined.

B. The Sahelian agroecosystem

1. The soils

In the Sub-Saharan Africa, about 44% of arable land is devoted to sorghum (Ryan and Oppen, 1984). With the growing population and deteriorating environment in the Sahel, it is projected that future food requirements will need to be met by increasing production per unit land area (FAO, 1989). Most arable uplands in the Sahel, particularly in Niger, are primarily sand or loamy sands reworked by wind erosion. Sand content in the sandy soil is usually higher than 80%, and the soils are used primarily for millet production. Significant investigations of crop water and nutrient use have been conducted on these soils in the past decade (Hartman and Gandah, 1982 ; IFDC/ICRISAT, 1986; Payne et al., 1990; Wendt et al., 1988; Zaongo, 1988; Franqin, 1984; Bationo et al. 1988; Onken and Wendt, 1989; ICRISAT, 1990). These studies suggest that rapid hydraulic conductivity and low water holding capacity constitute the main physical constraints associated with these soils (Payne et al, 1990, 1987; Zaongo, 1988). Main chemical soil constraints include N and P deficiencies, high acidity, and high aluminum (Al) and manganese (Mn) toxicity (Wendt et al., 1988).

Soils in lowlands are usually clayey alluvial deposits with higher fertility and higher soil pH. These soils are used primarily for sorghum, corn, cotton, and sugar cane production. Few investigations have been conducted in these soils. The physical, hydrological, and chemical characteristics of these soils are different from sandy upland soils (TropSoils, 1989). Higher clay and silt accumulation from alluvial deposits causes water movement in these soils to be slower, and water and nutrient holding capacity to be higher than in sandy upland soils. Even though those soils are considered to be marginal because their total area is lower than the area of upland sandy soils they offer a significant production potential. Therefore, with the increasing food requirements in this region, these soils will play an increasing role in future agricultural production.

Soils in the Sahel exhibit chemical characteristics (pH, nutrient status, Mn and Al toxicity and surface crusting) that vary between sites. Variability between sites can be so drastic that it completely changes the management requirements Wilding et al. 1989. Therefore, before any water and/or nutrient management can be developed for a given site, the specific soil characteristics must be determined and understood so that the research findings can relate better to other sites.

2. The sorghum plant

Even though recent research by local institutions (INRAN, 1988; ICRISAT, 1989) have focused on millet grown on sandy soils, sorghum offers a great potential for increased grain production in the Sahel. Domesticated sorghum originated in tropical Africa (Coopération Française, 1974). Native sorghum is primarily a short day plant, but most domesticated varieties are day neutral. It is well adapted to the semi-arid tropics and is cultivated in the rainfall isohyet from 300 to more than 800 mm. It is extensively grown in regions that are either too hot or too dry for corn production. Grain yield ranges from more than 4800 kg ha^{-1} in North America to less than 400 kg ha^{-1} in the Far East with a world wide mean estimate of 750 kg ha^{-1} (Arnon, 1972). Grain sorghum can be grown on a wide variety of soils provided they are fertile and in good tilth. However, soil pH has a major effect on sorghum growth. Optimum soil pH ranges from 7 to 9 and values of pH lower than 4.5 cause drastic yield reduction due to poor root growth (Tarr, 1962). It is grown in Africa for human (grain) and animal (leaves) consumption, as well as for combustion and construction material (stalks). Most varieties require air temperatures between 27 and 30°C and a growth period of about 110 days (Quinby et al., 1958). However, selection over extended periods has led to adapted local varieties with a reduced growth period (as short as 80 days) and higher tolerance to heat. In Niger, grain sorghum is usually produced under manual cultivation without fertilization, and with a low plant density, e.g., 10,000 to 15,000 hills ha^{-1}. The national research institute (INRAN) recommends 45 kg ha^{-1} nitrogen as urea or calcium ammonium nitrate and 22.5 kg ha^{-1} phosphorus as triple super phosphate.

Sorghum leaf morphology and orientation, combined with its extensive rooting system, provide this crop with a marked resistance to drought. Adaptation mechanisms such as leaf curling, cuticular stomata regulation during vegetative growth, wax, rapid and conservative reactions to stress and physical injuries, and capability to withstand extended flooding are unique features to sorghum (Tarr, 1962). Studies conducted by Glover (1957) showed that sorghum is able to recover after a severe water stress period lasting 14 days or more. The rooting system of sorghum plays an important role in the WUE of sorghum. Sorghum has a very effective rooting system for extraction of water and nutrients compared to other cereal crops. It has twice as many secondary roots as corn (Gloveer, 1957), yet only 1.5 times the leaf area of corn. Studies on sandy Sahelian soils have indicated that sorghum maximum rooting depth can exceed 2 m (Zaongo, 1988) and lateral spread can exceed 0.9 m from the stalk.

Even though sorghum has resistance to moisture stress, drought periods in the Sahel can be severe enough to cause frequent crop failure. In dry land production, sorghum yield on fertile soils is closely related to soil moisture, particularly at sowing time (Cooperation Française, 1974). Within the 350 mm critical limits, every additional mm of water from rainfall or irrigation above the minimum requirement may result in an additional production of 10 to 20 kg ha^{-1} of grain. Important sorghum production factors in the Sahel are rainfall distribution, soil fertility particularly P nutrient (Bationo et al., 1988), plant density and rooting pattern (Zaongo, 1988) that determine the ability of the crop to use seasonal rainfall (Sivakumar, 1989).

Many sorghum varieties have been improved, introduced, and bred in the Sahel (INRAN, 1990). However, due to food habits and specific local needs, the highest yielding varieties are usually not the most desired ones. Many "improved" varieties or hybrids have been rejected by farmers after tedious and costly selection efforts. Not only do local varieties selected by the farmers meet their needs better, but they have proven themselves to be best adapted to local environments. Therefore, local varieties should not be overlooked. Instead, they should be given first priority in agronomic experimentation.

3. The Sahelian weather

Sahelian countries are characterized by two weather types, a rainy season and a dry season. The rainy season prevails from June to September and the dry season from October to May. The dry season is cool from November to February and hot during the remainder of the time.

Air circulation is fundamental in the characterization of the Sahelian climate. This circulation determines the occurrence and duration of the rainy season. Konate (1984; Forest and Lidon, 1982) described the earth's rotation and the temperature difference between the tropical and polar regions as being the primary causes of air circulation in the African continent. He suggested that weather changes in west African tropics are brought by three subtropical anticlones, Azores, Libyan, and Saint Helena. Air tends to subside, resulting in gradual hot and dry air accumulation in these cyclones. High

atmospheric pressure causes this air to escape towards the north and the equator. The earth's rotation deflects the escaping air that deviates to the right in the northern hemisphere and to the left in the southern hemisphere. In the northern hemisphere this air gives rise to the hot and dry trade winds that blow from northeast to southwest. Resulting hot and wet trade winds in the southern hemisphere blow from southeast to northwest. The two different air masses collide at the Inter-Tropical Conversion Zone (ITCZ), also called the Inter Tropical Front (ITF). The ITF is built up along the equator and moves from north to south depending on the season and the direction of the three anticlones, closely following the change of the sun position with a six-week delay. It moves up to 20 to 25° N longitude in August. During this period heavy rainfall is brought by the Saint Helena anticlone which has loaded moisture while passing over the ocean (monsoon). In January the ITF reaches 5° N pushed by the Libyan anticlone from north to northeast and the Azores anticlone from north to east.

The dry hot dusty current from the eastern sector is a typical sahelian wind called the harmattan that blows from November to May. The ITF is also an atmospheric phenomenon characteristic of the Sahel. It governs the Sahelian climate by dictating rainfall. The ITF consists of longitudinal bands of cumulonimbus clouds moving from east to west and bringing in most of the moisture. Rainfall occurs only south of the ITF, therefore, only during northward movement of the ITF (from July to September) for the Sahel. Large scale geographic uniformity of the region insures a regular rainfall pattern associated with this movement.

Rainfall remains the governing agroclimatic feature in this region. Even though climate is barsh (Bairs, 1987), total rainwater supply is sufficient for cereal crop production (ICRISAT, 1978). In 1950 rainfall was 250% the annual mean in the whole region. However, rainfall was below average in 1970 in the whole region. Since 1969 annual rainfall has been 20 to 40% below normal. In addition, high air temperatures, intensive global irradiance and strong winds induce high annual potential evapotranspiration. This has also led to the definition of the Sahel as the tropical African region north of the equator where annual potential evapotranspiration ranges from 1600 to 2200 mm (Dancette and Hall, 1989). Due to erratic rainfall and intensive solar irradiance, water dynamics tend to be rapid in the Sahelian agroecosystems.

4. The soil-plant-atmosphere relationships

Although soil fertility tends to be poor and water dynamics rapid, the cultivated crops in this ecosystem are highly adapted to this harsh environment of poorly distributed rainfall, prevailing high evapotranspiration demand, and low soil fertility. Given the high evapotranspirational demand and the irregularities in rainfall distribution and amount since 1969, many researchers (Frere, 1972; Forest and Lidon, 1982; Konate, 1984; Sivakumar and Wallace, 1991) have suggested a definition of the Sahel based on the duration of the growing season. Soil moisture availability has therefore been the main

criterion in Sahelian agriculture. This has led to the definition of the Sahel as the African Soudano semi-arid tropics with a growing season ranging from 60 to 150 days (Sivakumar, 1989). Furthermore, it illustrates the need to examine each production system in terms of the interactions of soil, plant and atmospheric components, rather than the classical examinations of isolated variables. However, many reports on drought are misleading, tending to reflect farmers' perceptions that are biased towards blaming climate (INRAN, 1989; Coopération Française, 1974). Climate is often blamed for drought by those who fail to appreciate land use relationships and the interactive components of the ecosystem on the water balance. Due to the climate, soil, cultivated crop species, and the production systems, the Sahelian agroecosystems have unique characteristics. Detailed characteristics of the ecosystem in the Maradi region are presented in Table 1. With the lack of both the quantitative effects of the soil-plant-atmosphere continuum (SPAC) relationships manipulation and the soil water balance and a consideration of the site specific problems of the Sahelian soils, such biased views will prevail.

Climatic drought is a cyclic phenomenon (Cocheme and Frankin, 1967; Nicholson, 1983) and the associated risk is part of Sahelian agriculture. Sustainable agriculture cannot be achieved without a thorough characterization and management of this constraint. Plant breeding has been the predominant discipline in both national and international centers. Unrealistic goals such as drought resistance, have been expected from the breeders (Sanders, 1988). Local farmers have developed various empirical strategies such as multiple cropping, different sowing dates, specific land allocation to crop varieties, plant densities, and selection of short growth cycle varieties to avoid this climatic risk (Z), but most of the strategies are oriented towards rainfall distribution rather than the subsequent dynamics of rainfall. Despite extensive and costly research work, drought still remains the threat it was in the late 1960's.

The importance of soil water is obvious from the definition of the Sahel as a semi-arid region. Water related studies can be severely limited by extended drought that may prevent crop establishment (TropSoils, 1989, INRAN, 1988). To enable adequate water studies in the Sahelian ecosystems additional means other than the usual cultural practices are often required.

Supplemental irrigation can constitute a valuable tool (Hanks et al., 1976) in regions like the Sahel where moisture deficit can interfere severely with crop establishment and impede with crop water use studies. Given this risk of crop failure, supplemental irrigation is a required tool for crop water use studies such as this one. By applying different amounts of supplemental irrigation water, various rainfall distribution patterns can be simulated therefore offering the possibility of studying the effects of different levels of moisture stress to plants during a single rainy season (O'Neil et al., 1980; Miller and Hang, 1980, Hanks et al., 1976; Krishna, 1980). There is a risk of salinization

Table 1. Summary of reported agroclimatic features of the Maradi area.

Parameter	Value
(World Meteorology, unpublished)	
Latitude	13.28° N
Longitude	7.05° E
Altitude above sea level	371 m
Atmospheric CO_2 concentration	3.4 10^{-4} L L^{-1}
Maximum daily air temperature	40.6° C (April)
Minimum daily air temperature	30.6° C (August)
Soil albedo at saturation	0.13
Water table depth	>15 m (from dune soils)
Mean relative humidity	75% (July-September) 50% (May-July) 40% (October-November); 20% (December-April)
(Konate, 1982)	
Rainfall isoyet	640 mm
Start of rainy season	05/15
Planting period	07/11 - 09/10
End of rainy period	10/09
End of growing season	10/18
(ICRISAT, 1990)	
Probability of dry spell >5 days during the rainfall season	60 - 70%
Probability of dry spell >20 during the rainfall season	28 - 36% d
(INRAN, 1990)	
Mean annual number of rains	27 - 38
Mean rainfall duration	1.5 h
Mean rainfall intensity	25 mm h^{-1}
Surface soil texture	sand
(Aéroport Maradi, 1991)	
Mean annual wind speed	8 m s^{-1}
Mean annual heat units (15°C)	9833°C
Mean daily insolation	9.2 h
Mean PET	2 - 12 mm d^{-1}
Hargreaves (1982)	
Growing season PET	720 mm
Annual PET	2055 mm
Cocheme and Fraquin (1967)	
Mean daily solar irradiance	18-21 MJ m^{-2}

associated with irrigation, but unlike full irrigation, this risk is lesser with supplemental irrigation (Miller and Hang, 1980).

5. Sorghum water use efficiency in the Sahelian agroecosystem

Kanemasu et al. (1984) compared yield and WUE of sorghum and millet in the Semi-Arid Tropics (SAT). They found that sorghum had a higher yield and WUE than millet. Mean grain yields for millet and sorghum were 2.3 and 6.1 Mg ha^{-1}, respectively. From the same study grain WUE and dry matter WUE for millet were 5.8 and 31.7 Mg ha^{-1} m^{-1}, and for sorghum the corresponding values were 12.8 and 44.1 Mg ha^{-1} m^{-1}. The same trend was found throughout the SAT region by Konate (1984). While mean millet yield in farmers' field was 610 kg ha^{-1}, sorghum yield was 950 kg ha^{-1}. Millet yield in African farmers' field is projected by Ryan and Oppen (1984) to increase from 610 kg ha^{-1} (1990) to 770 kg ha^{-1} (year 2000). For the same period sorghum yield is projected to increase from 950 kg ha^{-1} to 1100 kg ha^{-1} (Ryan and Oppen, 1984).

Within the Sahelian rainfed area (350 - 900 mm annual rainfall) grain sorghum yield is lesser than 1.5 Mg ha^{-1} (INRAN, 1990) while it can reach 12 to 15 Mg ha^{-1} (ICRISAT, 1990). The literature review on soil and climate (Barrow, 1987; Cocheme and Franquin, 1974; Frere, 1972; INRAN, 1988, ICRISAT, 1989; Konate, 1984) suggested that water use sorghum in the Sahel may be inefficient due to soil nutrient deficiency and poor rainfall distribution that result in low crop water availability. Water use efficiency (ratio of biomass production to evapotranspiration or transpiration) of grain sorghum depends on many factors, such as, soil physical and chemical environment, air temperatures, nutrient availability, and water availability (Parameswana et al. 1981). Under favorable soil and climatic environment such as those of the Sahelian agroecosystem studied, water and nutrient availability are the most important factors in evapotranspirational water use efficiency (WUE(ET)). Under rainfed conditions Onken and Wendt (1989) found significant positive effect of increasing N on grain WUE(ET) of four genotypes in conditions similar to that of the Sahelian agroecosystem. Besides nutrient crop WUE(ET) depend largely on crop transpiration. For a given cultivar increased plant transpiration within the same environment usually is an indicator of increased biomass production. Low crop transpiration may be caused by water losses from runoff, evaporation, or deep drainage that prevents rainfall from being available to the plant. It can also be caused by unfavorable soil physical or chemical environment or nutrient deficiency that prevent the crop from using soil available water. Low crop water use, due to unfavorable physical and chemical environment prevail primarily on the upland sandy soils. The main ones are soil acidity, Al and Mn toxicity, and high soil temperatures (Zaongo, 1988).

Three important sources of water losses in Sahelian lowlands are runoff, evaporation and drainage below the crop rooting depth (Payne et al. 1990; Zaongo, 1988). Lower infiltration rate on lowland soils may cause occasional runoff. However, with proper surface soil control run-on such as ridging

runoff is easily controlled on these soils. In terms of water availability, evaporation and drainage are the primary sources of concern.

Transpiration from a crop is a necessary and desirable physiological process associated with crop growth. Investigations on transpiration and above ground biomass production lead by De Wit (1958) suggest that transpirational water use efficiency (WUE(T)) may be standardized by:

$$WUE(T) = M / E_O \qquad [1]$$

where M is a constant associated with the crop species (kg ha^{-1} d^{-1}), and E_O is the relative mean daily atmospheric evaporative demand (m d^{-1}) as determined by pan evaporation or potential evapotranspiration, or vapor pressure deficit (MOnteith and Unsworth, 1990). The term E_O can be used to standardize the value of M between different sites. Equation [1] suggests that from an agronomic point of view, WUE(T) for a given crop can be manipulated only by changing evaporative demand. However, increased WUE(T) may be the result of reduced growth characteristic of disastrous yields. Therefore, it is appropriate to pose the question how increased grain sorghum transpiration in the Sahelian ecosystem affects yield and WUE(T).

Soil evaporation (E) in contrast to crop transpiration (T) is a loss that needs to be controlled in order to maximize crop available water. Water evaporation (from the soil or the crop leaf) requires energy referred to as the specific heat of vaporization. The basic relationships between the forms of energy involved in the soil-plant-atmosphere continuum are described by the energy balance.

$$R_n = G + LE + H + P_s + C_s \qquad [2]$$

where R_n is the net radiation (MJ m^{-2} h^{-1}), H is the sensible heat flux to the air (MJ m^{-2} h^{-1}), LE is the latent heat of vaporization (MJ m^{-2} h^{-1}), G is the sensible heat to the soil (MJ m^{-2} h^{-1}), P_s is the energy used for photosynthesis (MJ m^{-2} h^{-1}), and C_s is the energy stored in the crop (MJ m^{-2} h^{-1}). P_s and C_s account for about 2% of R_n and are considered to be negligible (Monteith and Unsworth, 1990)). This assumption can be easily justified when one takes into account the experimental error associated with the determination of the other components. Input energy is provided by net irradiance (R_n) from the sky. Since soil evaporation requires energy and the source of this energy is known, one way of reducing soil evaporation is to prevent or reduce the energy input to the soil, hence reduce radiation energy transfer to the soil. When such an interference with the energy balance is effective, less heat is transmitted to the soil surface, and consequently soil surface temperature is reduced (Hillel, 1980). In addition, less heat is stored in the soil and there is less heat flux (latent heat flux) from the soil surface to the air. The interference can be achieved by introducing mulch on the soil surface. Many types of mulches can be

used for specific purposes. The characteristics of the mulch play an important role in the energy and water balance. Impermeable mulch such as plastic films can be used as a physical barrier to water vapor movement. This form of mulch is costly and very effective under ideal conditions. However, should it accidentally have a leak or be broken at some point, it becomes inefficient. Transparent films tend to create a greenhouse effect and increase surface soil temperature. Partial soil surface coverage with crop residue may provide shading and greater albedo (hence greater radiance reflection and cooler surface soil) when the albedo of the residue is greater than that of the bare soil. Research conducted by INRAN (1989) on mulching with crop residues suggested a minimum application of 8 to 10 Mg ha^{-1} sorghum and millet residues for significant conservation of surface soil moisture. In addition to the effects mentioned above, increased surface soil roughness from crop residues mulch tends to reduce wind speed at the soil surface and therefore reduce turbulent water vapor transport away from the soil surface (Heilman et al. 1992).

High hydraulic conductivity on these soils may also contribute to some drainage losses (Payne et al. 1990). Water harvesting studies conducted by Zaongo (1988) in the Sahel suggested that sorghum crop roots may not always follow the seasonal wetting front. This suggested that in instances when the maximum wetting front is deeper than the maximum rooting depth drainage occurs and can account for a significant portion of the water budget. Therefore, it is appropriate to question the occurrence and extent of drainage losses in the Sahelian agroecosystem.

Phosphorus (P) and nitrogen (N) are the major deficient soil nutrients on both upland and lowland soils (Bationo et al. 1988). Deficiencies of these two elements are often the causes for low sorghum biomass yield and low water use efficiency in the Sahel (Bationo et al., 1988; IFDC/ICRISAT, 1986; Zaongo, 1988). Many studies (De Wit. 1958; Fisher and Turner, 1978) suggested that nutrient availability increases WUE(ET). These studies attributed increased WUE(ET) to reduced soil evaporation caused by higher leaf index (LAI). This is another advantage of vigorous crop growth associated with proper nutrient supply. Further, they suggested that WUE(T) is reduced only when nutrients become deficient. Recent studies suggested that mild nitrogen deficiency may affect WUE(T). By including root mass in the evaluation of WUE(T) Onken and Wendt (1989) found significant differences among grain sorghum cultivars WUE(T). They also found that fertilizer and water availability interact to a point where water becomes limiting. Beyond that point, increased nutrient input does not cause either higher yield or higher WUE(ET). Further, recent studies with nitrogen by Parameswaram et al. (1981) found highly significant interaction between nitrogen and water treatment on grain and straw WUE(T) of wheat. Therefore, it is appropriate to investigate whether grain sorghum and WUE(T) may be limited by poor soil fertility.

C. Modeling of Sahelian soil water balance and crop water use

1. Scope of modeling

Models can be classified in three broad types: empirical, object-oriented, and mechanistic (Van Bavel and Lascano, 1987). Empirical modeling involves the development of fitted curve and regression relationships for descriptive projection within the scope of these relationships, estimation of missing data, and prediction of value from other data. Due to its empirical nature this type of model may not take into account fundamental processes involved in these relationships, therefore, they may lead to the development of erroneous relationships due to the choice of the dependent variables that may be completely unrelated to the response variable. They are data summaries that may not be manipulated and are not appropriate for crop water use studies.

Object oriented models deal with individuals (one leaf, one plant, etc.) as an entity. A change of state of this entity creates demands from other entities or states. Such models are not appropriate for crop water use studies because of the involvement of many entities that can not be considered individually (crop individual leaves, root, etc.).

Mechanistic models are dynamic, with various levels of resolution, and based on given processes. They are used to explain complex systems such as the soil-plant-atmosphere water relationships. Therefore, they can be formulated before data collection. In addition, assumptions based on physical, chemical, genetic, meteorological and other data may be used. With these types of models mechanisms can be identified, understood, given a universal applicability, and therefore help form the foundation of science. Crop water use involves processes such as water infiltration, evaporation, root water uptake, and climatic as well as crop characteristics. These processes can be integrated in a mechanistic model. However, in the selection of the mechanistic model a number of criteria and theoretical considerations should be taken into account.

2. Importance of modeling for the Sahel

In the Sahel where research and development resources are limited, modeling offers an alternative to evaluate the efficient use of resources, and avoid efforts towards attractive "quick-results" that may be costly and ineffective in the long run. Models are valuable tools in the search for a better understanding of the dynamics of soil moisture and its effects on crop growth and yield (Campbell, 1985; Butler, 1989: Van Keulen et al. 1976; McCree and Fernandez, 1989; Steiner et al., 1987; Steiner, 1989). Models allow extensive and integrated studies of processes that could not otherwise be studied in an appropriate way. General procedures and recommendations in modeling the agroecosystem have been formulated by many authors (ICRISAT, 1978; Bidwell, 1977; Van Keulen et al., 1976). However,

unless they are validated with experimental data, simulation models remain gross approximations that may not be applicable and therefore may not serve their purposes (Van Keulen et al., 1976).

Modeling is a representation of an uncertain assertion about the relationships among elements or components. Two approaches may be used in modeling, inductive (combination of specific pieces of a larger system leading to generalized relationships or mechanism that are not yet understood), or deductive (general principles are used to produce results). Studying sorghum WUE requires accurate measurement and characterization of the soil water balance. The water balance components can be determined through direct measurements but these measurements are rather tedious and can be costly. In addition, a measurement collected for a given season may not be extrapolated to a different season for the same agroecosystem. Given the erratic rainfall distribution between years in the Sahel, studying the water balance of a given site may require rather lengthy and extensively repeated measures. Modeling is an effective tool that can be used to study and characterize water balance and crop WUE. It can be used to project soil water dynamics over time or simulated natural conditions that may have occurred but did not, and to interpret processes and their meaning for crop behavior and resources management. Therefore, it is a very valuable research tool that can lead researcher to productive solutions in a shorter amount of time, particularly in the Sahel where resources are limited.

3. Theoretical considerations

The first and most important characteristic of a model is its purpose. A model is appropriate only when used for its intended purpose. Transpiration and soil evaporation are necessary parameters in determining crop WUE. Therefore, establishing an accurate soil water balance is an important step. Direct soil evaporation and crop transpiration can be measured in the field but they require intensive instrumentation and lengthy measurements. Since these processes are universal and well known they can be accurately modeled, provided the necessary input data are available. When precipitation, irrigation, initial soil temperature and moisture profiles are known, evaporation (from the soil or the crop) can be predicted from weather data. This is a task for which the ENWATBAL model has been designed (Lascano et al. 1987). It is a mechanistic evapotranspiration model designed to separate calculation of soil and crop evaporation as a function of crop development and climatic conditions.

Another important parameter in modeling is performance criteria. This involves the minimum acceptance level of precision and accuracy, and the analogies between the model and the real situation. The ENWATBAL model computes evaporation based on the energy and water balance of the soil-plant-atmosphere system. For each simulation period a precision of 2 to 3% of the total amount of water in storage, or that lost by evapotranspiration is provided.

The system components in this model are the crop, soil, and weather. Therefore, it relates specifically to the real system under consideration. This model considers the crop canopy as single

layer and the soil as multiple layers with specific hydraulic properties. Water flow in the soil is considered to occur according to Darcy's law, and radiation balance based upon soil and crop optical properties (albedo and LAI). The energy balance and the transfer resistances between the soil surface and the canopy are used to calculate E and T separately (Lascano et al., 1987). In both cases transfer resistance is calculated as a function of LAI and the bare soil aerodynamic resistance. Crop root water uptake is determined by partitioning transpiration over the multiple soil layers of the root zone and as a function of relative canopy water potential, soil water potential, fractional root density, LAI, and crop hydraulic resistance.

Using E, T, and ET as criteria, Evett and Lascano (1993) performed stability and sensitivity analysis for surface roughness length, maximum crop water potential, soil reflectance to short wave radiation, and crop hydraulic resistance.

The structure of the ENWATBAL model is presented in Fig. 2. The model is formulated in four main parts: an initial part where the soil system and initial moisture and temperature status are defined, an input part where soil, crop, and weather data are incorporated, and a dynamic part where energy and water balances are computed and ET partitioned. At the end of the third part results from the simulation are stored (terminal part).

4. Model selection

Besides the desirable characteristics discussed earlier, the ENWATBAL model has been validated for sorghum crop in areas that have similar soils and weather characteristics than those of the Sahel (Van Bavel and Lascano, 1987; Krieg and Lascano, 1989). This model is a research-oriented tool that has produced satisfactory results in agroecosystems that are similar to those of the Sahel. In addition, it can run on regular micro-computers (PC), and has the potential ability to integrate the environmental conditions specific to the Sahel. Therefore, it was considered to be an appropriate model for this study.

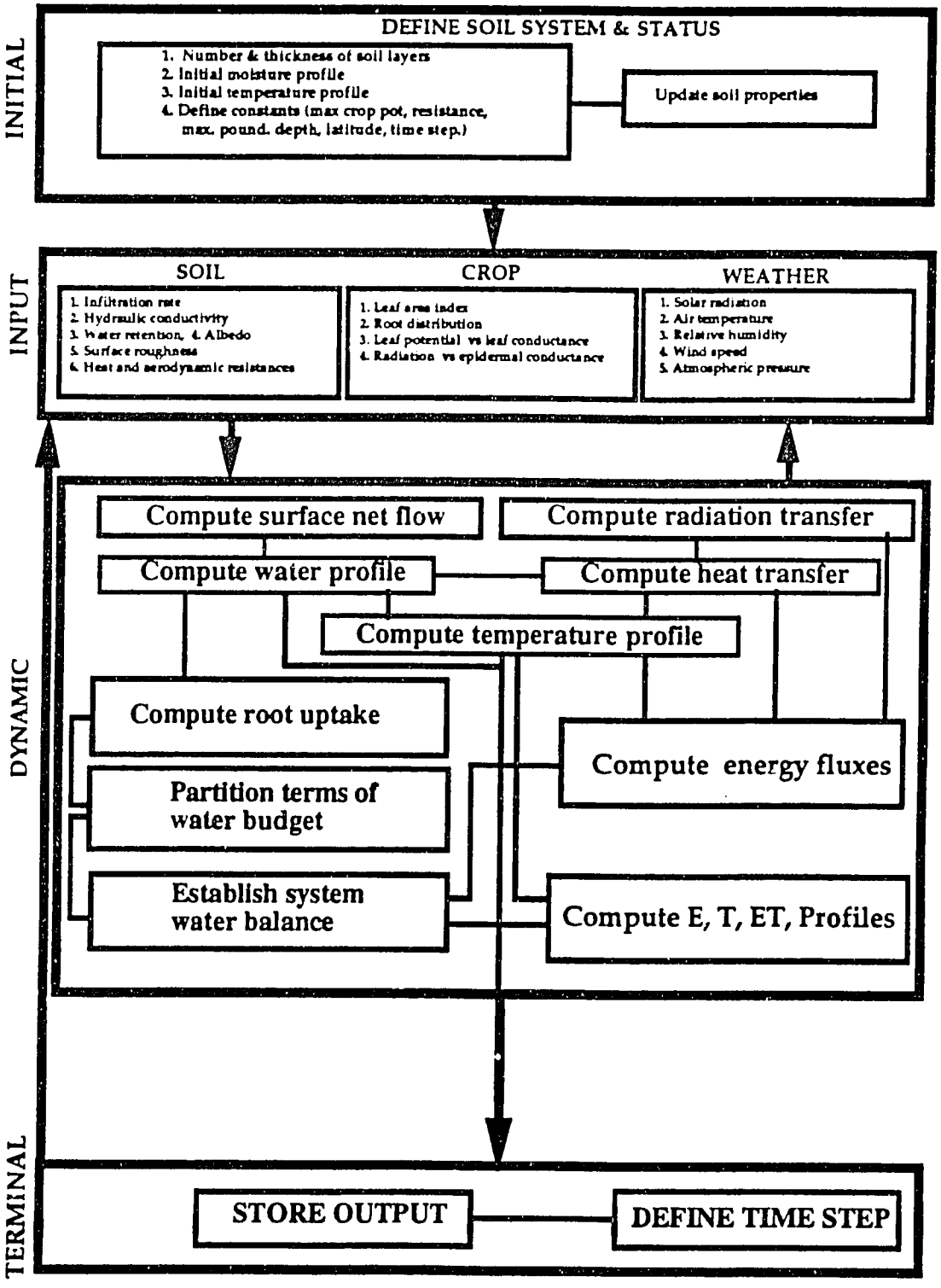

Figure 2. Simplified structure of the ENWATBAL model after Lascano et al., 1987.

VI. MATERIALS AND METHODS

A. Hypotheses

The literature review on soil moisture deficit in the Sahelian ecosystem indicated problems that cause to inefficient crop water use. The fundamental challenge is to modify the soil environment to improve crop WUE (Pathak et al., 1983). This improvement can be obtained through improved WUE(ET) and/or improved WUE(T). This requires a judicious manipulation of the soil water balance through the soil-plant-atmosphere water relationships. The overall hypothesis of this study is that the soil water balance of the Sahelian agroecosystem can be manipulated to improve sorghum WUE. The manipulation scheme is presented in Fig. 3. This manipulation is made through two main avenues, by altering the energy balance, and by altering the water balance. The energy balance can be altered with mulch which increases reflectance, reduces wind speed at the soil surface, shades the soil surface, and increases the resistance to vapor flux. The water balance can be manipulated by increasing the water budget (supplemental irrigation), an increased crop uptake and transpiration due to nutrient availability, indirect increase of infiltration and reduced surface soil evaporation due to mulch.

The literature review suggested that Sahelian soils tend to have nutrient deficiencies, particularly N. Since this nutrient is a main agronomic factor in crop WUE(ET) the first specific hypothesis is that sorghum WUE(ET) of the Sahelian agroecosystem can be improved by N nutrient input.

Since biomass production is a function of the amount of water transpired by the crop the water budget during the growth period of that crop is a determining factor for total biomass production, hence for WUE(ET). As mentioned in the literature review, the climatic risk associated with drought causes supplemental irrigation to be a necessary tool for water related studies in the Sahel. It provides additional water to the crop, therefore increasing the total water budget. The second hypothesis is that WE(ET) can be improved by supplemental irrigation.

The literature review suggested that WUE(T) can only be improved by reducing soil evaporation. The most effective way to reduce soil evaporation is to alter the soil-plant-atmosphere water relationships to reduce heat transfer from the air to the soil, and to increase the aerodynamic resistance at the soil surface. Since crop residue may be used as mulch, the third hypothesis of this study is that sorghum WUE(T) of the Sahelian agroecosystem can be improved by the use of crop residue mulch.

B. Objectives

To test the above hypotheses, the specific objectives of this study were: (1) to manipulate the soil water balance of a Sahelian agroecosystem with supplemental irrigation, mulch and nitrogen, (2) to

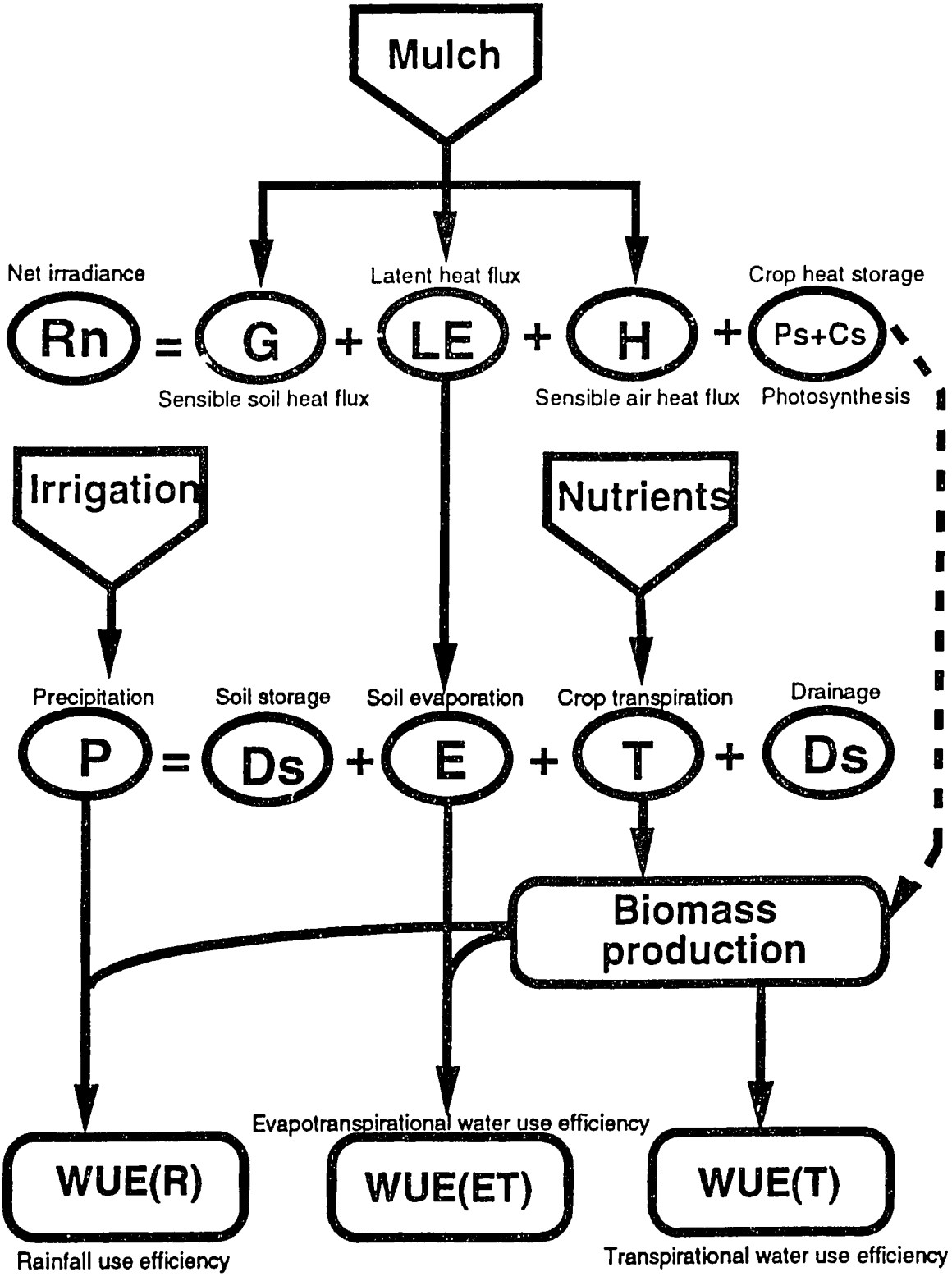

Figure 3. Energy and water balance manipulation scheme and components as defined by the study hypotheses.

characterize sorghum growth, and water use as affected by these factors, (3) to integrate the specific environmental and soil-plant-atmosphere relationships of the agroecosystem in a mechanistic model capable of predicting the water balance, soil evaporation and crop transpiration.

C. General procedure

1. Conceptual approach

Theories and concepts can be built and tested in a laboratory or in a confined system. However, with respect to the specificity of the real environment, the ultimate test is the one that takes place under field conditions. To fulfill this objective all aspects of field experiments, laboratory analysis, and scientific theories of this study were related to field conditions in the Sahelian environment. The conceptual approach and major components of the study are shown in Fig. 4. This framework is well represented in the model structure presented in Fig. 2 (page 18) and supports the fact that this model is well suited for this study.

A complete (chemical, physical, and hydrological) characterization of the soil was conducted. Crop characteristics (growth and water use) were measured in a field experiment where experimental factors consisted of supplemental irrigation, mulch, and nutrients. Weather characteristics were determined during the crop growth period. Once these characteristics were determined, they were integrated into the model to predict the water balance, soil evaporation, crop transpiration, and crop water use efficiency.

2. Experiment site

The experiment site was located 3 km east of the Goulbi river, 45 km from the Nigerian border (Fig.1), at Maradi (Tarna Experiment Station) in Niger, (West Africa). This site was located 13.28^{o} north latitude, 7.05^{o} east longitude, and at an elevation of 371 m above sea level (Aéroport Maradi, 1991).

The site has a mean annual rainfall of 559 mm. Mean annual potential evaporation is 2055 mm (Hargreaves, 1982) and the mean rainy season length is 135 to 150 days (Sivakumar, 1989). Only 35% of the annual potential evapotranspiration occurs during the growing season from June to September. Detailed characteristics of the experiment site are presented in Table 1 (page 9).

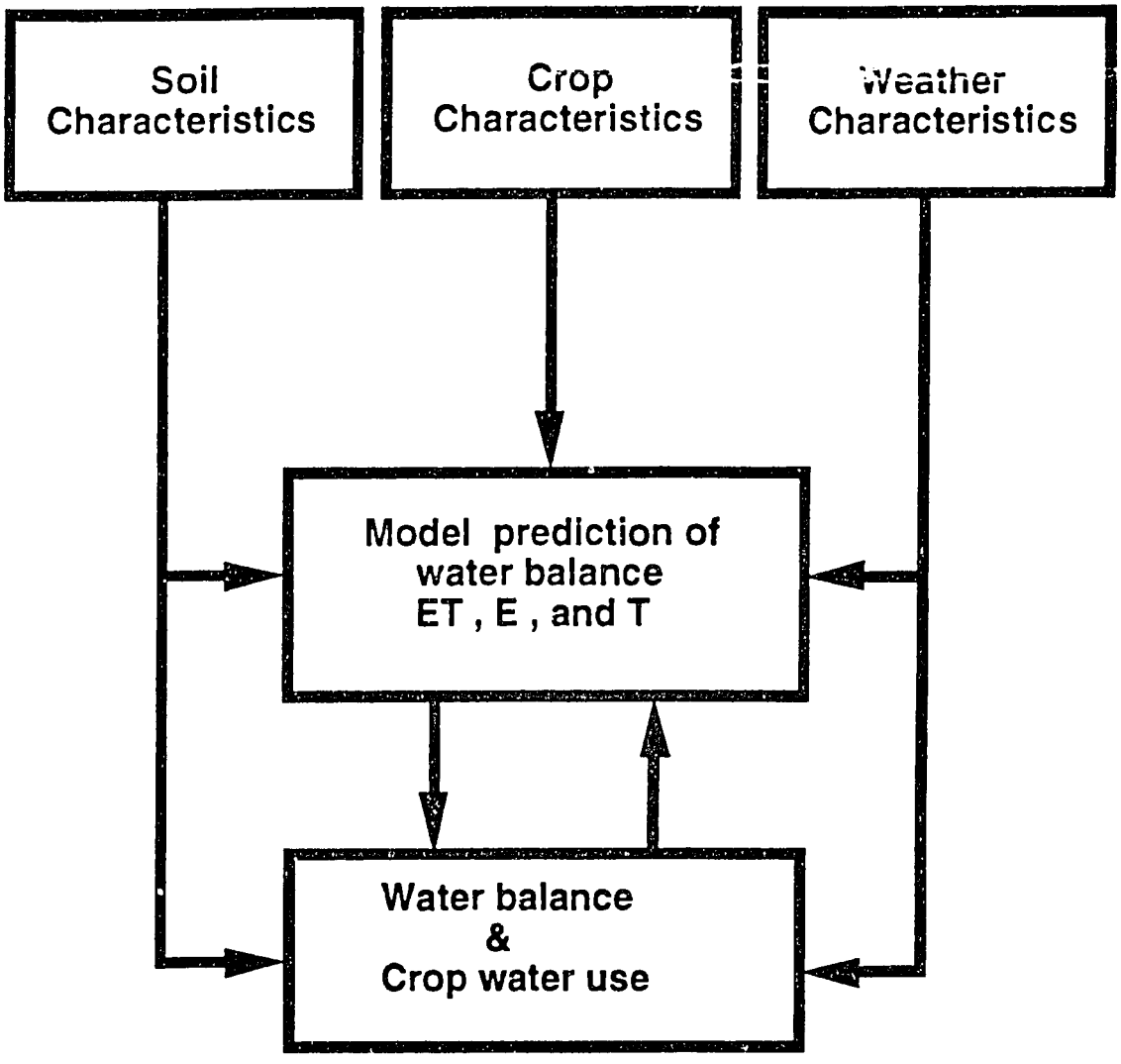

Figure 4. Conceptual approach and major components of the study.

D. Soil characteristics

1. Soil pedologic characterization

The soil of the experiment site was described using pedons excavated at the site. Undisturbed cores and composite samples were also collected for soil chemical, physical and hydrological characteristic determinations. Descriptions are presented in the Results and Discussion section.

2. Soil physical and hydraulic characterizations

Measurements included bulk density, particle size distribution (Day, 1965), water infiltration rate, water retention above -100 kPa tension, and hydraulic conductivity. Soil bulk density was measured using the ring method (Blake, 1965). For this purpose three replicate samples were collected for each soil horizon.

Water infiltration rate was measured using the double ring flooding method (Beouwer, 1982). Measurements were replicated four times on uncultivated plots before the growing season, and on both uncultivated and cultivated plots at the end of the rainy season.

Water retention above -100 kPa tension was determined by simultaneous measurements of soil water potential measurement with tensiometer and soil water content with a neutron probe. Moisture retention at field capacity of each horizon was determined gravimetrically after the soil was saturated, then covered with a polyethylene sheet and allowed to drain for two days. Water retention at remaining tensions was determined in the laboratory using pressure plates (Gardner, 1986).

Hydraulic conductivity was measured using the internal drainage method (Hartman and Gandah, 1982) based on Darcy's law. Based on internal drainage data, hydraulic conductivity at observed moisture contents was calculated as defined by Jackson's formula (Hillel, 1980) page 211:

$$K_i = K_s * (\theta_i/\theta_s) * \Sigma[(2j+1-2i) * \psi^{-2}] / [(\Sigma 2j-1) * \psi^{-2}] \qquad [3]$$

where K_i is unsaturated hydraulic conductivity (mm h^{-1}), K_s is the saturated hydraulic conductivity (mm h^{-1}), $\theta i/\theta_s$ is the water ratio, ψ is the actual moisture tension (-kPa), i and j are indices of soil moisture content range. The concept of the Phillip's model (Jury et al., 1991) was used to determine saturated conductivity of the surface soil layer. Saturated hydraulic conductivity was derived as the asymptotic limit of water intake rate, from the water intake regression equation as a function of the inverse of square root of time when time tends to infinity:

$$K_s = \lim_{t \to \infty}(K_o + S * (t)^{-0.5}) \qquad [4]$$

where K_s is the saturated hydraulic conductivity of the surface soil (mm h^{-1}), K_o is a constant, S is the soil sorptivity (mm $s^{-0.5}$), and t is time (h). This calculation was made for each soil horizon previously described.

3. Laboratory soil characterizations

Two types of soil samples were collected: (1) undisturbed cores from each soil horizon as defined by the soil description for pore size distribution and moisture retention determination, and (2) composite profile samples collected from each horizon of the pit.

Particle size distribution was measured in the laboratory using the hydrometer method (Day, 1965). Moisture retention function below -100 kPa pressure was measured using pressure plates (Richards, 1965). Specific tensions were: -2000, -1500, -1000, -500 and -100 kPa.

Total porosity (Jury et al., 1991) was calculated from bulk density data:

$$\Phi = 1 - (\rho_b/\rho_d) \qquad [5]$$

where Φ is the total volumetric porosity fraction, ρ_b is the soil bulk density (Mg m^{-3}), and ρ_d is the soil particle density (Mg m^{-3}).

Many methods are available for the measurement of pore size distribution, e.g., computed tomography (Warner et al., 1989), image analysis and water retention (Bui et al., 1989), water desorption and mercury intrusion (Danielson and Sutherland, 1982), and resin cast techniques (Tippkotter, 1983). These methods require extensive equipment or lack the precision to quantify the pore size distribution (Radulovich et al., 1989). In this study, soil pore size distribution was determined using the water breakthrough curves method described by Radulovich et al. (1989). The method is relatively simple and is based on dynamic measurements, making them more applicable to water flow models. The method is based on the capillary rise theory as applied to the ink-bottle model of water retention (desorption); e.g., water is retained in a pore of a given diameter until the condition defined as follows is true:

$$\gamma_a < \gamma * \mathrm{Cos}\alpha / (\rho w * g * r) \qquad [6]$$

where γ_a is the applied tension (J m^{-2}), γ is the surface tension (J m^{-2}), α is the angle of contact of water to the surface of the pore (radian), ρw is the water density (Mg m^{-3}), g is gravity acceleration (m^2 s^{-1}), and r is the radius (neck) of the pore corresponding to an equivalent capillary tube (mm). Therefore, at a given applied tension the radius r is defined by:

$$r = (4 * \gamma_a * 10^5)/(\rho_w * g * \psi) \qquad [7]$$

where, ψ is the matrix suction (cm water) and γ_a is the applied tension (cm water). Based on Eq. [7], the relative change of pore radius, with tension gradient, was measured from the moisture desorption function for each soil horizon.

Macro-aggregation measures aggregates of particles less than 50 μm in diameter. It was used to evaluate the degree of aggregation of fine particles. This parameter is closely related to the behavior of organic matter and clay, controls soil permeability, particularly in sandy soils with low organic matter content (Kemperan and Rosenau, 1982). Using the hydrometer method, both dispersed and non-dispersed samples were used to determine percent macro-aggregation. Macro-aggregation was used as an index of soil structure in the field. Under field conditions, the wetting process (especially from raindrops) causes dissolution and/or flexibility of cementing agents. It also causes a pull of water between the clay plates by ion hydration and osmotic forces, and disintegration of aggregates by air trapped within the aggregate. These processes are the primary destructors of soil structure, particularly at the soil surface. Wetting (wetting sieve method) was used as a disintegration force for this measurement (Kemperan and Rosenau, 1986).

In addition to physical and hydrological characteristics, composite samples were collected for laboratory chemical analysis. These analyses included pH, total N, Bray-1 extractable P, cation exchange capacity (CEC), exchangeable bases, and organic matter content. Four replicates of each sample were analyzed.

Soil pH in water was determined at a 2:1 ratio using a glass electrode-calomel pH meter (McLean, 1982). Total nitrogen was measured by wet oxidation using the Kjeldahl method (Bremner and Mulvaney, 1982). Extractable phosphorus was measured using the Bray 1 method (Bray and Kurtz, 1945). Cation Exchange Capacity (CEC) was measured using the Polemio and Rhoades (Thomas, 1982) recommended for arid soils. Exchangeable bases were measured using the ammonium acetate method (Richards, 1965). Soil organic matter content was extracted with sodium hydroxide and sodium metaphosphate as described by Schnitzer (1986).

Sodium absorption ratio (SAR) of each horizon was determined from soil paste extract and calculated as defined by Bolt and Buggenwert, 1978):

$$SAR = Na / ((Ca + Mg)/2)^{0.5} \qquad [8]$$

where SAR is expressed in $mmole^{0.5}\ l^{-0.5}$, Ca and Mg are concentrations of calcium and magnesium respectively ($mmole\ l^{-1}$).

Exchangeable sodium percentage (ESP) was calculated as:

$$ESP = 100 * Na / CEC \quad [9]$$

where ESP is expressed in (%), Na is the exchangeable sodium concentration (cmole (+) kg^{-1}), and CEC is the cation exchange capacity (cmole (+) kg^{-1}).

E. Crop characteristics

1. Cropping

In this study a local sorghum variety "Mota Maradi" was used. This is a tall sorghum, about 2.1 m at maturity with a reproductive cycle of about 95 days and described to have a potential yield of 3 tons ha^{-1} under favorable conditions (INRAN, 1989). This variety yields an average of 800 to 1500 kg ha^{-1} in farmers fields.

2. Treatments

In the rainy season two water levels were assigned to main plots: (1) rainfall with no supplemental irrigation, and (2) rainfall plus irrigation to field capacity when soil moisture content reached a predetermined management allowed deficit (MAD) limit. The second factor in this study was nitrogen (N) fertilizer. It consisted of two rates of 0 and 50 kg N ha^{-1} as calcium ammonium nitrate ($C_aCH_3NO_3$). The 50 kg N ha^{-1} was split into two applications of 25 kg ha^{-1}, and applied the third and tenth week after sowing. Phosphorus is one of the limiting factors in crop production in Niger. To avoid confounding effects that could undermine the main experimental objectives, an application of 23 kg P_2O_5 ha^{-1} as triple superphosphate (TSP) was made on all plots as recommended by INRAN's previous studies. The third factor studied was mulch, with a mixture of 50% sorghum and 50% millet stalks and leaves cut into pieces 0.3 m long. Mulch was applied before seeding, and as discussed earlier was intended to shade and cool the soil surface, reduce wind speed at the soil surface, protect the soil from raindrop impact, and to serve as a physical barrier to evaporation (increased resistance to vapor flux). By reducing soil evaporation, this management strategy was expected to alter the water balance in favor of the crop. The two treatments of mulching were 0 and 12 Mg ha^{-1}. With the two treatments of irrigation, two treatments of nitrogen and two treatments of mulch, there were a total of eight different treatments or management systems. The eight treatments were: (1) control, (2) mulch, (3) nitrogen, (4) nitrogen/mulch, (5) irrigation, (6) irrigation/mulch, (7) irrigation/nitrogen, and (8) irrigation/mulch/nitrogen. Individual plot (experimental unit) dimensions were 8 by 20 m.

3. Experimental design and statistical analysis

The first field experiment consisted of a 3^n factorial experiment in a split plot design where

fertility and mulch levels were combined and randomly assigned within each water level over six replications. Replications were oriented perpendicular to the main slope of the field. The field slope was 2% according to a topographic survey conducted in the experiment site. One replication was dedicated to continuous harvest for above ground dry matter production and root measurements, and was destructively sampled during the experiment. Consequently, only five replications were considered in the statistical analysis of the data collected.

Statistical analysis of crop growth data consisted of analysis of variance (ANOVA) performed every ten days. The set up of the ANOVA table is presented in Table 2. Two different error terms were used for the determination of significances. Significance of replication and irrigation were tested against Error(1) while significance of the other terms (nutrients, mulch, and interactions) was tested against Error(2).

Statistical significance for main factors was determined using F test at a 95% probability level. For significant interaction effects treatment means were separated using the least significant difference (LSD) procedure at a 95% probability level.

4. Field operations

All field operations were done manually by local farmers using local practices. Table 3 presents the detailed schedule of field operations. Crops were seeded on straight rows oriented from east to west 0.8 m apart, in hills 0.3 m apart. About 10 seeds were initially sown in each hill. Thinning was made to 3 plants per hill after germination. Therefore, plant density after thinning was 42,667 hills ha^{-1} (667 hills $plot^{-1}$) or 125,000 plants ha^{-1} (2,000 plants $plot^{-1}$).

5. Parameters measured

The possibility of soil chemical variability was a concern because of possible interferences with experimental factor effect. Therefore, soil chemical variability between plots was evaluated statistically using surface soil pH, N, P, and ρ_b. Three Soil samples were randomly collected from the surface 0.3 m in each plot for that purpose. No statistical difference was found between plots. This indicated a lack of significant variability between plots which was desirable. Results of this analysis are presented in Appendix B.

Initial crop stand and final crop survival are two important parameters because they determine the number of plants that can grow and produce biomass. Crop survival was determined as the proportion of hills that had a good stand two weeks after sowing:

$$\text{Stand (\%)} = 100 * \text{number good stand per plot} / 667 \qquad [10]$$

Table 2. ANOVA table format for statistical analysis of crop growth parameters.

Source	degree of freedom	Sum of Squares	Mean Square	Error term for F value
Replication	4	-	-	Error (1)
Irrigation (I)	1	-	-	Error (1)
Error (1)	4	-	-	-
Nutrient (N)	1	-	-	Error (2)
N x I	1	-	-	Error (2)
Mulch (M)	1	-	-	Error (2)
M x I	1	-	-	Error (2)
M x N	1	-	-	Error (2)
M x I x N	1	-	-	Error (2)
Error (2)	24	-	-	-

Table 3. Summary of field operations performed during the crop growth experiment.

Operation	Day of the year (1991)
Shrub, grass and small tree removal	163
Phosphorus fertilizer application	180
Preplant tillage (0.20 m deep)	180
Mulch application	181
Sowing	186 and 197
First nitrogen application	199
First weeding	199
Thinning (3 plants per hill)	202 and 218
Second sowing	202
Pesticide application against stem borrers (Karate, ULV 0.8% from 8 g L^{-1} LamdaAcyHalotrine)	242
Second nitrogen application	242
Third weeding	245
First sorghum harvest	295
Sorghum heads threshing	322
Stalks partial removal	306
Fourth weeding	349
Irrigation applications	186, 225, 258, 269, 274, 289

where 667 is the maximum number of hills per plot, and a good stand (according to local farmers) was defined as a hill with at least five 0.15 m high plants.

Crop survival was measured as the percentage of plants that grew from thinning to maturity. For a given plot with 667 seeds:

Survival (%) = 100 * final number of live plant / number of plants after thinning. [11]

Therefore, a count of the total number of live plant was made after thinning and before harvest. Live plants at harvest was determined as the number of plants with a head filled with grains.

Grain yield and above ground dry matter production are the primary reasons for growing cereal crops in the Sahel. Therefore, they are important variables that were measured along with the related agronomic and physiological characteristics. Plant height, a growth indicator, was measured in each plot every ten days, and at harvest. Five hills were randomly selected and the height of each plant was measured from the base of the plant to the top of the stretched upper leaves. The average plant height for the plot was computed as the mean of the fifteen measured plants.

Above ground dry matter production was measured every ten days using a partial harvest on one replicate during the growing season. After height was measured in each plot the same plants were harvested, dried at 50^{0} C for 4 days, then weighed to 0.1 g precision.

Leaf area index is the ratio of leaf area per unit ground area. A simple and non-destructive method (Wolfe et al., 1988) that computes the total leaf area by measuring an average leaf area per individual plant then extrapolating to the number of plants per unit area was used. Total leaf area per plant was measured by drawing the shape of the leaves on paper then digitizing the drawing to compute the corresponding area. Measurements were made every ten days along with dry matter production and rooting measurements.

After each harvest trenches were dug to measure rooting depth and distribution as defined by Bohm (1979). Neutron probe data were also used to confirm that the maximum depth of crop water uptake was consistent with visual observation of maximum rooting depth.

Grain yield was measured at the end of the growing season, after harvest and threshing. After heads were exposed to the sun for four weeks, threshing was performed with locally made wooden mortars. Grains from each plot were then separated and weighed to one g precision. Grain moisture content was determined gravimetrically using dry samples. Moisture mass was then computed and subtracted from the total mass so that yield was reported in equivalent dry grain. The same procedure was used for reporting biomass production.

Yield components measured included harvest index (ratio of grain to total above ground biomass), number of heads per m^2, mean percent of fertile heads, mean head mass, mean seed mass, and

mean number of seeds per head. Number of good, medium and poor heads per plot and total heads mass per plot were determined before threshing. After threshing, the mass per 1000 seeds was measured. Total above ground biomass production was computed as the sum of heads, stalks, and leaves mass.

The effect of drought on crop included crop wilt and crop death. Crop wilt was evaluated visually and was considered to have affected a plot when at least one third of the plants on that plot wilted between 6 and 9 AM. Crop death was measured as the percentage of plants that died. The last dry spell occurred at the end of the growing season after crop panicle initiation. Therefore, the presence of a panicle was a characteristic feature of plants that died from that spell had a panicle. Dry matter lost was measured as the percentage of the total biomass represented by dead plants with a panicle.

F. Weather characteristics

Throughout the growing season weather data were collected for input to the model. Data included: time of occurrence, duration, and amount of each rainfall event, dew and dry air temperatures, wind speed, and daily insolation. Detailed description of rainfall measurement is presented in the next section (page 31).

Daily air temperatures (including maximum and minimum) were continuously measured by a Rustrak model Z25A hydrothermograph (Davis Instruments, Baltimore MD) located 2 m from the soil surface in a meteorological shelter.

Atmospheric pressure data were available from measurements made by a VAISALA model PTA 427 barometric pressure transducer (Davis Instruments, Baltimore MD) at the local Maradi meteorological station. Equation [14] page, (Jensen, 1968) was also used to compute atmospheric pressure at the experiment:

$$P = P_o * ((T_o - (A*H)) / (T_o))^{(g/2R)} \qquad [12]$$

where P is the computed atmospheric pressure (kPa), P_o is the absolute pressure at sea level (101.3 kPa), T_o is the absolute temperature ($15^oC + 273 = 288^o$ K) at one standard atmosphere, A is the lapse rate (0.0065 K m^{-1}), H is the elevation above sea level (m), R is the specific gas constant for dry air (287 J kg^{-1} K^{-1}).

Absolute humidity was continuously measured by psychrometry from dry and wet bulb temperatures. Teten's equation (Eq. 13) as defined by Jensen (1968) was used to compute the saturated vapor pressure from temperature data:

$$E_s = 6.1078 * EXP(17.269 * T_a / (237.3 + T_a)) \qquad [13]$$

where E_s is the saturated vapor pressure (mbar) and T_a is the air temperature (^oC).

Harrison's equation (Eq. [16]) as defined by Slavik (1974) was used to compute actual vapor pressure:

$$E_a = RH * E_s \qquad [14]$$

where E_a is actual vapor pressure (mbar) and RH is the relative humidity (%).

Murray's equation as defined by Jensen (1968) was used to compute dew point temperature from actual vapor pressure:

$$T_d = (237.3 * \ln(E_a/6.1078)) / (17.269 - \ln(E_a/6.1078) \qquad [15]$$

where T_d is the dew point temperature (^oC).

Wind speed was measured at 2 m from the soil surface, using a 3 cup anemometer (R.M. Young, Traverse City, MI) to measure total daily wind run. Average daily wind speed was obtained by deriving the total daily wind run by the duration of the recording period.

Clear sky daily solar irradiance (GR) was computed using Eq. [16] (Avaste, 1967). This value was adjusted with respect to the daily insolation duration data measured at the local airport meteorological station located 7 km from the experiment field.

$$GR = 0.86467+(7.2396*SEL)+(0.43386*SEL^2)-(6.6192\ 10^{-3}*SEL^3)+(2.6677\ 10^{-6}*SEL^4) \qquad [16]$$

where GR is the global irradiance ($W\ m^{-2}$) and SEL is the solar angle,

$$SEL = SIN^{-1}(SIN(LAT) * SIN(DEC) * COS(LAT) * COS(DEC) * COS(H)) \qquad [17]$$

where LAT is the latitude of the location (^{o}), H is the hour angle (^{o}), and DEC is the sun declination at the location (^{o}):

$$H = 15 * (LST - SN) \qquad [18]$$

$$DEC = 23.5* SIN((360/365) * (Day\ number - 81.25)) \qquad [19]$$

where Day number is the day number of the year, LST is the local standard time, and SN is the local standard time at which solar noon occurs:

$$SN = 12 - E/60 - 4 * ((360/365) * (\text{Day number} - 81.25) - LOB) / 60 \quad [20]$$

where E is the equation of time (min) and LOB is the longitude of the location (^{o}):

$$E = 9.87 * SIN(2*B) - 7.53 * COS(B) - 1.5 * SIN(B) \quad [21]$$

$$B = (360/365) * (\text{Day number} - 81.25). \quad [22]$$

Potential evapotranspiration (PET) was computed by the Penman combination equation as modified by Frere (1972) for limited instrumentation and high advection:

$$PET = ((Po/P)(\Delta/\gamma) * (0.75*RA*(A+B * n/N) - (\sigma * T_a^4 * (0.56-0.079 * (Ed)^{0.5}) \quad [23]$$

where Δ is the slope of the saturated vapor pressure versus temperature function, γ is the psychometric constant, R_A is the short wave radiation received at the edge of the earth's atmosphere (m of water, where 1 mm water = 246.86 kJ), A and B are coefficients used to convert hours of sunshine to radiation (W m^{-2}), n is the number of daily sunshine hour (h), N is the number of theoretically possible daily sunshine hours for a particular month and latitude (h), σ is the Stephan Boltzmann constant, T_a is the ambient temperature (^{o}K), U is the average daily wind speed (m s^{-1}), and Ed is the vapor pressure of the ambient air (kPa). The wind speed coefficient (0.56) is used to compensate for increased advection and may therefore increase to as much as 0.89, depending on the differences between daily air temperature extremes.

G. Water balance

1. Water balance equation

Proper management or monitoring of soil water requires a detailed description of all input and output. The water balance of a given cropped area with a known rooting depth is defined by:

$$P_r + IR = D_s + E + T + D_a + R_f - (G_o + R_o) \quad [24]$$

where P_r is rainfall (m), IR is water input from irrigation (m), D_s is the change of soil moisture storage in the root zone (m), E is evaporation from the soil surface (m), T is transpiration from the plant canopy (m), D_a is deep drainage in the soil out of the root zone (m), R_f is runoff (m), G_o is the upward ground water flow into the root zone (m), and R_o is run-on or surface inflow into the surface of the soil layer (m). Determinations of the balance components are described below.

2. Monitoring water balance components

The amount of precipitation (P_R) received as rain per unit surface area was measured after each rainfall event with four non-recording 0.17 m diameter rain gages installed in the experiment field 2 m above the soil surface. The water depth of each rain event was computed by dividing the mean volume of water collected by the surface area of the rain gage. Since variation between gages were less than one tenth mm for each rainfall, rainfall distribution within the experiment field was assumed to be uniform.

Supplemental irrigation (IR) water was supplied from a local shallow well (6.5 to 9 m deep) using a fuel activated water pump. Aluminum pipe was used to convey water from the well to the plots. Water was applied by flooding individual plots. Application was undertaken whenever soil moisture content reached the management allowable soil moisture deficit (MAD) limit. Figure 5 shows the irrigation management procedure and parameters used in this experiment. The management procedure and parameters presented were based on soil hydraulic characteristics, changes of soil moisture content, and plant rooting depth. Linear regression equations of cumulative soil water content at field capacity and cumulative MAD as a function of depth were used to determine when and how much water to apply, respectively. According to the moisture retention functions the upper MAD limit was less than 0.09 m^3 m^{-3} water content in the top 1 m. Below 1.5 m, high sand content contributed to lower water holding capacity values. However, little moisture increase and root activity were observed at these depths. Therefore, soil water management was restricted to soil layers in the upper 1.5 m. The MAD in the upper 1.5 m for each 0.10 m soil layer was determined by:

$$\theta_{MAD} = \theta_{WP} + 0.25 \cdot (\theta_{FC} - \theta_{WP}) \qquad [25]$$

where θ_{MAD} is the volumetric soil moisture content of the root zone at the MAD limit (m^3 m^{-3}), θ_{WP} is the soil moisture content of the root zone at wilting point (m^3 m^{-3}), and θ_{FC} is the soil moisture content of the root zone at field capacity (m^3 m^{-3}). Since the objective of supplemental irrigation was to keep soil moisture content at a safe level for the crops, this equation assumed that the plant could extract only 75% of the available water (instead of 100%) without being affected by stress. This assumption was based on the fact that any risk of moisture stress were to be avoided on irrigated plots. Irrigation was undertaken whenever measured ("actual") soil moisture content in the root zone reached the MAD value in that root zone. During each irrigation soil water content was brought to field capacity.

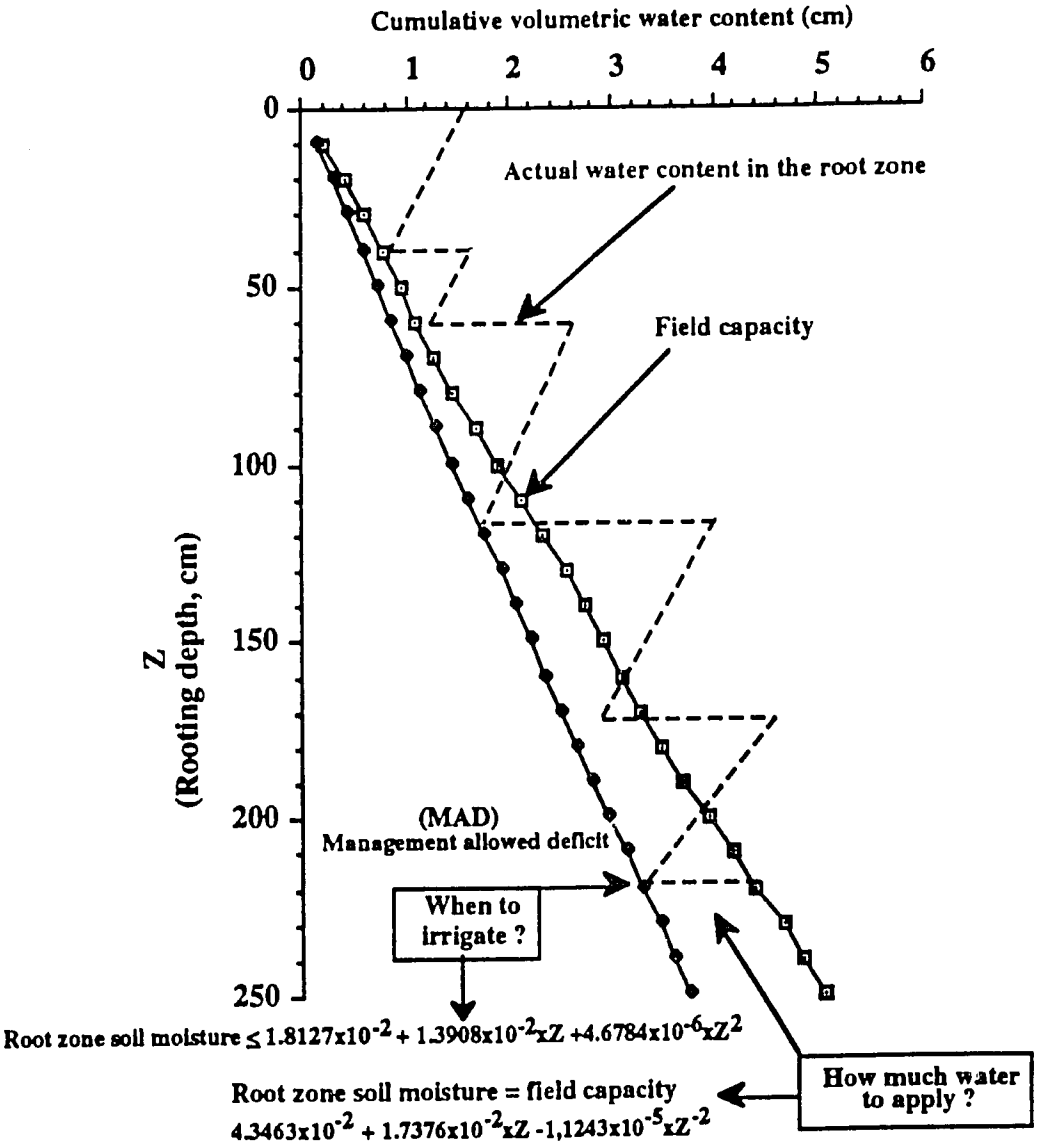

Figure 5. Irrigation management parameters and procedure.

Therefore, irrigation was undertaken whenever one of the following conditions became true:

$$\Sigma(\theta_{FCi} - \theta_i) > \Sigma(-\theta_{MADi}) \quad [26]$$

$$\theta_{MADi} > \theta_i \quad [27]$$

$$\theta_{MAD} = \theta_i \quad [28]$$

where θ_{FCi} is the soil moisture content of soil layer number i at field capacity ($m^3\ m^{-3}$), θ_i is the actual moisture content of soil layer number i ($m^3\ m^{-3}$), and θ_{MADi} is the MAD moisture content of soil layer number i ($m^3\ m^{-3}$). The volume of water to apply was calculated as:

$$V = (\theta_{FCi} - \theta_i) * 10 * A\ 10^{-4} \quad [29]$$

where V is the depth of water to be applied (mm), and A is the area of the individual plot (160 m^2). The irrigation depth was divided by the irrigation delivery rate (2 to 6 L s^{-1} depending on pump speed) to obtain the duration of application. During each irrigation soil moisture was brought to field capacity by flooding using the following time T (min) defined by:

$$T = 60 * V * FR^{-1} \quad [30]$$

where FR is the water flow rate (L s^{-1}).

Chemical analysis of the irrigation water was performed as a routine check to determine possible chemical interferences on treatment effects. Determinations included electrical conductivity, pH, and ion concentrations. These results are presented in Appendix A.

Changes of soil moisture content as a function of depth ($d\theta/dZ$) were monitored throughout the growing season. Measurements included gravimetric determination of water content in the top 0.30 m surface layer and using a Troxler H-1916 neutron probe (Greacen, 1981) below 0.30 m depth. A calibrated Troxler 875 scaler rate meter (Greacen, 1981) was used for the deeper soil layers. Measurements were made every 0.1 m to a depth of 2.50 m every 5 days and after each rainfall event. The neutron probe was calibrated using gravimetric samples from a progressively drying soil profile. Changes of soil moisture content with depth ($d\theta/dZ$) was used to monitor the maximum wetting front.

Two methods were available for the determination of potential ET, computation from weather data and estimation from pan evaporation. Evapotranspiration (ET) was determined as the sum of evaporation (E) from the soil surface and transpiration (T) from the crop canopy. Determination of actual ET was made from water balance:

$$ET = P_r + IR + G_o + R_o - (D_s + Da + R_f) \quad [31]$$

Soil evaporation was measured with weighing micro-lysimeters (Lascano et al., 1987). Three replicate measurements were made on each plot every day. Using evaporation data, ET was partitioned between E and T. Measured values were then compared to the simulated values obtained with the ENWATBAL model (Lascano et al., 1987).

The free water table at the experiment site was below four m (as observed from wells in this area). Consequently, contact between the wetting front and the water table was avoided throughout the growing season. Due to a relatively impermeable soil horizon located between 0.95 and 1.2 m depth, the maximum wetting front at the end of the growing season was less than 1.5 m. In addition, depth of neutron access tubes was greater than 2 m which was deeper than both the root zone and the maximum wetting front. The possibility of drainage losses from unsaturated water flow was considered to be negligible since saturated hydraulic conductivity of the impermeable horizon was less than 0.5 mm h^{-1}. Therefore, deep drainage (DA) was considered to be the amount of water that drained below the maximum root zone. Consequently, it was determined as the amount of water between the maximum rooting depth and the wetting front:

$$D_a = \Delta Z * \Delta\theta * 1000 \quad [32]$$

where ΔZ is the vertical distance between the maximum rooting depth and the wetting front (m), $\Delta\theta$ is the difference between the mean soil moisture content ($m^3\ m^{-3}$) at sowing and at harvest, and 1000 is a conversion factor used to express D_a in mm. It is assumed in this equation that water flow is negligible when soil moisture content is less than 0.05 $m^3\ m^{-3}$.

Runoff and run-on were prevented at the experiment site. Individual plots were protected with closed ridges 0.30 m high. This measure was taken not only to prevent run-on and possible induced solute transport between plots, but also to prevent runoff from individual plots. Therefore, both runoff (R_f) and run on (R_o) were assumed to be zero.

As mentioned earlier, the water table was deep enough that liquid water movement from the root zone to the water table and vice versa was prevented. Therefore ground water inflow (G_o) was reduced to zero in this study.

3. Adjusted water balance equation

Taking into account the above considerations, and combining E and T into ET and solving for ET (Eq. 24) can be written as

$$ET = P_R + IR - D_S - D_A \quad [33]$$

H. Crop water use efficiency

To properly evaluate WUE with respect to the agroecosystem productivity and efficiency, different parameters were used. These expressions included WUE(ET), WUE(T), total water use efficiency WUE (R+I) and rainfall use efficiency RUE(R). This parameter was based on above ground biomass that is relevant for this study. Therefore, root mass was assumed to be constant across all treatments. Based on soil water balance of each treatment ET and T for each treatment was determined and used to establish these parameters. They were defined as follows:

$$WUE(ET) = 0.1 * Y/ET \quad [34]$$

where 0.1 is a conversion factor from Kg ha^{-1} mm^{-1} to kg L^{-1} or Kg kg^{-1}, WUE(ET) is the evapotranspirational water use efficiency (g kg^{-1}), Y is crop yield (kg ha^{-1}) and ET is evapotranspiration (mm);

$$WUE(T) = 0.1 * Y/T \quad [35]$$

where WUE(T) is the transpirational water use efficiency (g kg^{-1}), and E is crop transpiration (mm);

$$WUE(R) = 0.1 * Y/R \quad [36]$$

where WUE(R) is the rainfall use efficiency (g kg^{-1}), and R is the total rainfall during the growing season (mm);

$$WUE\ (R+I) = 0.1 * Y/(R+I) \quad [37]$$

where WUE (R+I) is the total water input use efficiency (g L^{-1}), I is the total amount of irrigation (mm).

One way of evaluating the efficiency of mulch in suppressing soil evaporation is to use WUE(ET) . As discussed earlier, reduced E causes higher WUE(ET). Therefore it may be used to evaluate the effectiveness of a given management system such as mulch to improve crop water use.

The use of WUE(T) is a desirable crop performance evaluation parameter, but may not be appropriate for evaluating total productivity or efficiency in the use of the water budget. For example, a

crop that transpired 100 mm and produced 1000 kg biomass may have the same WUE(T) as a crop that transpired 200 mm and produced 2000 kg biomass within the same water conditions. Therefore, in assessing WUE, one needs to take into account the total water budget provided to the crop.

With RUE(R) it is possible to compare different systems in terms of how they efficiently utilize the valuable natural resource (rainfall) when these systems evolve in the same environment. The reason for using supplemental irrigation is the inability of the crop to utilize rainfall. Therefore, when irrigation input is included in a management system it should be evaluated in terms of how it improves the use of the rainfall it intends to supplement. That helps address the question of how irrigation does really contribute to a better use of rainfall. It was therefore appropriate to use WUE(R+I) to evaluate rainfall use when supplemental irrigation is used.

Of all these parameters none alone gives a complete description of the total productivity of the system in question. Since improved WUE may occur at low productivity levels it is appropriate when using the terms previously defined to present the total productivity. In addition, specific growth functions were developed to relate crop water use to biomass production for each treatment.

I. Water balance model

The basic frame of the simulation model used was the ENWATBAL model (Lascano et al., 1987). A simplified structure of this model is presented in Fig. 2 (page 16). This model is a numeric method for computing water loss from a cropped soil surface by evapotranspiration (ET). It partitions ET into transpiration and evaporation based on both the water and the energy balance of the soil surface and crop canopy.

1. Modification of the base model: ENWATBAL

ENWATBAL is a dynamic simulation model that has been tested with a cotton crop at Lubbock, TX, where climatic and soil conditions are similar to those of Niger. Results of this test indicated no significant difference between predicted and measured values of evapotranspiration, soil evaporation, soil temperature and soil water content (Lascano et al., 1987). Krieg and Lascano (1989) suggested that the components of the water balance equation for a sorghum crop could also be calculated using ENWATBAL.

In the previous sections, it has been proven why this model is appropriate for this study. Parameters were adjusted to relate the model function and output to specific field conditions and experimental treatments. Specific parameters and constants used are presented in Table 4. The simulation was performed from day 190 to 274 using daily average climatic data. Soil surface roughness length (Z_o) was determined using an empirical relationship (Campbell, 1985, Eq. 4.12 and 4.13)

Table 4. Specific parameters and constants used for the modeling of soil water balance.

Simulation period	Day 190 to 274
Type of input data	Daily average
Surface roughness (Zo)	0.001 m
Latitude	16.3° N
Pounded water detention capacity	0.20 m
Average barometric pressure	873 mbar
Crop specific hydraulic resistance	1×10^9 s
Number of soil layers	21

$$Z_o = 0.026 \cdot h \qquad [40]$$

where h is the height of the crop (m). The soil was divided into two groups of 21 layers (Table 5) of variable thickness. The protective ridge built around individual plots was 0.30 m high. Therefore a conservative value of 0.2 m was used for the ponded water detention capacity.

One limitation of the model was the fact that it was not designed to simulate mulched soil surfaces. This specific question has been addressed by Heilman et al. (1992) who found that mulch decreases evaporation from the soil surface due to a 1.2 to 2.7 times lower water vapor conductance as compared to bare soils. To account for mulch the introduction of an additional resistance to the sensible and latent and latent heat fluxes from the soil surface in the ENWATBAL model was suggested by Lascano (personal communication, 1993). This is accomplished using h_v as defined by Eq. [41]:

$$h_v = 2.4 \cdot (1.0 + 0.35 \cdot U) \qquad [41]$$

where h_v is the vapor conductance (mm s^{-1}), and U is the wind speed (m s^{-1}). This procedure was used for the simulation of mulched plots.

2. Input data

System parameters consisted of soil geometry and the number and thickness of soil layers. The initial conditions included temperature and moisture profile. Initial as well as subsequent measurement of temperature profiles were made using thermocouples. Initial and subsequent moisture profiles were measured using a neutron scattering method. These methods were described earlier in the section on Soil characterization section (page 21) and Monitoring water balance components (page 31). Input data required for the model included soil, crop and weather parameters.

Soil data include the water retention curve, unsaturated conductivity, and initial water and temperature profiles. Initial soil moisture and temperature were measured from the soil surface to a depth of 2.4 m using copper-constantan thermocouples and recorded by a Campbell data logger model 21X (Campbel Scientific, Logan UT). Thermocouple junctions were located 0.1 m apart starting at 0.05 m from the soil surface. Crop data included (1) the relation between leaf conductance versus leaf water potential (Lascano et al., 1987), (2) root distribution as a function of time and depth, and (3) LAI as a function of time. Weather data include daily solar radiation, daily minimum and maximum air and dew point temperatures, and daily wind speed. Irrigations and rainfall events were entered with same format: time when the event began, ended, and amount. Detailed input data are presented in Appendix C.

The ENWATBAL model was evaluated by comparing measured and simulated results. Simulated results were obtained by using the input data for the specific site mentioned above.

Table 5. Definition of soil layers for the modeling of soil water balance.

Layer number	Depth	Thickness
m	m	m
1	0.005	0.005
2	0.015	0.010
3	0.030	0.015
4	0.050	0.020
5	0.070	0.020
6	0.090	0.020
7	0.115	0.025
8	0.145	0.030
9	0.175	0.030
10	0.210	0.035
11	0.250	0.040
12	0.290	0.040
13	0.340	0.050
14	0.400	0.060
15	0.470	0.070
16	0.550	0.080
17	0.640	0.090
18	0.790	0.150
19	0.990	0.200
20	1.340	0.350
21	1.700	0.360

VII. RESULTS AND DISCUSSION

A. Agroecosystem characterization

1. Soil characteristics

a. Soil landscape, background, and profile

The experiment field was located in the INRAN Maradi Research Station near the Tarna village. This field is located on an old river terrace and was used as a major irrigation research field by French researchers from IRAT (Institut de Recherche en Agronomie Tropicale) from 1963 to 1973. Due to deterioration of irrigation wells caused by sedimentation, surface soil salinity, and development of other major irrigation projects (at Jiratawa), IRAT and INRAN research activities were discontinued in 1973. A profile description of the soil is given in Table 6.

This soil was classified as an Ustifluvent formed from alluvial and eolian parent materials with a relatively flat topography (2% slope). The most predominant feature in this soil is the presence of distinct depository layers of varied texture and color.

b. Soil physical characteristics

Soil particle size distribution as a function of depth is presented in Fig. 6. Texture of the top soil (0 to 0.65 m) was sandy loam (field determination). Sand size particle content increased with depth, ranging from 45 to 55% in the top 0.6 m, from 75 to 85% in the 0.6 to 2.0 m depth, and greater than 90% below 2 m depth. Silt content was lower than sand content at all depths, but higher than clay content. However, clay content was the same as silt content below 2 m.

Change of silt content with depth was the most dominant textural factor. This relative change (decrease) was the greatest among all particle sizes, 94% as compared to 50 and 80% for sand and clay respectively. Clay content within the profile ranged from 13 to less than 5% tending to decrease with depth.

Based on the USDA textural class, this profile is sandy loam for the top 0.6 m, loamy sand from 0.6 to 2.0 m, and sand below 2 m. Profile description and textural analysis suggest that below 1.5 m this soil has the same textural characteristics as upland soils (about 90% sand content). Statistical variability of particle size distribution was low (Fig. 6). Soil horizons can be divided into two main groups: 0 - 0.90 m and 0.90 - 2.00 m. This suggested that the top layers represent an accumulation of alluvial materials from flooding of the Goulbi river, located approximately 5 km from the experiment site.

Table 6. Soil profile description of the experiment site at Maradi.

Location	: Maradi, Niger, West Africa (3 km east of the Goulbi river, 13.28° north latitude, 7.05° east longitude, 371 m altitude)
Landform	: Valley system, upper footslope
Slope	: 2%
Parent material	: alluvial deposits
Land use	: Fallow since 1976
Drainage	: Poor
Collectors	: M. Ouattara, M. Issaka, M. Lawali, M. Gandah, M. Sabiu, H. Kadi Kadi, and C.G.L. Zaongo

Horizon	Depth (m)	Description
A1	0 - 0.25	Pale brown† (10 YR 6/3). Fine loam, brown to dark brown (10 YR 4/3) moist; moderate coarse subangular blocky; slightly hard; pH 7.9; gradual smooth boundary.
AC	0.25 - 0.46	Brown to dark brown (10 YR 6/3) fine loam, brown to dark brown (10 YR 4/3) moist; moderate fine and medium subangular blocky; hard; pH 7.8; abrupt broken boundary.
C1	0.46 - 0.65	Brownish yellow (10 YR 6/7) fine loam, brown to dark brown; moderate medium subangular blocky; hard; pH 7.6; abrupt broken boundary.
C2	0.65 - 0.82	Very pale brown (10 YR 7/3) sand, brown (10 YR 5/3) moist; weak coarse subangular blocky; soft to slightly hard; pH 7.5; abrupt broken boundary.
C3	0.82 - 1.07	Dark grayish brown (10 YR 4/2) moist; clay loam; massive; hard; pH 7.7; abrupt smooth boundary.
C4	1.07 - 1.58	Dark brown (10 YR 3/3) moist; sandy loam; massive; hard to slightly hard; pH 7.3; clear smooth boundary.
C5	1.58 - 1.89	Brown to dark brown (10 YR 4/3) moist; loamy fine sand; massive; friable; pH 7.9; abrupt broken boundary.
C6	1.89 - 2.11	Light brown (7.5 YR 6/4) moist; fine sand; friable; abrupt smooth boundary; pH 7.9; clear smooth boundary.
C7	2.11 - 2.43	Variable brown (10 YR 5/3) and dark brown (10 YR 4/3) moist; loamy sand; massive; friable; pH 7.8. clear smooth boundary.

† Colors are for dry soil unless otherwise indicated.

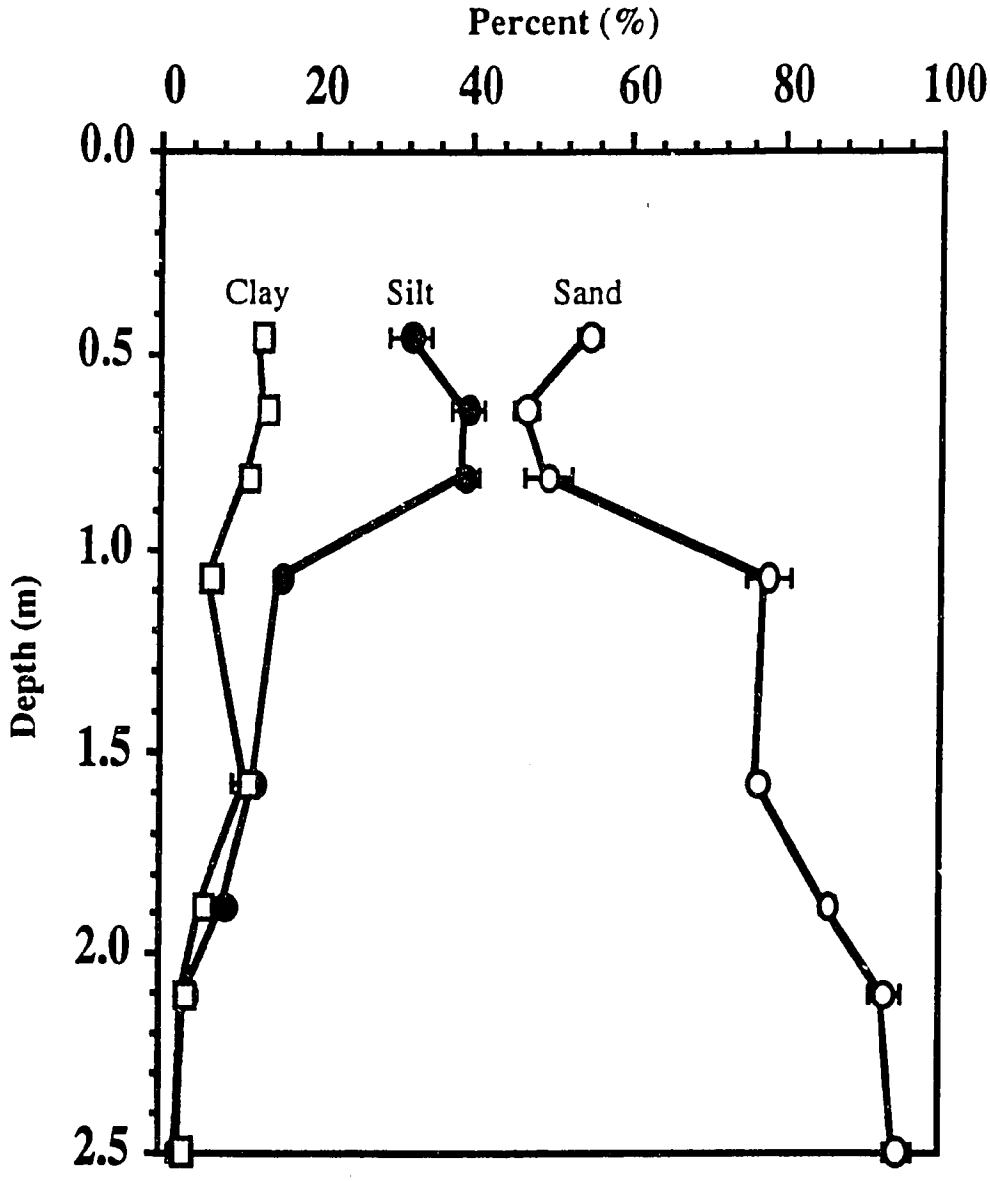

Figure 6. Mean soil particle size distribution with depth at the experiment site according to USDA classification. Horizontal bar is the standard deviation of the mean (n = 3) and is not visible when less than the width of the symbol.

Although flooding was not documented by the research station, local farmers recall floods but were unable to establish the exact years when they took place. Therefore, dominant parent materials are primarily alluvial silt and fine sand. Continuous eolian deposits are characteristic of these regions, as suggested by Wilding and Hossner (1989) and are possible significant contributors to the formation of the top soil. Finer texture of the top soil suggests a higher potential for holding water and nutrients than the subsoil.

Soil bulk density as a function of depth is presented in Fig. 7. Maximum standard deviation was less than 0.09 Mg m^{-3}. Surface soil bulk density was 1.44 Mg m^{-3}. It increased slightly from 0.2 to 0.3 m depth, decreased from 1.47 Mg m^{-3} to 1.29 Mg m^{-3} at 0.72 m as a result of the slight increase in clay content and increased soil porosity from intense animal and plant root activity. An increase of the bulk density to 1.46 Mg m^{-3} was measured between 0.9 and 1.1 m. This increase matched the corresponding increase in sand content (Fig. 7). Bulk density fluctuated around 1.45 Mg m^{-3} below 1 m.

From the surface to 0.6 m this soil exhibited a lower bulk density than those generally observed on sandy dune soils (1.64 Mg m^{-3}; Zaongo, 1988). Based on textural and bulk density data there was no physical limitation to root growth within the 2.5 m deep profile. Nevertheless, these textural and bulk density changes may be a valid indication that movement of the wetting front could be slowed in the top 0.6 m, as observed during the internal drainage experiment, due to relatively high clay content and poor soil structure. The sharp increase of bulk density between 0.7 and 1.0 m depth may be an indicator of discontinuity in soil hydrological properties. The corresponding increase in sand content in that layer could be a factor in slowing water movement. In some cases it is necessary for the zone above the high sand zone to become saturated before water movement can occur.

Organic matter content is an important factor in the development of a good soil structure. Mean organic matter content in the surface soil was 2.3 % (Fig. 8a) which is considered to be high for this region. The high value was probably due to the accumulation of organic matter from trees, shrubs, and grass deposits as well as root activity during the fallow period from 1971 to 1990. However, organic matter content decreased drastically with soil depth to less than 0.1 % at 2.5 m. The structure of this soil is predominantly subangular blocky from the surface to 0.82 m depth. Structure was massive from 0.82 to 1.89 m, and friable or single grained below 1.89 m (Table 6).

Quantitative evaluation of macro-aggregation is presented in Fig. 8b. Macro-aggregation decreased from 80% at the soil surface to 70% at 0.25 m, 40% at 0.70 m, and 12% at 1.1 m. As for texture and bulk density, there was a consistent and significant decrease between 0.7 and 1 m depth. There was a significant ($R^2 > 0.95$) and positive relationship between macro-aggregation and silt size particle content.

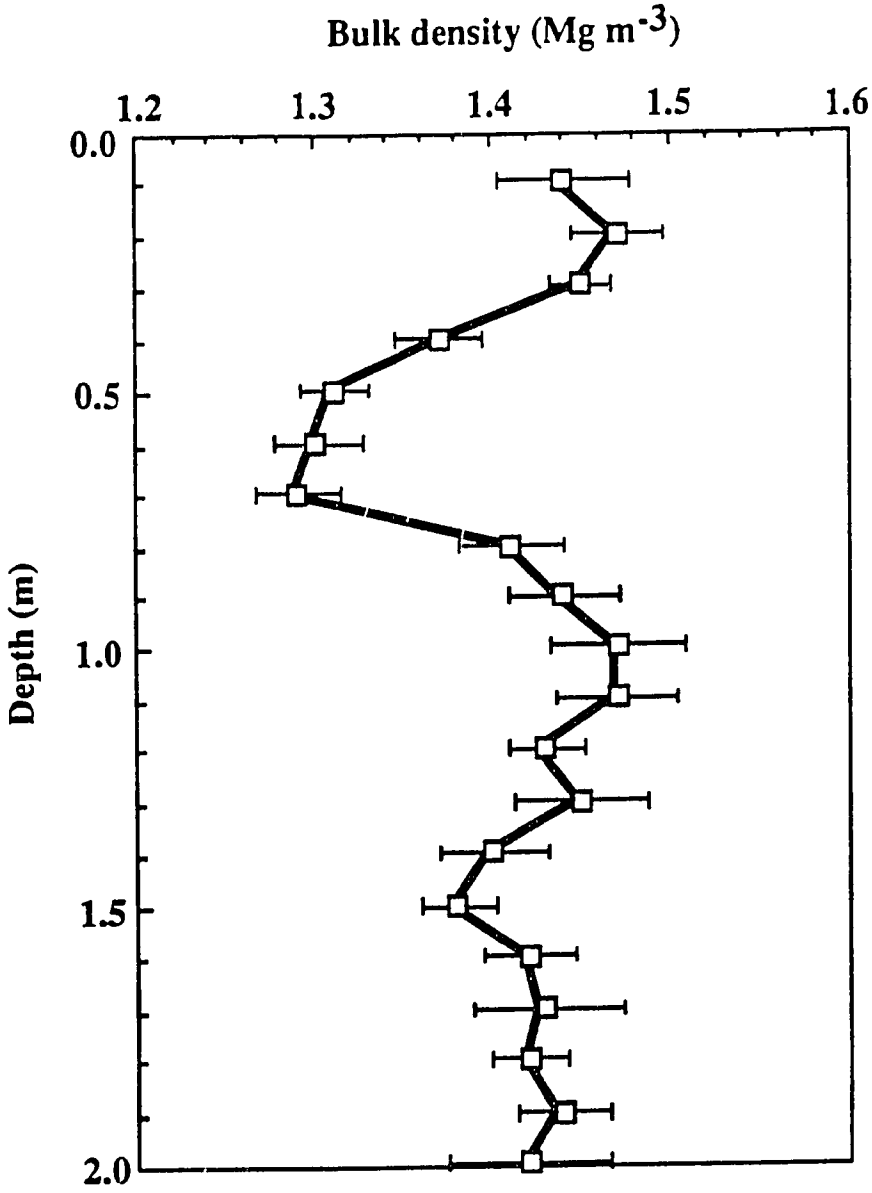

Figure 7. Distribution of mean soil bulk density with depth at the experiment site. Horizontal bar is the standard deviation of the mean (n = 3).

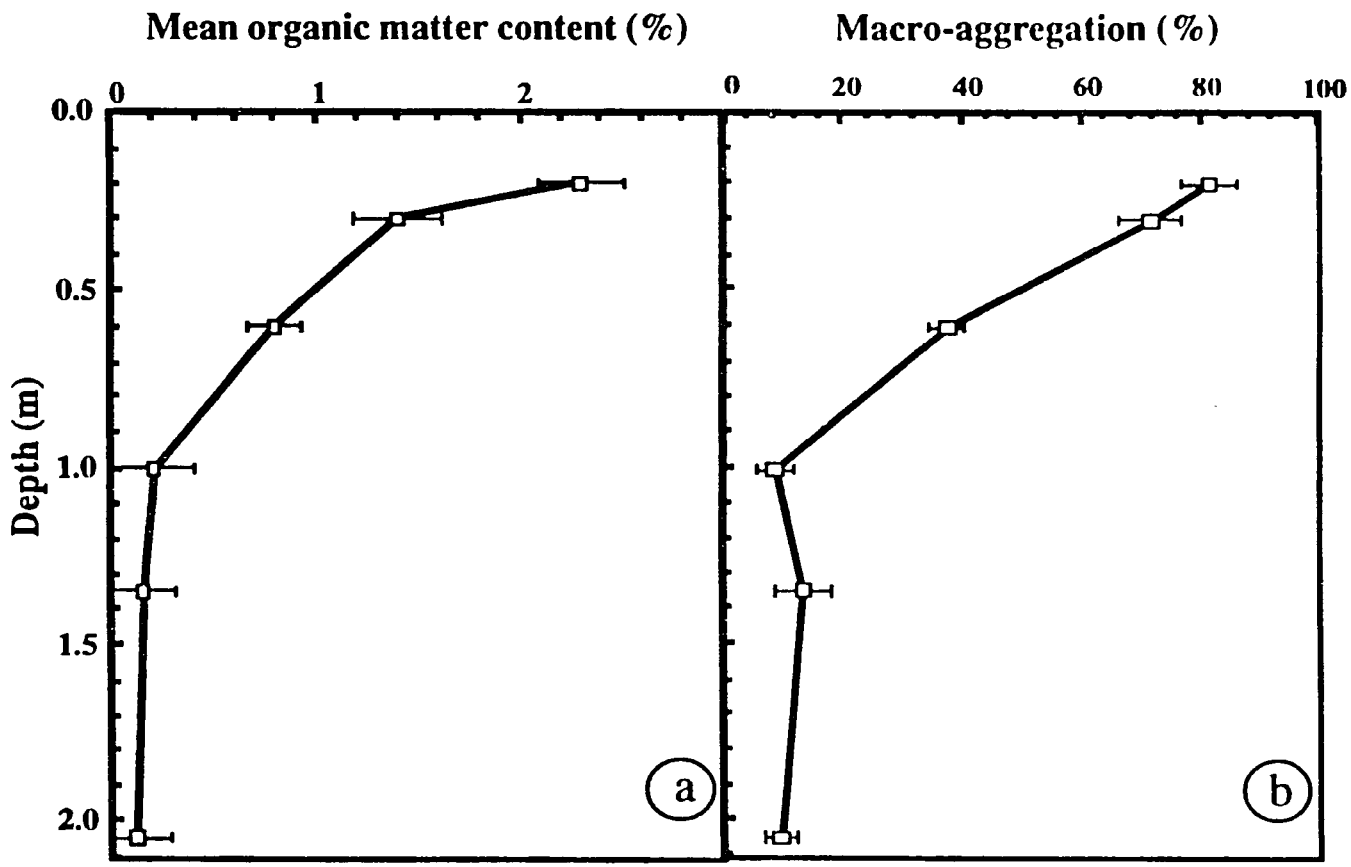

Figure 8. Mean soil organic matter (a) and macro-aggregation (b) with depth at the experiment site. Horizontal bar is the standard deviation of the mean (n=3).

Direct observation of roots from a trench indicated that maximum rooting of the vegetative cover was limited to about 0.8 to 0.9 m depth. Root exudations and death promote microbial activity resulting in the production of humic cement. Maintenance of the balance of the root-microbe-cement system was insured by a continuous supply of organic matter from litter (Tisdale and Nelson, 1985). This requires flocculation of clay and recementation by some agents. Therefore, organic matter content and macro-aggregation were adequate for improved soil structure only in the top 0.5 to 0.6 m. However, a significant statistical relationship between macro-aggregation and silt size particles content suggests that silt content was a determining factor for macro-aggregation. At 1 and 2 m, macro-aggregation was less than 20% and clay content less than 16%. This suggested poor soil structure, and consequently poor water and nutrient retention. Therefore the soil layers below 1.5 m have a low potential for effective plant root activity.

Organic matter content and macro-aggregation (Fig. 8a and 8b) trends were similar. However, no statistical significant ($R^2 > 0.95$) linear relationship existed between these two parameters. Results suggested that a cubic rather than linear model should be used to characterize the relationship between these parameters.

Total porosity and pore size distribution for different soil horizons is presented in Fig. 9. Total porosity in the top 1.5 m ranged from 0.45 to 0.48. With the exception of the third horizon (0.72 to 0.82 m) pore size distribution in all layers followed the same trend, about 44% of the total pores having less than 20 μm diameter and 75% less than 40 μm. Pores in those layers can be classified into four groups: 0 to 4, 4 to 16, 16 to 24, and greater than 24 μm. However, the proportion of pores with a diameter > 80 μm increased with depth. This is probably due to the increase in sand size particles and decreased aggregation, in addition to low water filled porosity (< 0.3) and higher bulk density. This indicates a tetrahedral or octahedral (coordination number of 12) packing of soil particles that results in single grained structure of polydispersed systems (Hillel, 1980). Pores in the third soil horizon were the smallest in the profile. In this horizon 80% of the pores had less than 18 μm diameter, and 95% had less than 70 μm. This could constitute a limitation to root activity and water movement (Hillel, 1980).

c. Soil hydrological characteristics

The water infiltration rate of an initially dry soil is presented in Fig. 10a. During the first five minutes following ponding, the infiltration rate remained very high ($> 6x10^{-7}$ m s^{-1}). However, it decreased sharply after 10 minutes to about $2x10^{-7}$ m s^{-1} and to $0.8x10^{-7}$ m s^{-1} at 30 min. After 90 minutes, the infiltration rate fluctuated around $0.5x10^{-7}$ m s^{-1}, tending to an asymptotic limit of $0.3x10^{-7}$ m s^{-1} after 3 hours. These values agree with the limits (10^{-7} to 10^{-6} m s^{-1}) suggested by Hillel (1980) for a steady state infiltration rate in sand to silt soils.

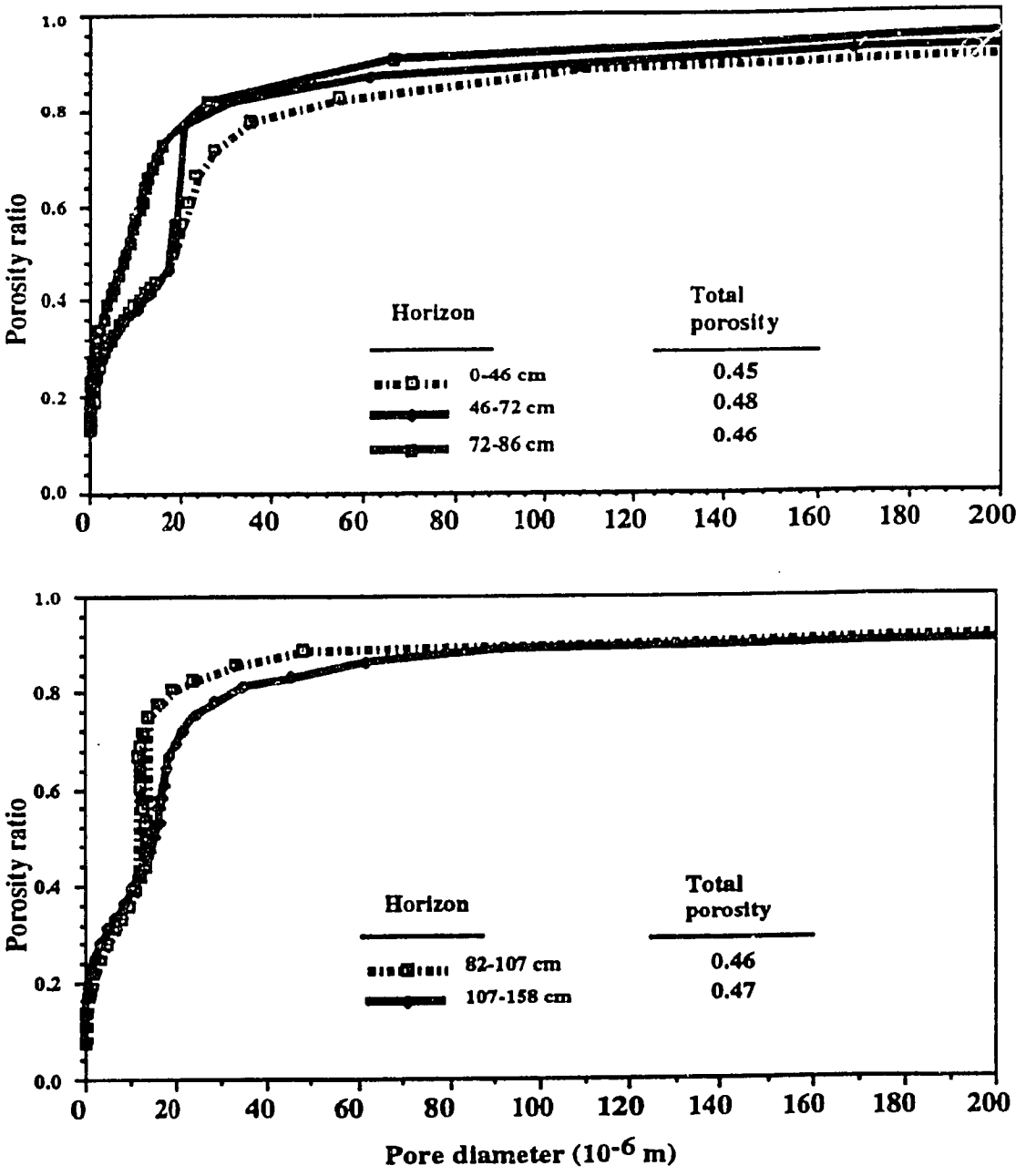

Figure 9. Pore size distribution and total porosity of the soil horizons at the experiment site.

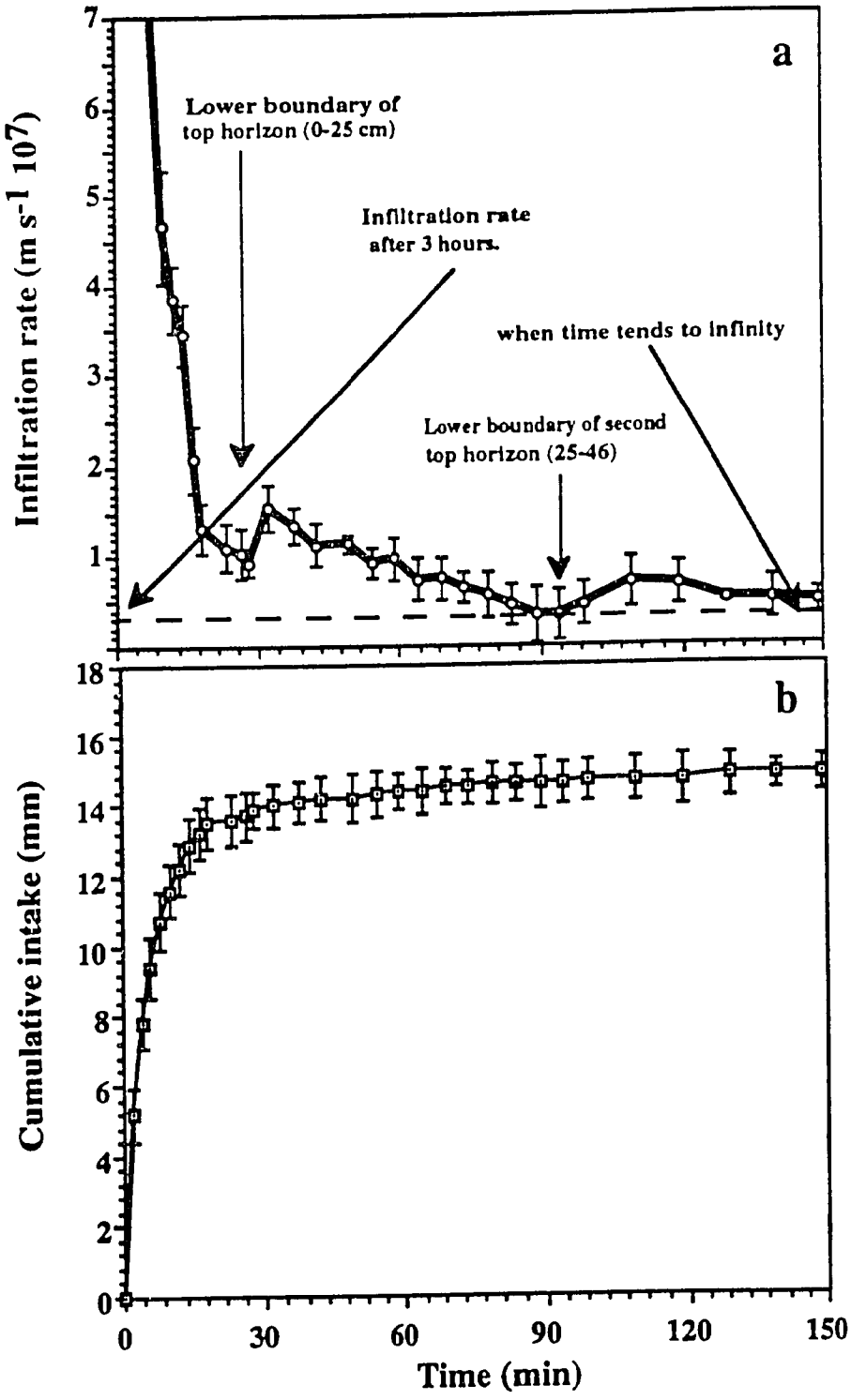

Figure 10. Mean infiltration rate (a) and mean cumulative water intake (b) as a function of time at the experiment site. Vertical bar is the standard deviation of the mean (n = 3).

This asymptote was limited by the saturated hydraulic conductivity of the horizons above, since results indicated that the two underlying layers had higher hydraulic conductivity. The first indication that the wetting front reached another soil horizon occurred between 20 to 30 minutes. At this time the wetting front reached 0.25 m, the lower limit of the top soil layer. The wetting front reached the lower limit of the second soil layer around 90 minutes after ponding. This indicated that it takes about 90 minutes to wet the soil to 0.46 m. However, it should be noticed that (1) the soil was dry and cracks may have contributed to initial penetration of the wetting front, (2) puddling by rain drops was eliminated, and (3) a constant water head was applied throughout the whole process. These specific conditions are probable reasons for the high initial infiltration rate and a fast advancing wetting front.

Given the average rainfall intensities of this area ($3x10^{-7}$ to $6x10^{-7}$ m s^{-1}), runoff may occur when cumulative rainfall exceeds 14 mm within 60 to 90 minutes (Fig 10b), and especially when the impact of raindrops destroy surface soil structure (Hillel, 1980; Richards, 1965). Tillage could improve short-term infiltration, while mulching could improve it on a long-term basis. This soil has a low steady state infiltration rate, compared to upland soils where steady state infiltration rate is about 25 mm h^{-1} (Zaongo, 1988). However, risk of flooding or water logging is associated with runon from other areas rather than poor infiltration rate.

Results on field soil water retention determination by internal drainage and laboratory determination with pressure plates are presented in Fig. 11. For the surface (0 to 0.6 m), water retention remained relatively high, ranging from 35% at saturation to 6% at wilting (-1500 kPa). From 0.6 to 1.8 m depth water retention ranged from 30% at saturation to less than 4% at -1500kPa. Below 1.8 m water retention ranged from 15% at saturation to less than 2% at -1500kPa. Water retention at -33kPa ranged from 17% at the soil surface to less than 6% at 2.1 m, decreasing consistently with depth. Curves for the top three horizons (0 to 0.82 min, Fig. 10) are typical of clayey soils, while the deeper horizon curves are typical of a sandy soil (Hillel, 1980). A common characteristic of these curves is their drastic increase in slope over a very narrow range of tension from -18 to -20 kPa. This sharp increase marks the difference between saturation and field capacity.

Hydraulic conductivity of the different soil horizons are presented in Fig. 12 and specific equations are summarized in Appendix E. Based on hydraulic conductivity, the soil horizons can be grouped into three groups (1) the two top silty horizons, from 0 to 0.8 m with mean saturated conductivity of 15.5 mm h^{-1}; (2) the "clogged" horizon (from 0.8 to 1.1 m) with mean saturated conductivity less than 0.5 mm h^{-1}, and (3) the sandy horizon with characteristics similar to upland soils (below 1.1 m) with mean saturated conductivity of 50.0 mm h^{-1}.

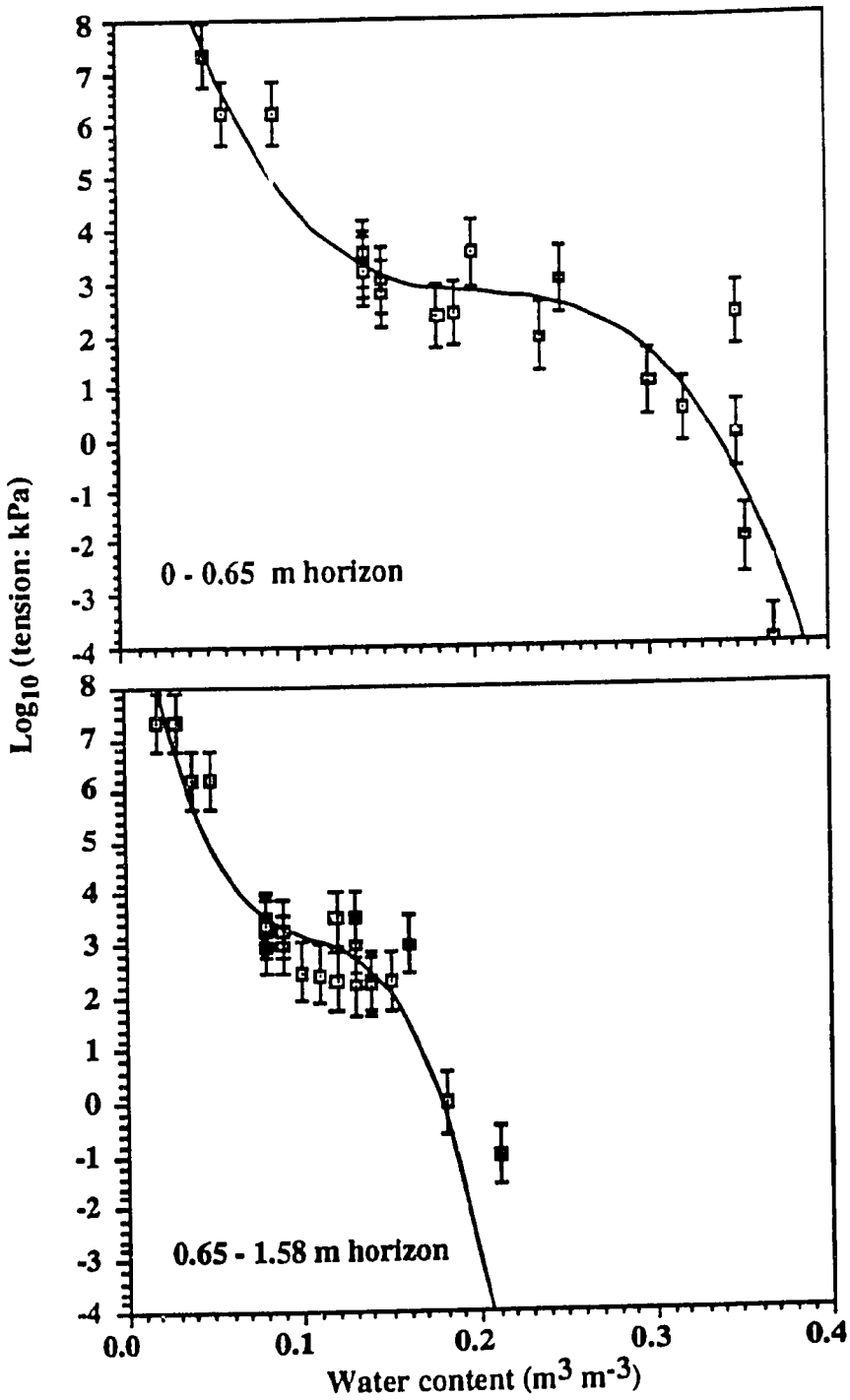

Figure 11. Mean (three replicates) water retention capacity of the soil horizons at the experiment site as determined by field and laboratory measurements. Vertical bar is one standard deviation of mean (n = 4).

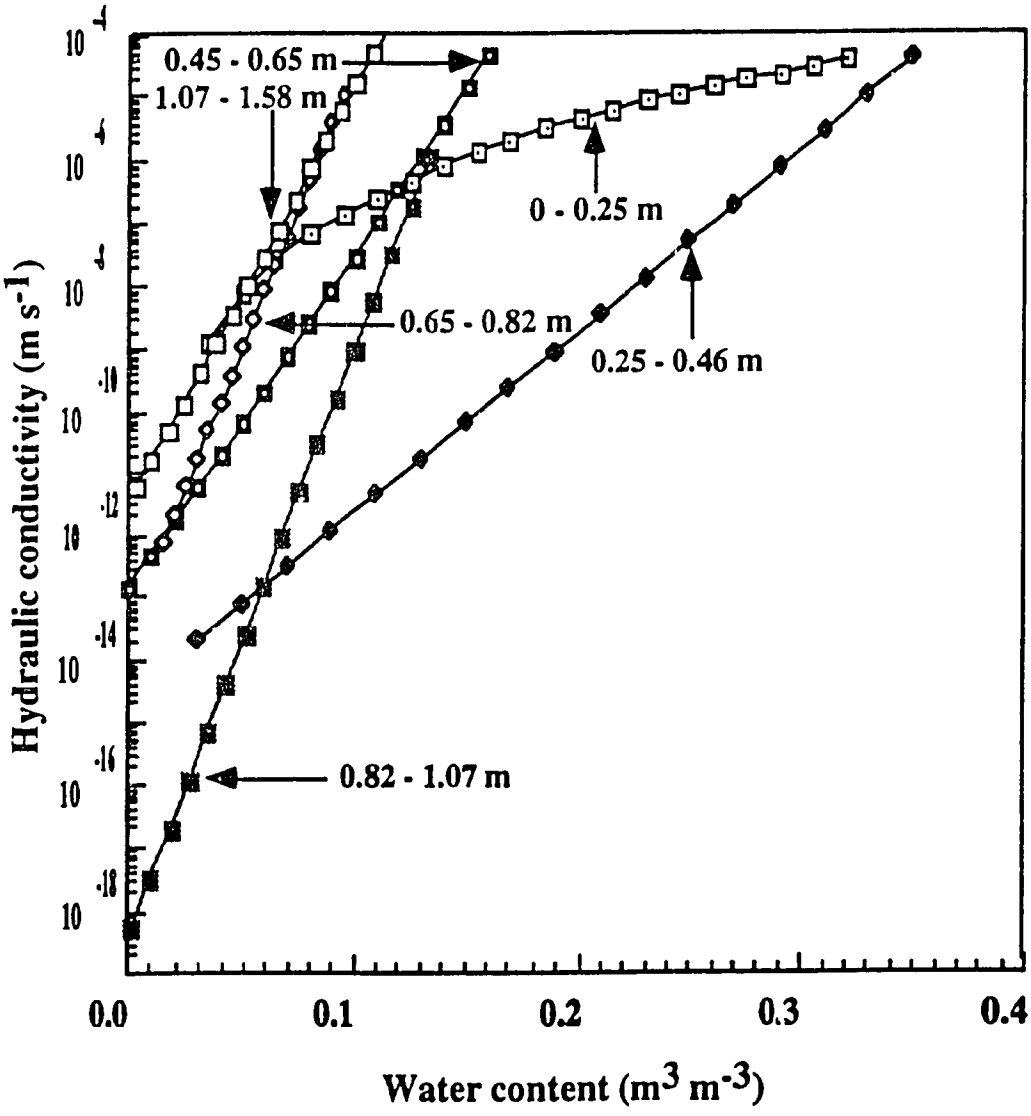

Figure 12. Mean (three replicates) soil hydraulic conductivity as a function of depth for the soil horizons at the experiment site.

Water movement across the "clogged" layer was greatly reduced. After water was applied for more than 12 hours with a hydraulic head of 0.15 m the wetting front stopped at 0.9 m. Furthermore, since the soil surface was covered with a plastic film to eliminate soil evaporation, significant changes of soil water content 372 hours after water application occurred only in the top 0.6 m. This determination was made on March 1991, six months after the rainy season. Therefore, the wetting front had passed the clogged layer, creating the possibility for significant water movement (normally considered as drainage) below that layer. Consequently water movement from the internal drainage experiment, did not represent water dynamics during the growing season.

In terms of soil water management, most of the rainfall supply is likely to be lost by evaporation and/or transpiration (see section on rainfall), given the high PET values in this region. Drainage is also slower on the lowland soils. Therefore, depending on root growth, distribution, and water uptake this restrictive horizon is likely to slow the wetting front significantly and to reduce the opportunity to enhance deep water penetration for conservation purposes. Based on the soil properties discussed above, three hypothesis can be formulated for the low hydraulic conductivity at 0.9 m depth; (1) soil compaction, (2) clay enrichment (clay pan like), and (3) clogged pores due to soil salinity. Even though there was an increase of bulk density at that horizon compared to the others, it still remained less than 1.6 Mg m^{-3}. Clay distribution with depth does not support the second hypothesis either.

Limited root growth and water movement during the growing season provide a strong support to the clogged pores hypothesis, making it the most likely. A schematic diagram, presented in Fig. 13, illustrates the occurrence of the low hydraulic conductivity observed between 0.82 and 1.07 m. It also explains the fate of the salt that was accumulated at the soil surface at that time. Irrigated agriculture stopped on this soil in 1973, and since then about 10 m of water (from rainfall) have been applied. The drastic textural transition observed in the restrictive soil layer caused infiltrating water to accumulate at the bottom of the upper layer before penetrating the transitional layer. The successive downward flow and accumulation of water that is charged with salt (from the surface) caused accumulation of salts. In addition, dispersed materials that are transported tend to accumulate. As a result (Kamphorst and Bolt, 1978), inter-aggregates are clogged and the soil is sealed, therefore, hydraulic conductivity was significantly lowered. This model suggests that the process occurred between 1973, when severe soi salinity problems developed, and 1990, when irrigation was initiated again. However, it cannot provid the duration for each step in the process. Sampling in the field for gravimetric water conten determination indicated that the sealed layer was present in the entire field. The mean depth of occurrenc was 0.9 m (9 replicates with a standard deviation of 0.15 m) and the mean thickness was 0.20 m (replicates with a standard deviation of 0.15 m).

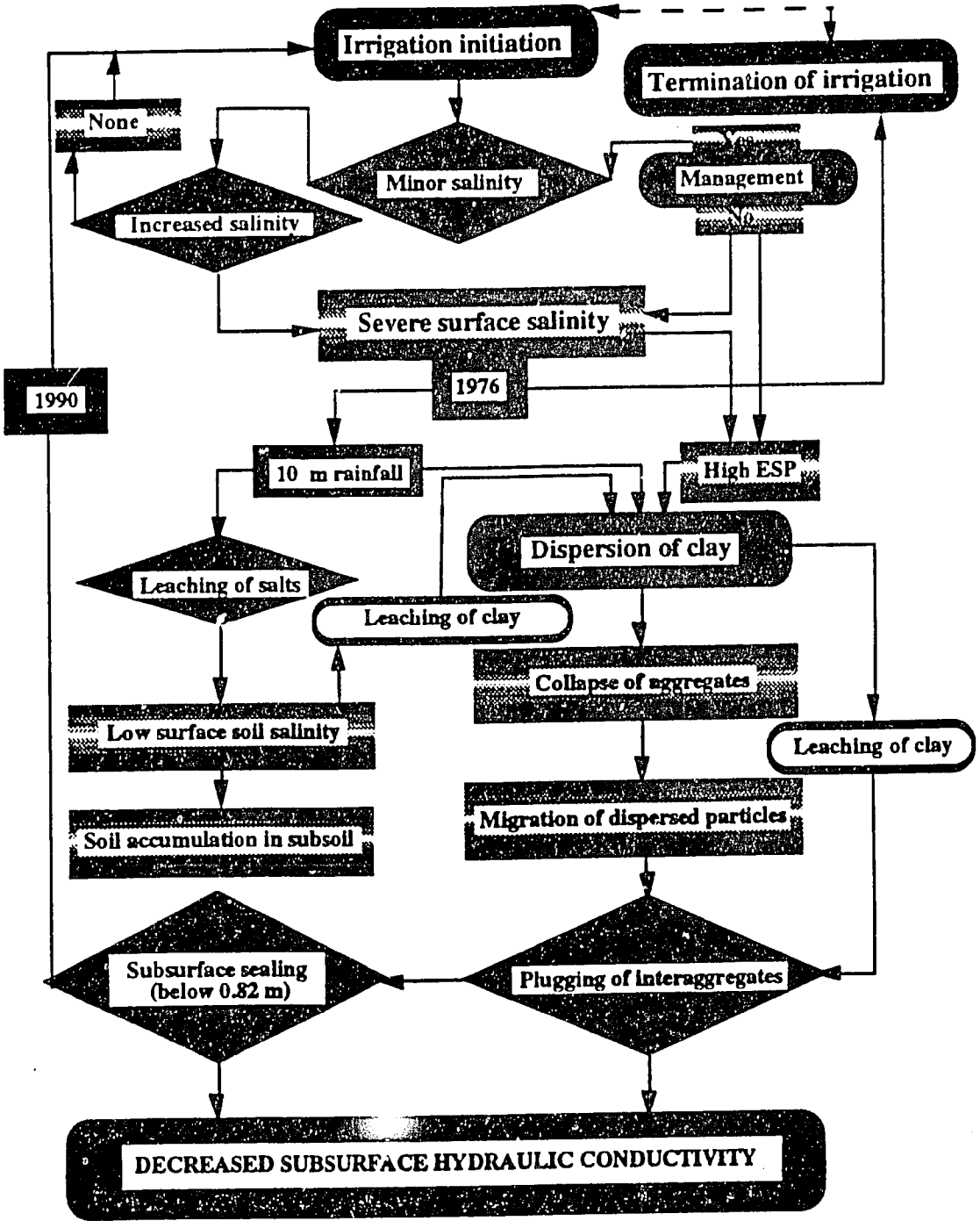

Figure 13. Proposed model for occurrence of the low subsoil hydraulic conductivity at the experiment site.

Soil sealing between 0.90 to 1.1 m depth constitutes a root barrier reducing the effective rooting zone. Cumulative water retention in the top 2 m is presented in Fig.14. Based on the combined field and laboratory soil water retention measurements the maximum amount of water this soil layer can hold is 237 mm, of which 64 mm is considered to be available water. Given the high evapotranspiration demand on this site, available water can be depleted in 7 to 10 days. Water input from either rainfall or irrigation should match this frequency to insure the proper water supply for plant growth. Special care (proper drainage system and leaching requirement) is required to avoid repeated development of surface salinity, otherwise, future reclamation may require not only leaching but also chemical treatment (gypsum).

d. Soil chemical properties

Selected soil chemical properties are given on Table 7. Soil pH (water) is neutral to slightly alkaline in the entire profile. It ranged from 7.8 at the surface to 6.7 between 0.46 and 0.65 m. The highest pH value, 8.1, occurred between 0.82 and 1.07 m; pH (KCl) ranged from 6.2 to 6.9. Unlike sandy upland soils, pH ranges from 5 to 6.5, CEC from 0.5 to 3 cmole(+) kg^{-1}, (Tropsoils, 1991) and acidity and aluminum toxicity are frequently present (Wendt, 1986; Zaongo, 1988; Wilding and Hossner, 1990, Zaongo etal. 1993). The CEC values ranged from 3.7 to 14.6 cmole(+) kg^{-1}.

Concentrations of different elements as a function of depth are presented in Table 8. Extractable phosphorus concentration are low throughout the profile, ranging from 0.012 g kg^{-1} at the surface to 0.002 g kg^{-1} between 1.58 and 1.89 m depth. This is high compared to upland sandy soils. However, levels are low compared to the minimum 0.2 g kg^{-1} soil solution value suggested by Tisdale et al. (1982) for proper plant nutrition. Therefore, phosphorus application is necessary to provide proper P nutrition in this soil. Total soil nitrogen content was relatively high compared to upland soils where concentrations ranged from 0.04 to 0.25 g kg^{-1} (TropSoils, 1991). Exchangeable potassium content are moderately high ranging from 0.27 to 2.21 cmole(+) kg^{-1}. The lowest value occurred at 0.75 m while the highest value occurs at about 2 m. Sodium ranged from 0.08 (at the surface) to 3.21 cmole(+) kg^{-1} between 1.07 and 1.58 m. Negligible salt concentration (0.1 cmole(+) kg^{-1}) at the surface is an indication of leaching of the surface soil salt initially accumulated from irrigation, prior to 1973. However, salt concentration in the rest of the profile particularly between 1.07 and 1.58 m depth is high. Sodium concentration was also relatively high (1.3 cmole (+) kg^{-1}) in the 0.82 to 1.07 m layer. The highest Na concentration was located underneath this horizon. Calcium concentration was 3 cmole(+) kg^{-1} in the soil surface and tended to decrease with depth down to 1.07 m. The concentration reached 3.3 cmole (+) kg^{-1}) below 1.07 m and tended to decrease thereafter. Magnesium concentration followed the same trend as calcium. However concentrations were much lower with Mg than Ca. The concentration of both Mg and Ca were adequate for plant growth. In the other horizons, mean concentration was about 0.88 cmole(+) kg^{-1}.

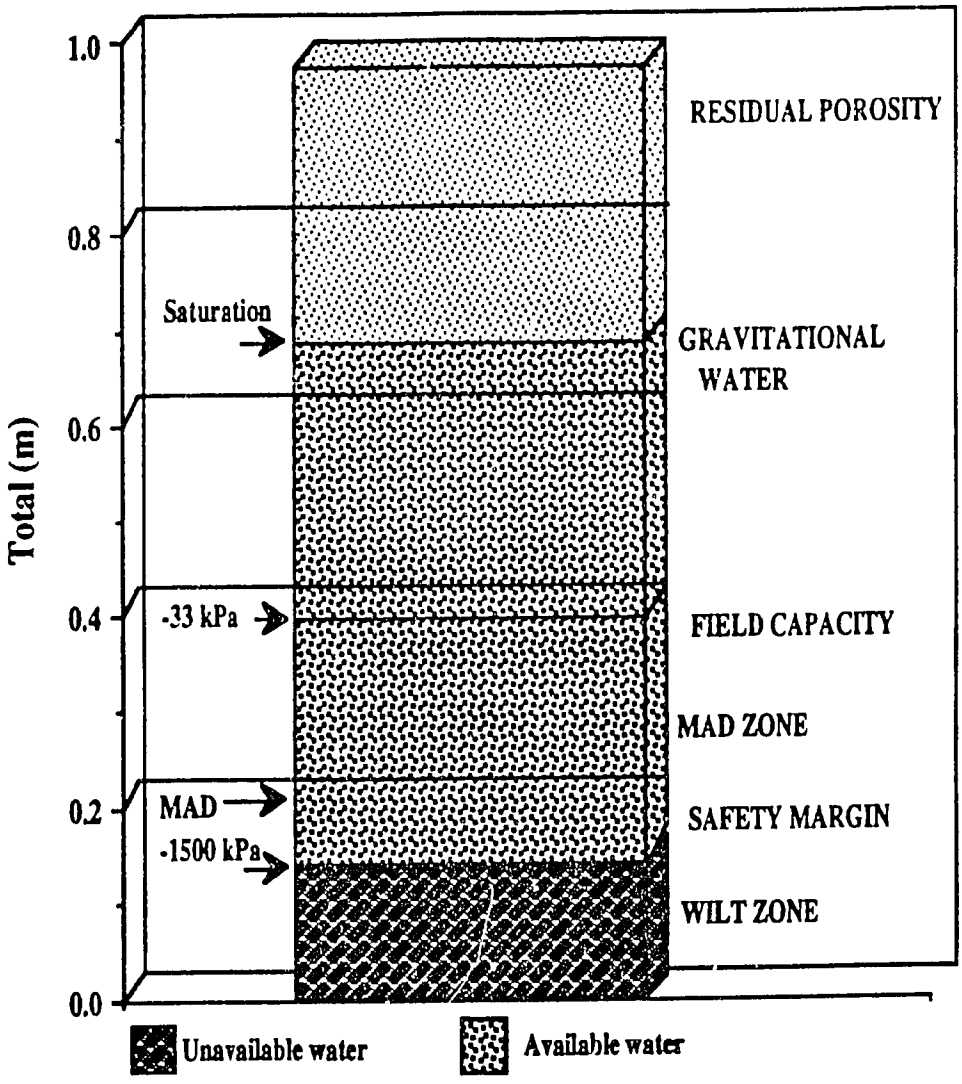

Figure 14. Cumulative porosity and water retention of the top 2 m soil at the experiment site.

Table 7. Mean and standard deviation (3 replicates) of soil pH, cations exchange capacity (CEC), and base saturation (BS) at the experiment site.

Soil depth	pH (2:1 extract)				CEC		BS	
(m)	H_2O		KCl		(cmole(+) kg^{-1})		(%)	
	Mean	SD†	Mean	SD	Mean	SD	Mean	SD
0.00 - 0.25	7.8	0.3	6.4	0.2	5.5	0.1	72	3
0.25 - 0.46	7.1	0.4	6.2	0.3	8.5	0.2	67	4
0.46 - 0.65	6.7	0.2	6.3	0.4	12.8	0.4	73	3
0.65 - 0.82	7.1	0.6	6.6	0.2	3.7	0.3	76	4
0.82 - 1.07	8.1	0.5	6.9	0.5	9.6	0.2	35	1
1.07 - 1.58	7.5	0.4	6.6	0.4	11.1	0.1	43	2
1.58 - 1.89	7.6	0.3	6.7	0.3	12.2	0.2	55	3
1.89 - 2.11	7.4	0.2	6.9	0.1	14.6	0.3	59	2
2.11 - 2.43	7.7	0.3	6.8	0.1	13.8	0.2	57	3

† Standard deviation.

Table 8. Mean and standard deviation (4 replicates) of soil total nitrogen (N), available phosphorus (P), extractable potassium (K), exchangeable sodium (Na), exchangeable calcium (Ca), and exchangeable magnesium (Mg) at the experiment site.

Soil depth	Elemental concentration					
			Exchangeable cations			
	Total N	Bray-1P	K	Na	Ca	Mg
m	g kg^{-1}		cmole(+) kg^{-1}			
	MEAN					
0.00 - 0.25	0.72	0.012	1.4	0.1	3.0	0.7
0.25 - 0.46	0.47	0.007	0.8	0.4	2.7	0.6
0.46 - 0.65	0.18	0.010	0.8	0.5	3.4	0.9
0.65 - 0.82	0.14	0.003	0.3	0.9	2.2	0.8
0.82 - 1.07	0.19	0.004	0.2	1.3	1.0	0.4
1.07 - 1.58	0.20	0.007	0.7	1.0	3.3	0.9
1.58 - 1.89	0.38	0.002	1.7	0.7	2.7	0.9
1.89 - 2.11	0.19	0.004	1.3	0.4	3.0	1.0
2.11 - 2.43	0.20	0.004	1.3	0.6	2.6	0.7
	STANDARD DEVIATION					
0.00 - 0.25	0.03	0.0008	0.1	0.05	0.4	0.1
0.25 - 0.46	0.02	0.0005	0.1	0.07	0.5	0.2
0.46 - 0.65	0.04	0.0004	0.2	0.03	0.3	0.1
0.65 - 0.82	0.03	0.0004	0.1	0.04	0.4	0.2
0.82 - 1.07	0.02	0.0002	0.1	0.08	0.5	0.1
1.07 - 1.58	0.04	0.0006	0.3	0.02	0.6	0.2
1.58 - 1.89	0.05	0.0008	0.2	0.07	0.4	0.1
1.89 - 2.11	0.03	0.0007	0.2	0.06	0.2	0.2
2.11 - 2.43	0.02	0.0001	0.1	0.03	0.3	0.1

Predominant characteristics of this soil were (1) neutral pH, (2) relatively high salinity (Table 9) in the subsoil, (3) low phosphorus content, and (4) low nitrogen content. Since soil salinity has been a cause for concern in the past, it was appropriate to assess the salinity characteristics. These characteristics are given in Table 9. Electrical conductivity of the surface soil was relatively low (0.106 10^4 S m^{-1}) and it tended to increase from the soil surface to a maximum of 0.9 S m^{-1} between 0.82 and 1.07 m. USDA (1954) suggested a growth threshold level 6.8 mmhos cm^{-1} (68 S m^{-1}) for sorghum and 4.9 mmhos (49 S m^{-1}) for cowpea. I- this layer, electrical conductivity was high enough (86 S m^{-1}) to limit root growth. Below this restrictive horizon EC decreased gradually to approximately 0.01 S m^{-1} below 2 m. Exchangeable sodium percentage (ESP) ranged from 1 to 23%. The highest value occurred in the restrictive layer. Hillel (1980) suggests that ESP value higher than 10 % are indicative of reasons for concern about salinity and low permeability problems.

Maximum SAR was 13 $mmole^{0.5}$ $l^{-0.5}$ and occurred in the sealed layer. This value is considered to be medium by Bolt and Bruggenwer (1978) and to present sodication hazards. This soil is characterized by neutral to slightly alkaline pH values, low CEC, low fertility (particularly N and P), and a subsoil layer (0.82 to 1.07 m) with relatively high ESP, SAR, and electrical conductivity. Subsoil characteristics confirm validity of the model suggested earlier for the occurrence of low subsurface hydraulic conductivity.

2. Atmospheric characteristics

a. Air temperatures

One of the most important weather characteristics for crop water use is air temperature. This parameter was recorded continuously during the crop growth period. Mean hourly values are presented in Fig. 15. Temperatures ranged from 17 to 37°C throughout the season. Maximum temperature generally occurred between 2 and 4 PM. They ranged from 27 to 37°C, decreasing from July to August. After August (day 256, 1450 h) maximum temperature increased gradually to 37°C. Minimum temperature ranged from 17 to 25°C and tended to decrease at the end of the growing season. Minimum temperatures occurred between 6 and 7:30 AM. Minimum amplitude between maximum and minimum temperature occurred generally during the rainy period. Amplitude was the greatest at the end of th growing season. Mean daily air temperature was 26°C. Maximum and minimum dew poir temperatures for the model were calculated from air temperature using Eq. [15]. It followed the sam trend as air temperature with the highest amplitudes at the end of the growing season. Mean daily de point temperature during the growing season was 24°C.

Table 9. Mean and standard deviation (4 replicates) of soil electrical conductivity (EC), exchangeable sodium percentage (ESP), and sodium absorption ratio (SAR) of saturated soil extract at the experiment site.

Soil depth	EC	ESP	SAR
___ m ___	10^{-4}S m^{-1}	%	$mmole^{0.5}$ $l^{-0.5}$
0.00 - 0.25	11 (2†)	1 (1)	0 (0.1)
0.25 - 0.46	13 (2)	5 (1)	2 (0.1)
0.46 - 0.65	14 (1)	4 (1)	2 (0.2)
0.65 - 0.82	21 (2)	9 (2)	4 (0.4)
0.82 - 1.07	86 (5)	23 (2)	13 (0.8)
1.07 - 1.58	63 (3)	9 (3)	8 (0.4)
1.58 - 1.89	12 (2)	6 (2)	6 (0.2)
1.89 - 2.11	10 (1)	3 (1)	4 (0.1)
2.11 - 2.43	11 (1)	5 (1)	5 (0.1)

† Standard deviation

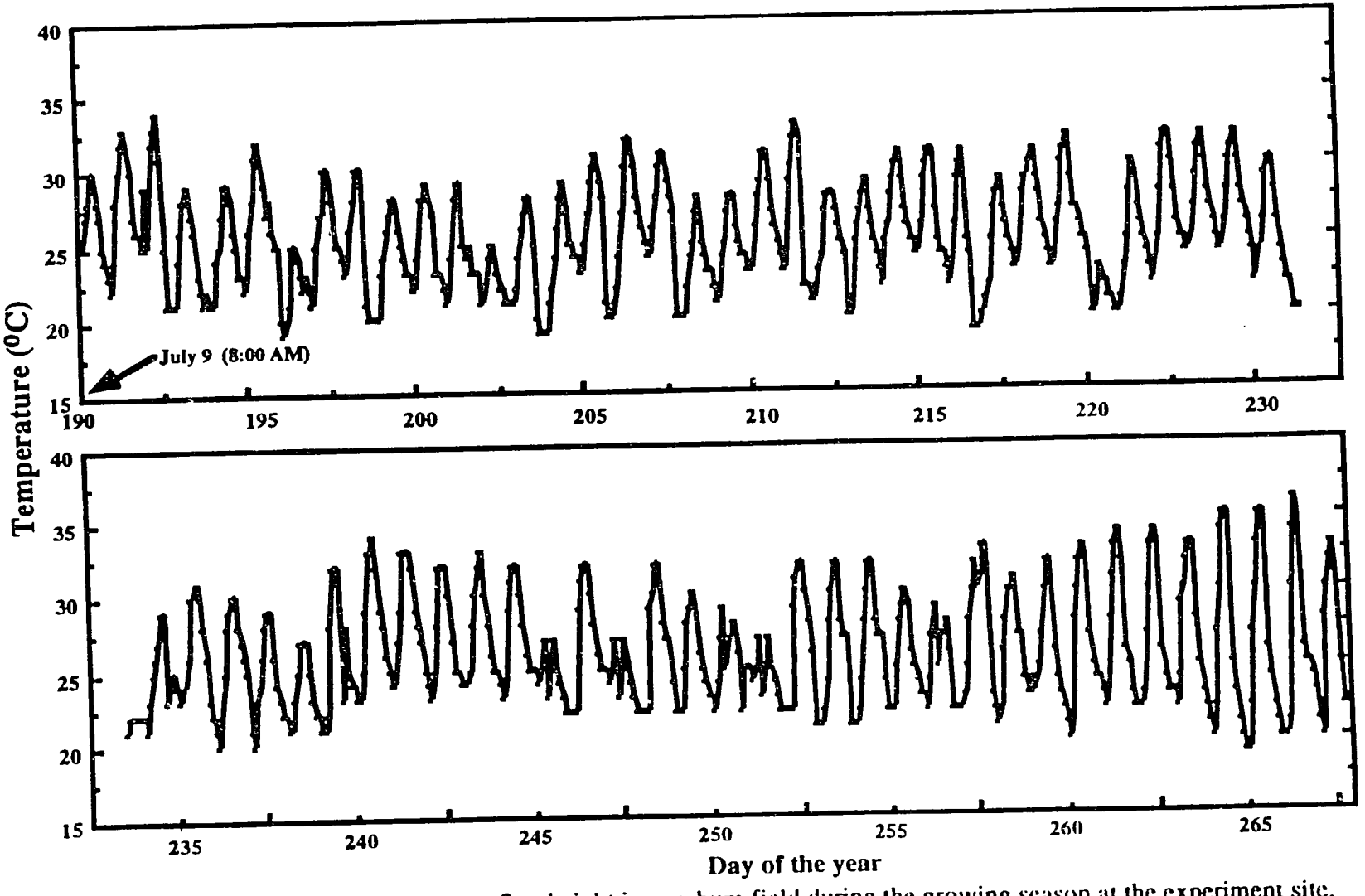

Figure 15. Mean hourly air temperature at 2 m height in sorghum field during the growing season at the experiment site.

b. Relative humidity

Relative humidity is presented in Fig. 16. Values ranged between 45 and 85% during the first part (day 195 to 235) of the growing season and between 15 and 85% after day 260. The wettest period occurred between day 245 and 260. Mean atmospheric pressure in the experiment site was 87.26 kPa (Aéroport Maradi, 1991).

c. Wind speed

Mean daily wind speed during the growing period was 1.2 m s^{-1} (Fig. 17). It tended to decrease from the beginning (day 180) to the end (day 300) of the season. Maximum daily wind speed was 4.8 m s^{-1} which corresponds to atmospheric perturbation brought in by the ITF. The occurrence of showers did not coincide with higher wind speed when compared to non-rainy days. From day 260 to the end of the growing season, wind speed tended to increase from 0.8 to 1.2 m s^{-1}. Total wind run from day 182 to day 320 was 9218 km.

d. Solar radiation

Mean daily solar radiation during the growing season was calculated to be 19.4 MJ m^2 day^{-1}. It increased from 24 (day 180) to a maximum (Y = 24.5 MJ m^{-2} d^{-1}) on day 203 when the maximum solar radiation occurred (Fig. 18). After day 208, day to day solar radiation decreased to an inflection point (18 MJ m^{-2} d^{-1}) with a slope of -0.125 (asymptote). Throughout the season, cloudiness contributed to reduced radiation especially during the period when rainfall occurred during the daytime. Most of the rainfall events occurred during the nighttime and therefore had little effect on radiation. The threshold limit defined by the Franquin model (Franquin, 1984) for photosensitivity occurred between day 240 and day 250 (22 to 23 MJ m^2 day^{-1}) and was determined by the intersection of the asymptote and the maximum. Photosensitive sorghum crops used in this study was expected to bloom during that period and did so independently of their vegetative stage.

e. Potential evapotranspiration

Potential evapotranspiration ranged from 2 to 14 mm per day . Mean daily PET decreased from 11 mm at the beginning of the rainy season to a minimum of 5 mm (between day 240 and 260) and then increased to 10.5 mm at the end of the season. During the growing season mean rainfall supply was in the exceeded mean PET (Fig. 19). This is a key climatic condition that allows rainfed crop production without irrigation in the Sahel (Konaté, 1982).

f. Rainfall

Total rainfall over the growing season was 354 mm. However, rainfall frequency was not the best for crop water demand as a function of time (Fig. 20). Qualitative terms of the seasonal rainfall are presented in Table 10. Of the 354 mm total rainfall, only 300 mm occurred during the crop growth period. The first effective rainfall (rainfall > 15 mm) occurred in early July which is relatively late for

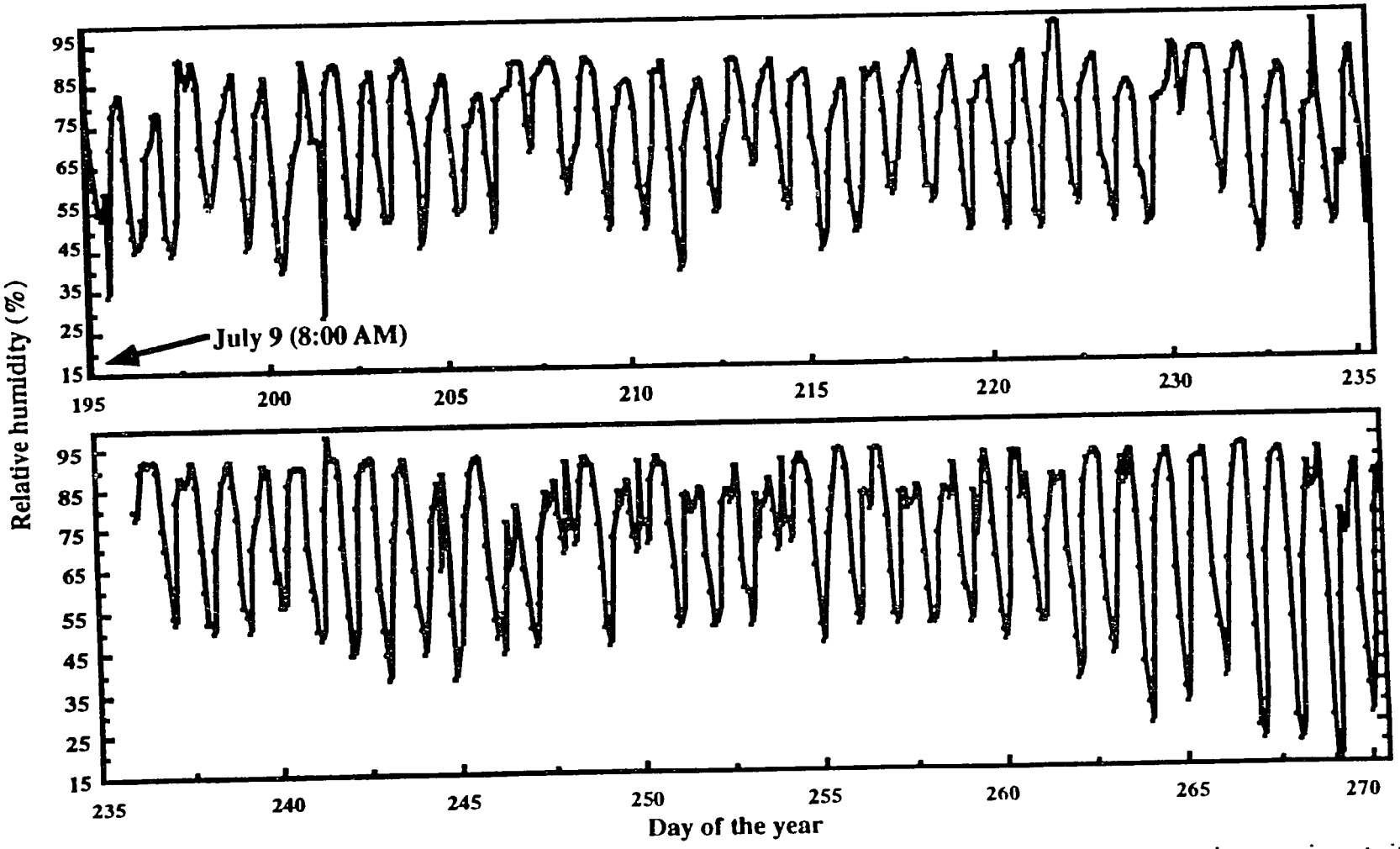

Figure 16. Mean hourly air relative humidity at 2 m height in the sorghum field during the growing season at the experiment site.

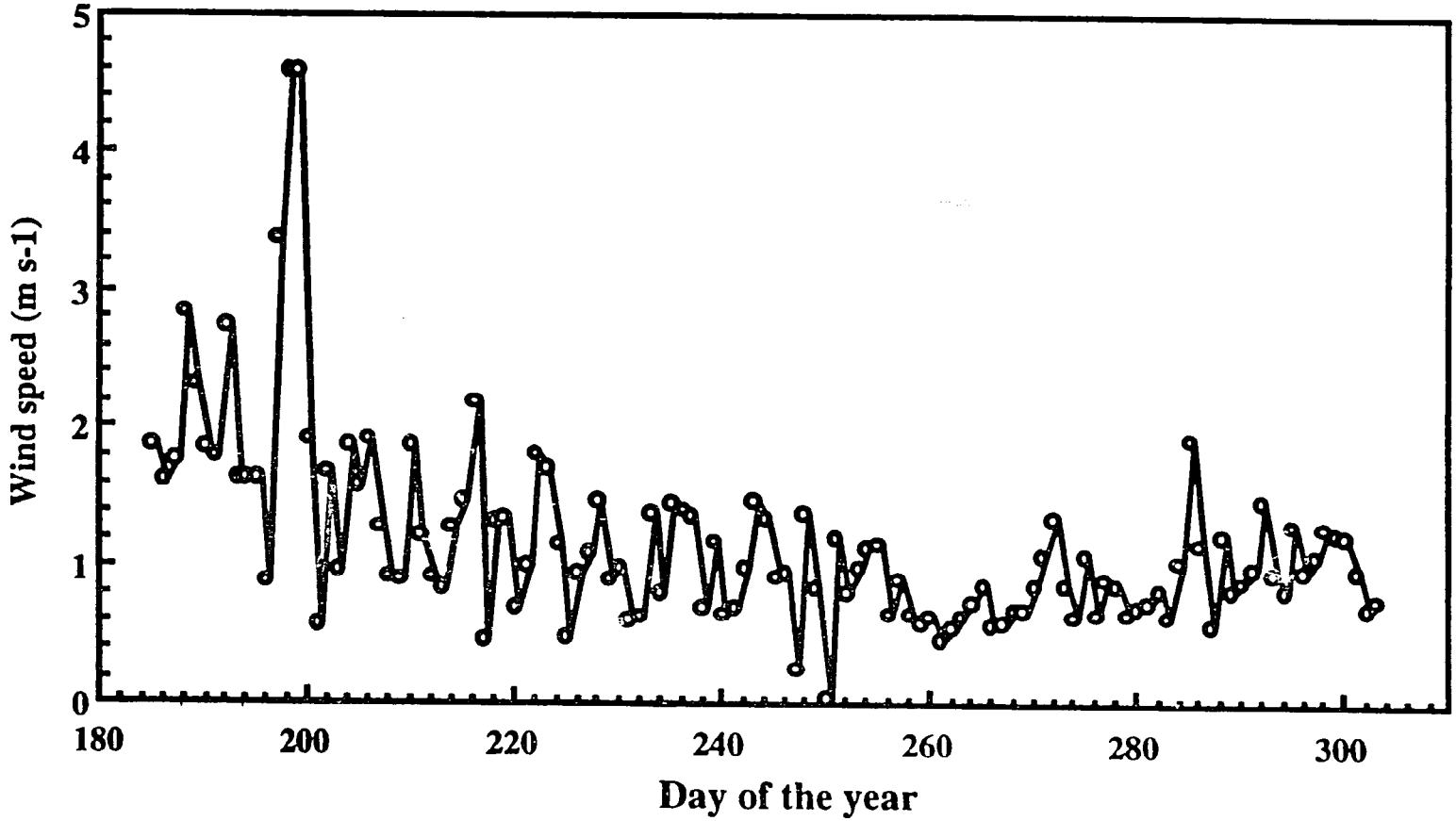

Figure 17. Mean daily wind speed at 2 m height during the growing season at the experiment site.

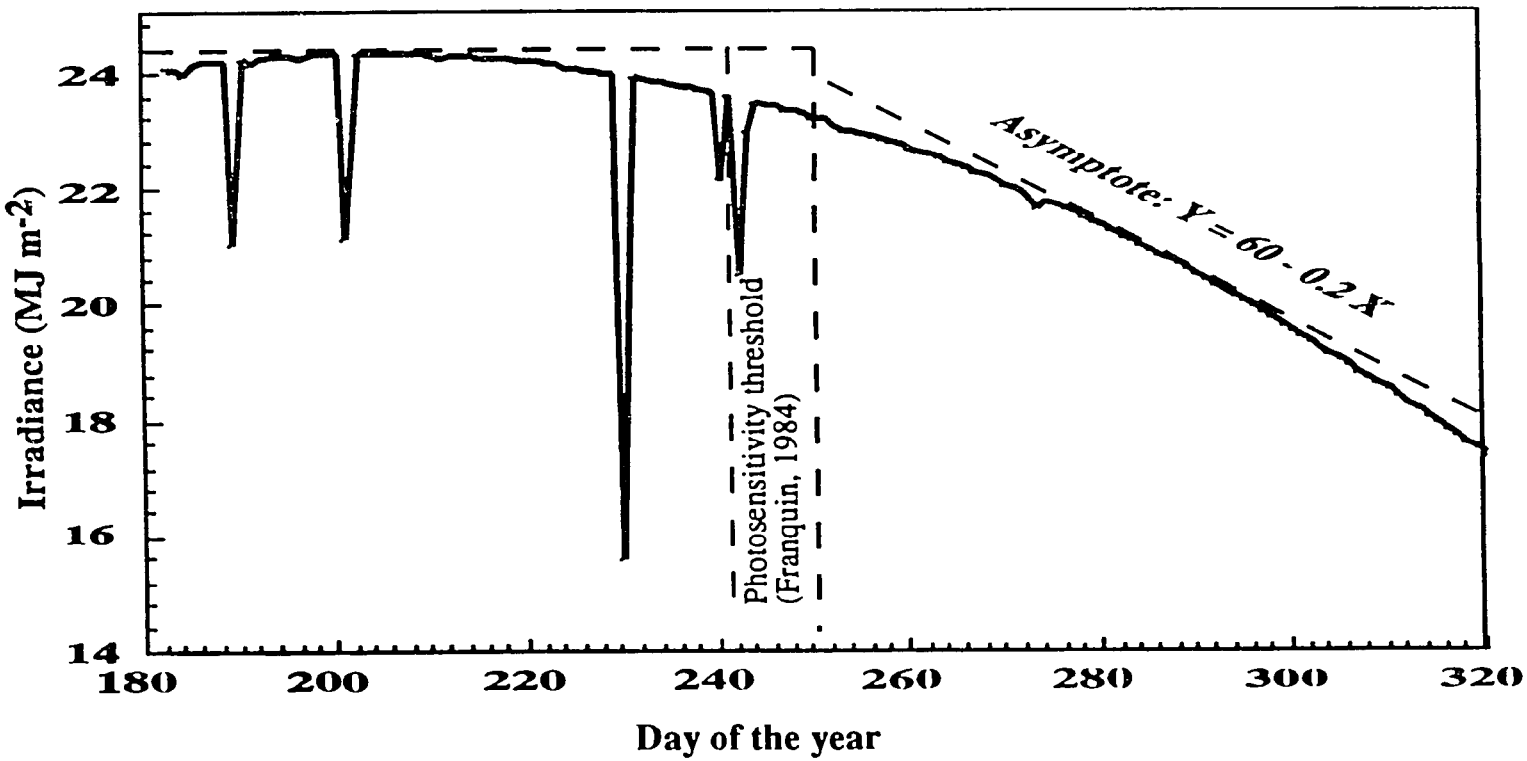

Figure 18. Mean total daily irradiance during the growing season at the experiment site.

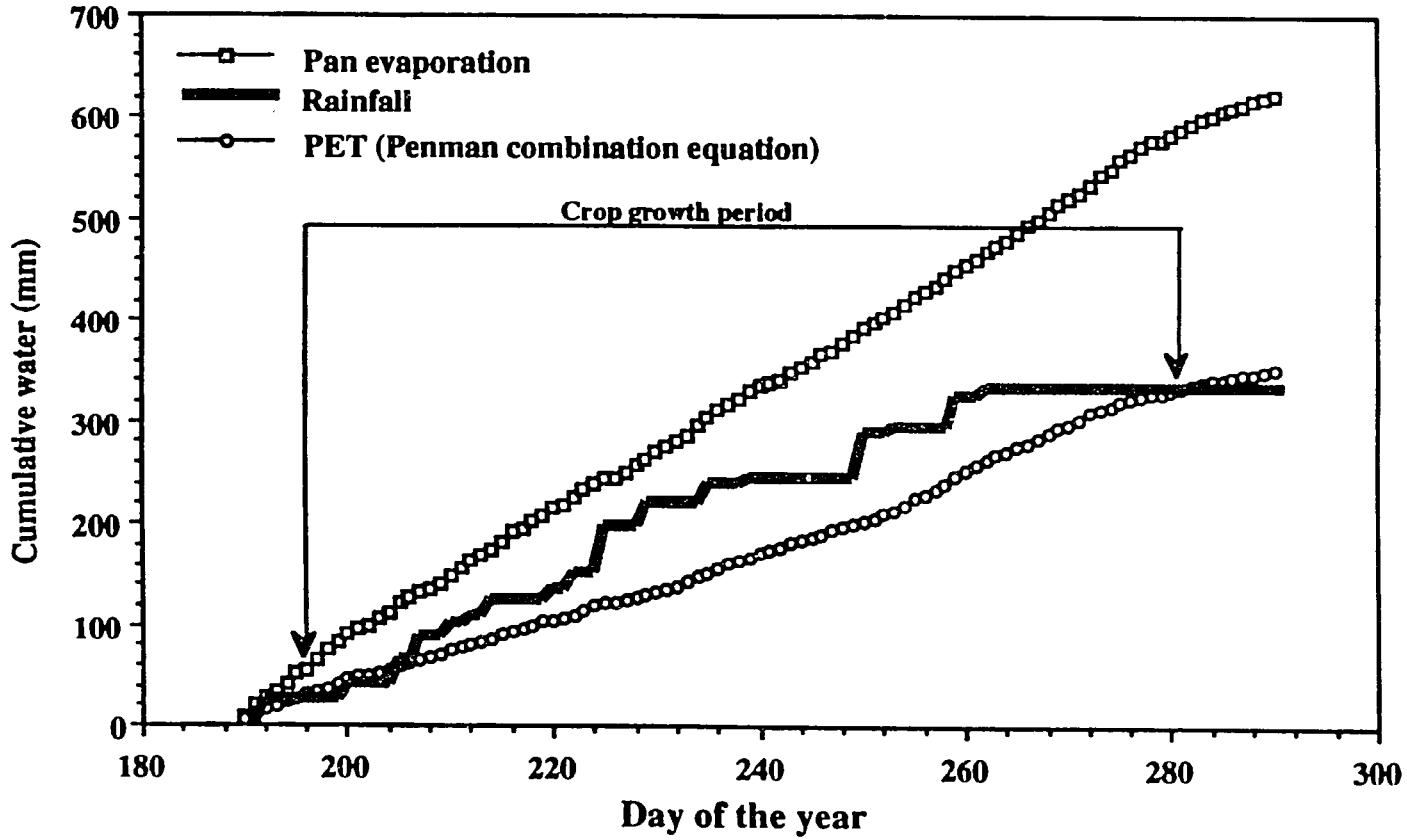

Figure 19. Cumulative evaporation, rainfall, and PET during the growing season at the experiment site.

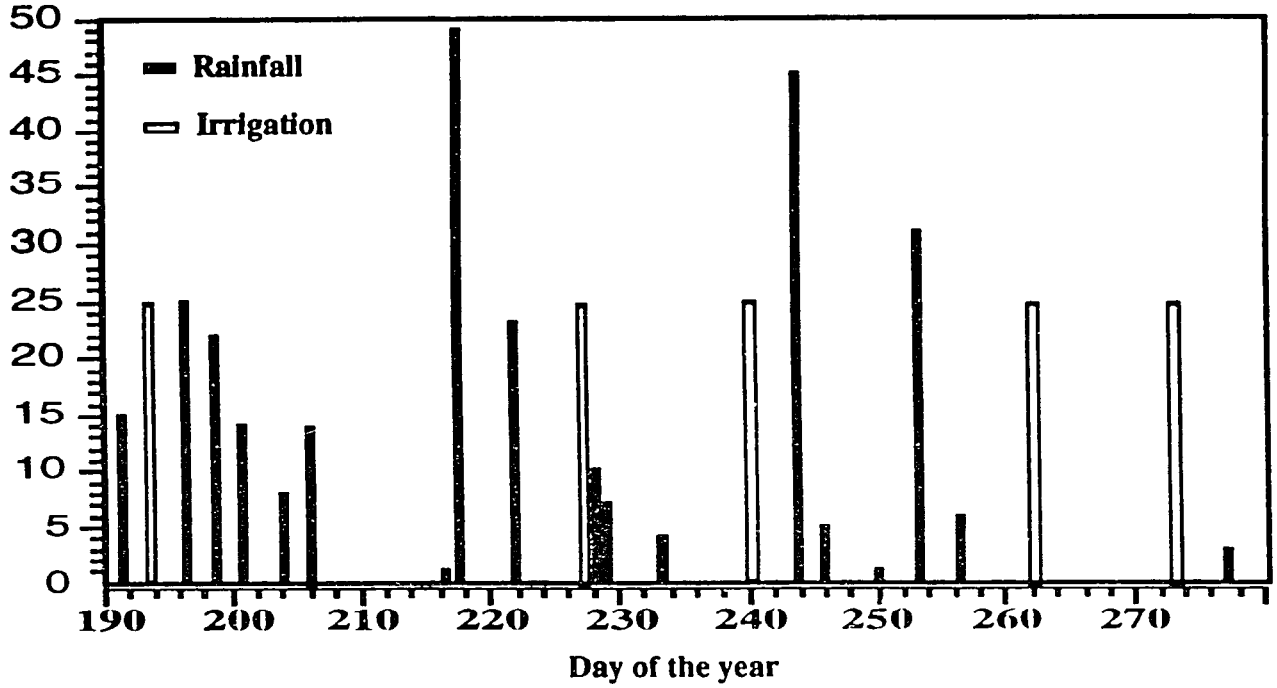

Figure 20. Rainfall and irrigation distribution during the growing season at the experiment site.

Table 10. Qualitative terms of seasonal rainfall.

Total annual rainfall	354 mm
Total growth period rainfall	300 mm
First effective† rain	July 3
Last effective rain	September 5
Duration of wet period	75 days
Total number of rains	22
Total numbers of effective rains	15
Mean rainfall intensity	12 mm h^{-1}

† Rainfall event greater than 15 mm.

sowing. In addition, the last effective rain occurred on September 4, which was early for the end of the rainy season. Therefore, the duration of the wet period was only 75 days.

Periods of moisture stress were encountered during the growing season. The first period resulted in poor seed germination on non-irrigated (dryland) plots (Table 11). The second induced crop wilting followed by crop death on the non-irrigated plots. The third period was the most critical; it occurred at the stage of grain formation and resulted in an increased number of empty heads on dryland plots. The occurrences of moisture stress was desirable from a research standpoint because it induced a wider range of water input levels. It also allowed an evaluation of the effects of different drought periods on yields. However, irrigation was required (Fig. 20). A total of 142 mm of irrigation water was applied to the irrigated plots.

To assess the agroecosystem climatic environment, weather characteristics are summarized in Appendix E. Mean relative humidity was 69% while total wind run was 9218 km. Heat units (above 15°C) were relatively high (1023°C), indicating that low air temperature was not a constraint to plant growth. The most outstanding feature in this ecosystem is the high amount of seasonal solar energy (2695 MJ m^{-2}) that is available during the rainy season. It is one of the indirect cause for the high evapotranspirational demand discussed earlier. This is supported by the seasonal evaporation (616 mm) recorded in the experiment site. In this region, temperatures can be as high as 45°C during the growing season in April.

B. Crop growth and production

1. Crop stand

Good crop germination and stand are the first steps toward a good crop growth and biomass production. Results on plant stand (two weeks after sowing) are shown in Fig. 21. Analysis of variance for this parameter are presented in Appendix C. Irrigation was the only factor with a significant effect on crop stand. It increased seed germination by 50%. This increase, as suggested by Konate (1982), gave an early advantage to crops on irrigated plots. There was no statistical significant differences between means of the non-irrigation treatments or between means of irrigated treatments.

Mulch increased crop stand by 1.3 % which was not statistically significant. This could be atrributed to the fact the sowing was performed shortly after rainfall and irrigation before the effect of mulch took place. Therefore, mulch had no effect on soil moisture at sowing. Irrigation was the only factor that increased soil moisture content at that time (Fig. 22).

Table 11. Observed moisture stress and their effect on crop during the growing season at the experiment site.

Begin	End	Duration	Rain	Observed effects
_____ Day of the year _____		days	mm	
183	191	8	0.9	Poor crop germination and stand on dryland plots.
226	241	14	4.4	Crop wilt, 15-20% crop death.
250	280	> 30	6.3	20% yield reduction.

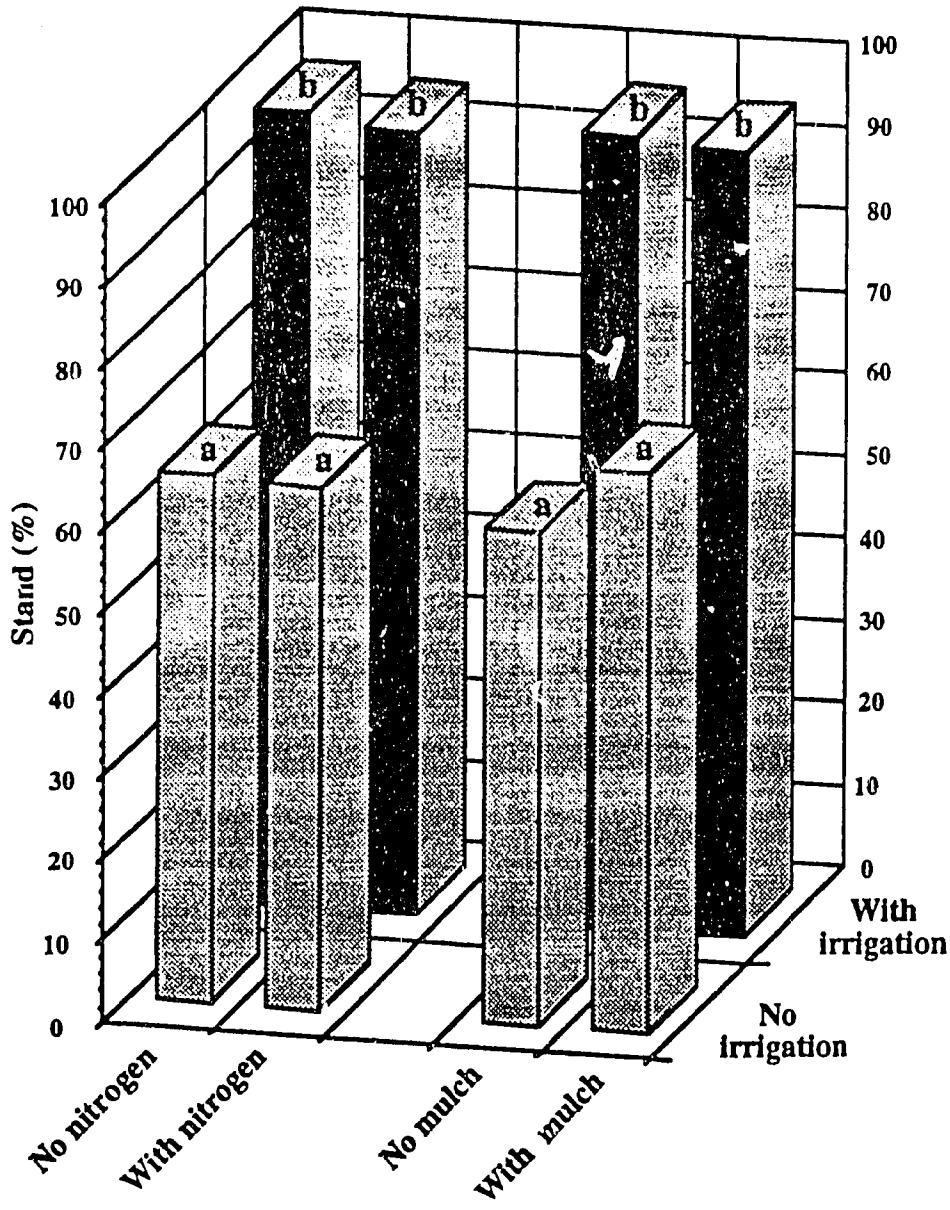

Figure 21. Effect of irrigation, nitrogen, and mulch on sorghum stand two weeks after sowing at the experiment site. Bars capped with different letters are statistically different (P = 0.05).

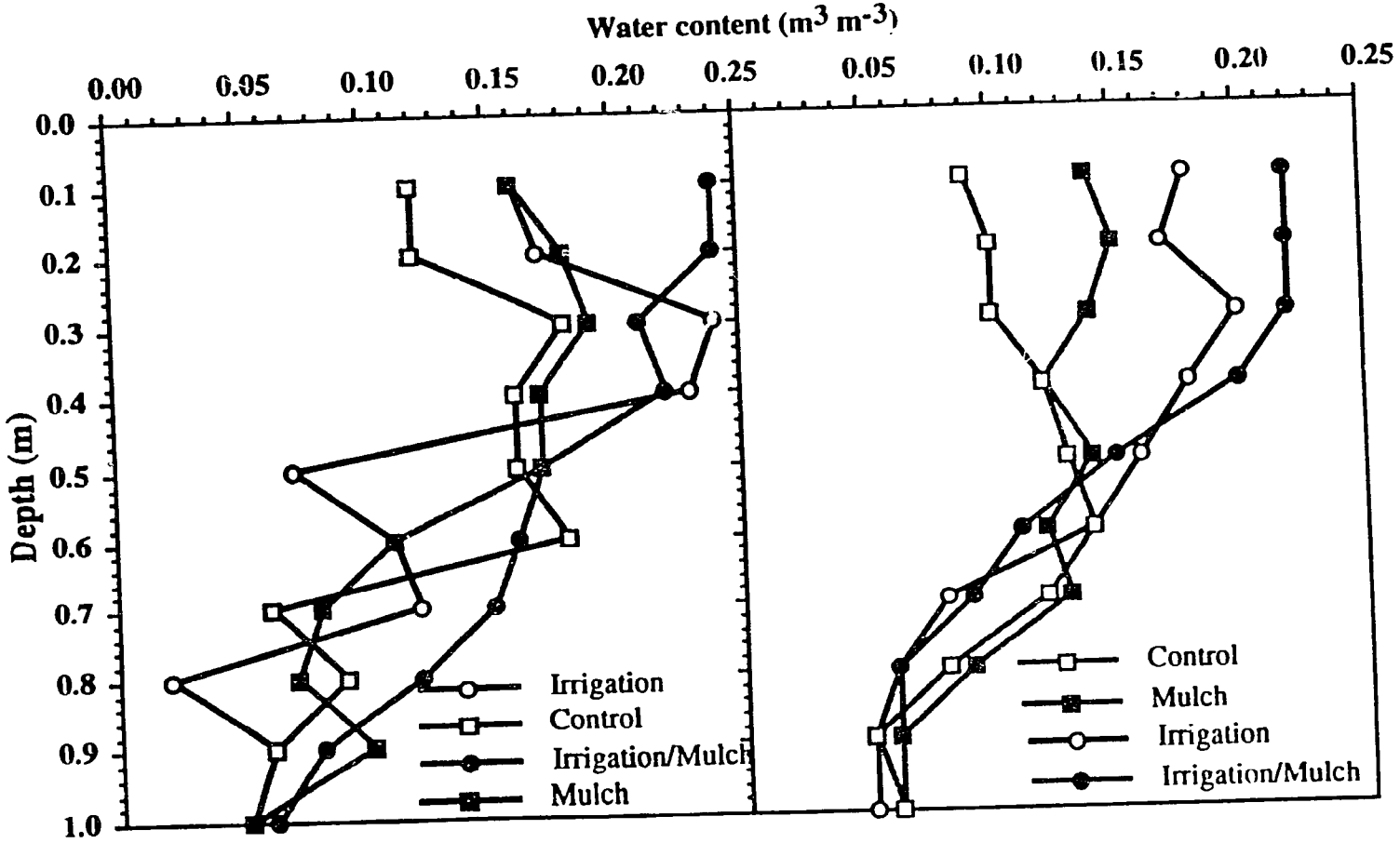

Figure 22. Effect of mulch on soil moisture distribution with depth at selected dates at the experiment sites

2. Crop survival

The conclusions drawn for crop establishment were also valid for crop survival. However, irrigation increased crop survival by 36%, which was statistically significant. Nitrogen did not have any significant effect on this crop parameter (Table 12). Mulch increased survival, but the increase was not statistically significant.

The lack of significant differences between treatments was primarily the result of the dry spells discussed earlier. Neither mulch nor nitrogen were able to offset the effects of these dry spells. Therefore, the spells caused crop death on dryland plots as indicated in Table 11. From crop stand and survival data analysis it can be concluded that irrigation had the greatest impact on crop response. However, one may wonder why mulch was not able to offset the effects of the dry spells. The response to this question may be found from results on root growth presented below.

3. Root growth and distribution

Root distribution is a key parameter for soil water and nutrient extraction by the crop. The fastest root development (maximum rooting depth and number of roots) for all the treatments occurred between day 237 and 258. Experimental factors affected rooting depth differently.

The effect of the control and irrigation treatments on root distribution during the growing season are presented in Fig. 23. From 0 to 0.5 m rooting was more intensive on irrigated plots compared to dryland plots. This trend was reversed below 0.5 m. After day 213 there was little increase in the number of roots in the top 0.2 m on dryland plots. The greatest increase occurred between 0.3 and 0.9 m. On irrigated plots there was a continuous increase of the number of roots in the top 0.8 m throughout the growing season.

Mulch and irrigation/mulch treatment (Fig. 24) followed the same trend as the control and irrigation treatments, but the number of roots in the top 0.5 m was higher. Unlike crops on the control treatment, crops on the mulch treatment had a steady and vigorous root growth throughout the growing season. The maximum rooting depth of crops on both treatments was limited to 0.8 m.

Final rooting depth of irrigation/nitrogen treatment (Fig. 24) was relatively deeper and denser as compared to the that of the irrigation treatment. Maximum rooting depth of the nitrogen treatment was shallower than that of the control treatment. Of all treatments, mulched and fertilized ones (nitrogen/mulch and irrigation/nitrogen/mulch) had the two shallowest rooting depth. irrigation/nitrogen/mulch treatment had the densest root system among all treatments. Most of the roots were concentrated between 0.2 and 0.35 m depth. In general, mulch and irrigation had a similar effect (shallow rooting) on root growth. They induced intense rooting in the soil surface, and reduced the maximum rooting depth to approximately 0.8 m.

Table 12. Effect of irrigation, nitrogen, and mulch on sorghum survival at the end of the growing season at the experiment site.

Parameter	Survival
	%
EXPERIMENTAL FACTOR: MAIN EFFECT	
Irrigation (I)	
None	70a†
With	95b
Nitrogen (N)	
None	81
With	83
Mulch (M)	
None	82
With	83
Mean	82
CV (%)	6
TREATMENT MEAN	
Control	65
M	71
N	73
N/M	70
I	94
I/M	96
I/N	96
I/N/M	94
LSD	
(5%)	7
(1%)	10

† Means within the same management factor followed by different letters are statistically significant (P = 0.05).

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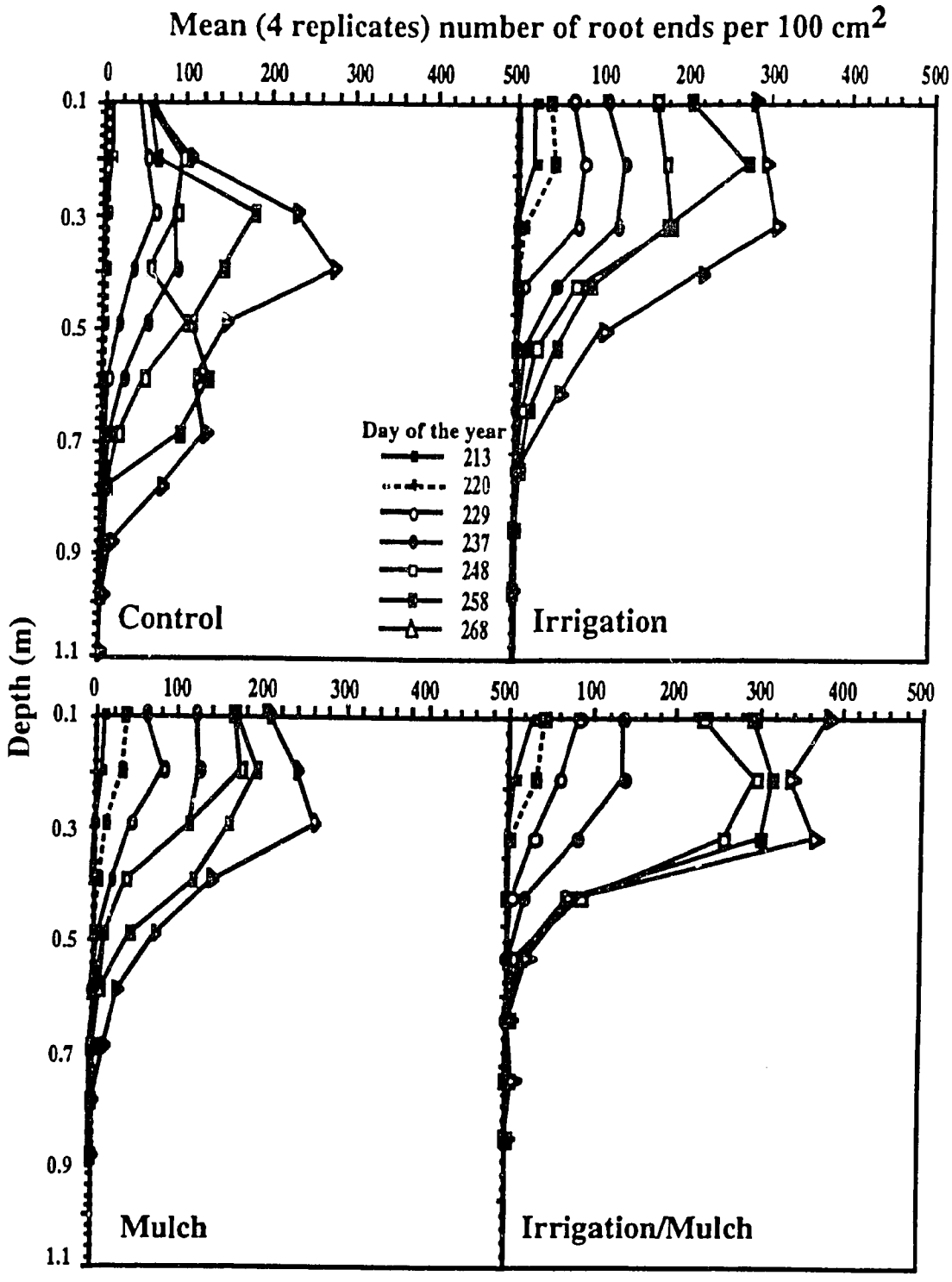

Figure 23. Effect of control, irrigation, mulch, and irrigation/mulch treatments on sorghum root distribution with depth at selected dates at the experiment site.

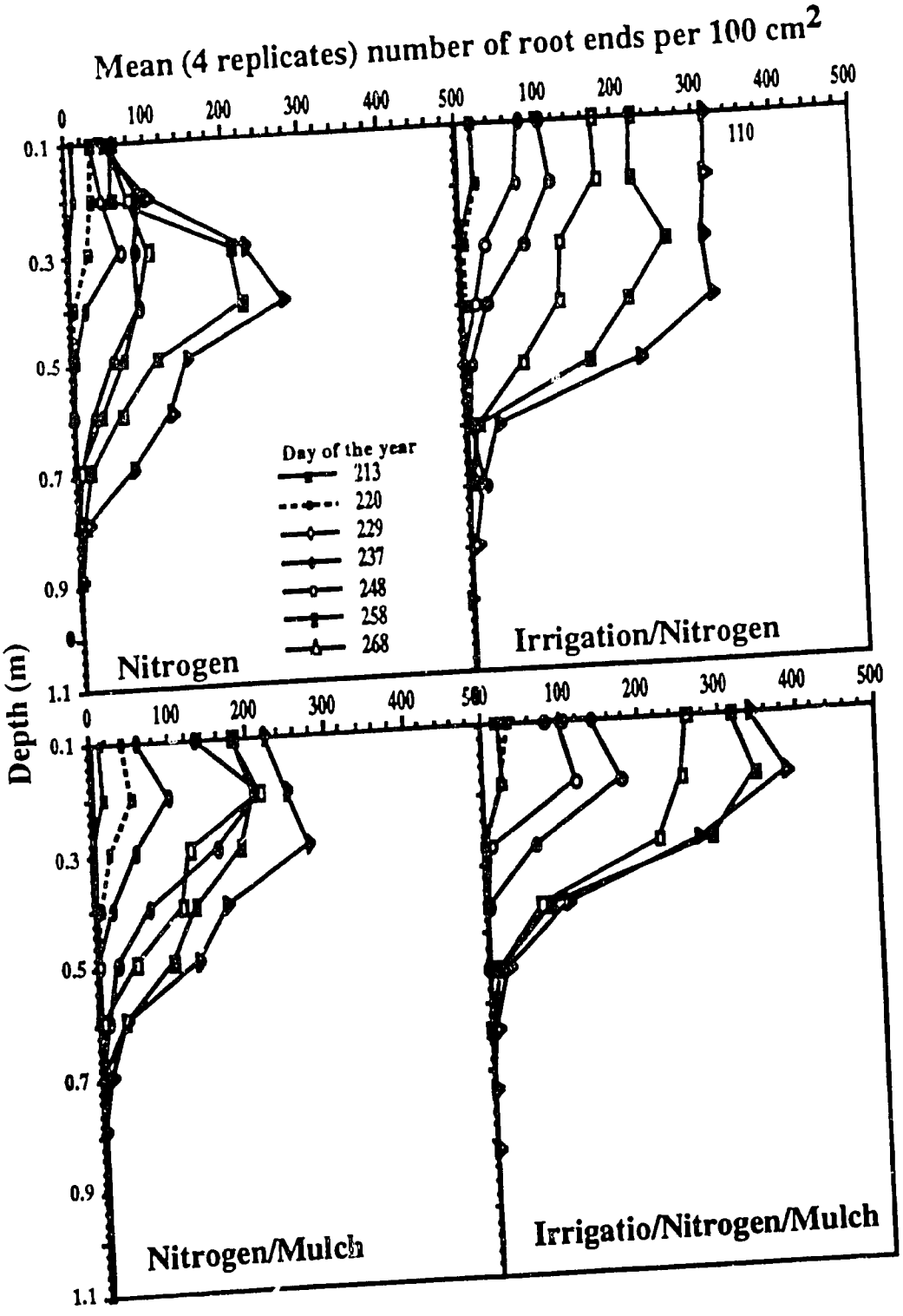

Figure 24. Effect of nitrogen/mulch, irrigation/nitrogen/mulch, irrigation/nitrogen, and nitrogen treatments on sorghum root distribution with depth at selected dates at the experiment site.

Causes for shallow rooting included cooler surface soil temperatures (5 to 8°C cooler) and a relatively prolonged conservation of surface soil moisture following rainfall or irrigation. This is discussed in details in the section on soil water balance. Both irrigation and mulch produced shallow rooting, but water was supplied in the irrigation treatment before moisture stress occurred. Water conservation was the only source of additional water on dryland plots. Therefore, the effect of extended moisture stress on mulched plots tended to be more drastic. Irrigation and mulch also caused a continuous and vigorous growth of roots in the top 0.5 m throughout the growing season. However, the effect of irrigation was Much greater than that of mulch (Fig. 23).

The effect of the different treatments on root growth can be grouped into three categories (Fig. 25) with distinct root concentrations in the top 0.2 m and distinct maximum rooting depths. The first category (nitrogen and control treatments) was characterized by less than 10% of the roots located in the top 0.2 m and an effective maximum rooting depth (90% of the top roots) of 0.65 m. The second category (mulch, nitrogen/mulch, irrigation, irrigation/nitrogen treatments) was characterized by 20% of the root located in the top 0.2 m and an effective maximum rooting depth of 0.35 m. The third category (irrigation/mulch and irrigation/nitrogen/mulch treatments) was characterized by 30% of the root located in the top 0.2 m and an effective maximum rooting depth of 0.25 m. In terms of soil nutrient and water extraction, the first category had the greatest efficiency since it caused the deepest root systems. Results of this study suggested that an addition of mulch and irrigation decreases the effective rooting depth. Therefore, it alters crop water use.

4. Plant height

Canopy structure and plant height are growth characteristics that affect soil-plant atmosphere energy and water relationships. They affect canopy aerodynamic resistance, crop resistance to heat, and momentum fluxes between the soil surface and the air. For all these reasons, they are important factors for soil evaporation and crop transpiration, hence crop WUE. Plant height as a function of time for the different treatments is presented in Table 13 and the ANOVA Table in Appendix C. Sorghum plants were less than 0.1 m for all treatments ten days after sowing but had an overall mean height of 2.61 m at harvest. Irrigation and mulch were the only treatments which significantly increased (33%) plant height on day 197. On that day, the combination of the three inputs (irrigation/mulch/nitrogen treatment) had the largest effect, followed by mulch, irrigation, and irrigation/nitrogen treatments. No interaction was statistically significant on that date.

Irrigation was the only factor with a statistically significant effect on day 208. Crop response to the different treatments followed the same pattern as that of day 197. However, mulch did not have a statistically significant effect and there was a statistically significant positive interaction between the three experimental factors on that date (Fig. 26).

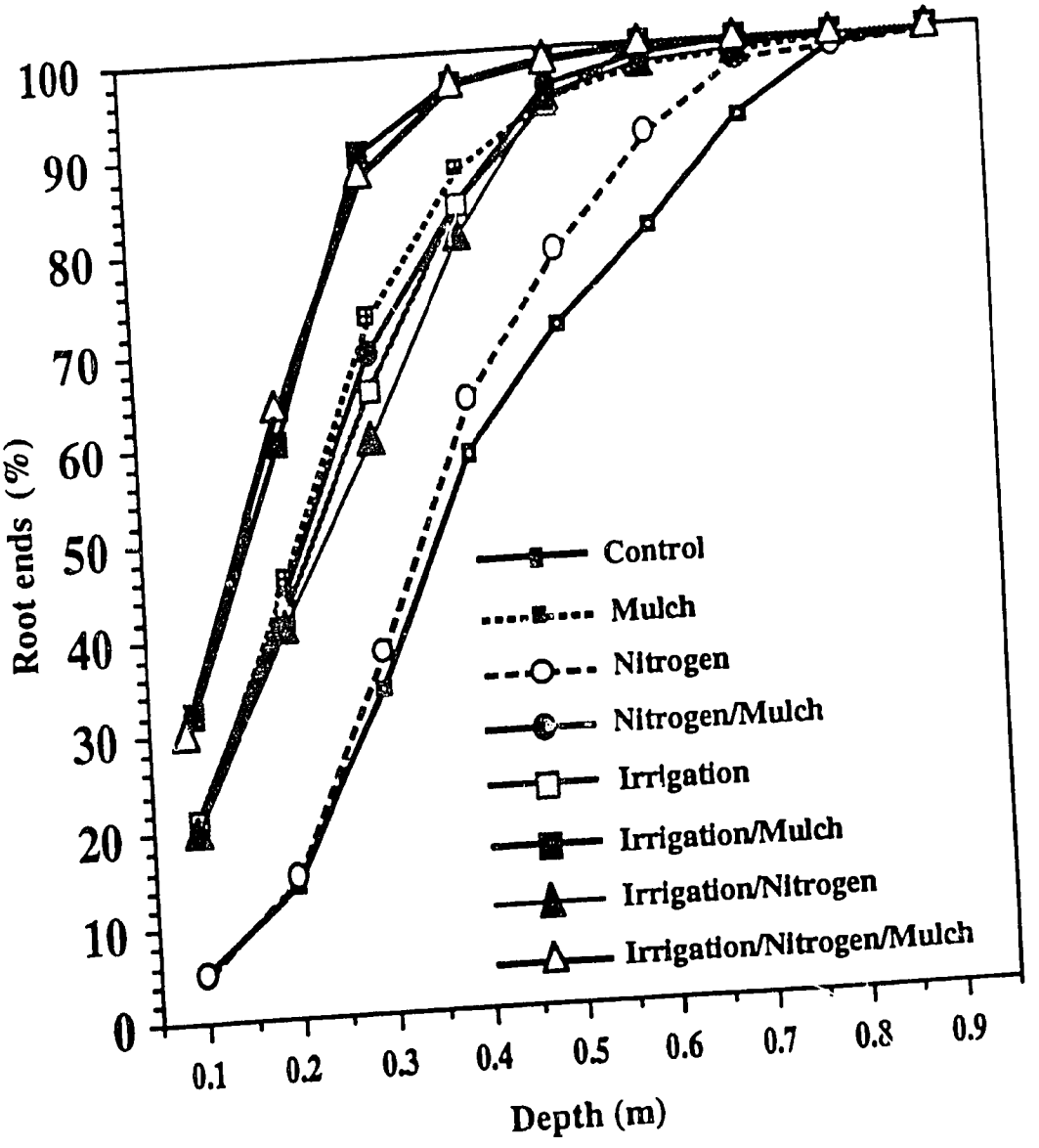

Figure 25. Effect of treatments on final cumulative number of root ends at the end of the growing season at the experiment site.

Table 13. Main factor mean (n = 20) and treatment mean (n = 5) plant height as affected by irrigation, nitrogen, and mulch during the growing season.

	Day of the year									
	197	208	213	218	229	237	248	258	268	278
	m									
EXPERIMENTAL FACTOR: MAIN EFFECT										
Irrigation (I)										
None	0.06a†	0.18a	0.66a	0.87a	1.39	2.20	2.40	2.52	2.56	2.29
With	0.08b	0.30b	0.80b	1.05b	1.76	2.25	2.57	2.53	2.67	2.64
Nitrogen (N)										
None	0.07	0.24	0.74	0.96	1.58	2.27	2.49	2.53	2.58	2.62
With	0.07	0.24	0.72	0.97	1.57	2.18	2.49	2.52	2.66	2.61
Mulch (M)										
None	0.06a	0.24	0.76	0.91a	1.61	2.26	2.47	2.53	2.64	2.58
With	0.08	0.23	0.70	1.01b	1.54	2.18	2.51	2.52	2.60	2.64
Mean	0.07	0.24	0.73	0.96	1.58	2.22	2.49	2.52	2.62	2.61
CV (%)	11	28	17	14	14	8	7	8	5	6
Interactions‡		IxNxM				IxM				NxM
TREATMENT MEAN										
Control	0.05	0.19	0.71	0.98	1.46	2.42	2.36	2.52	2.57	2.62
Mulch	0.07	0.20	0.64	0.76	1.40	2.14	2.44	2.45	2.46	2.55
Nitrogen	0.06	0.22	0.68	0.90	1.40	2.17	2.42	2.47	2.58	2.50
N/M	0.06	0.12	0.60	0.83	1.30	2.05	2.39	2.62	2.63	2.69
Irrigation	0.07	0.30	0.85	1.06	1.85	2.17	2.53	2.47	2.62	2.66
I/M	0.09	0.28	0.77	1.05	1.62	2.33	2.61	2.70	2.65	2.64
I/N	0.07	0.27	0.81	0.99	1.74	2.28	2.55	2.48	2.77	2.55
I/N/M	0.09	0.33	0.78	1.11	1.84	2.21	2.58	2.48	2.66	2.69
LSD										
(5%)	0.01	0.08	0.16	0.18	0.29	0.23	0.23	0.26	0.18	0.19
(1%)	0.02	0.11	0.22	0.24	0.40	0.31	0.32	0.36	0.24	0.26

† Means within the same management factor followed by different letters are statistically significant (P = 0.05).

‡ Significant (P = 0.05) interactions where W is water, N is nitrogen, and M is mulch.

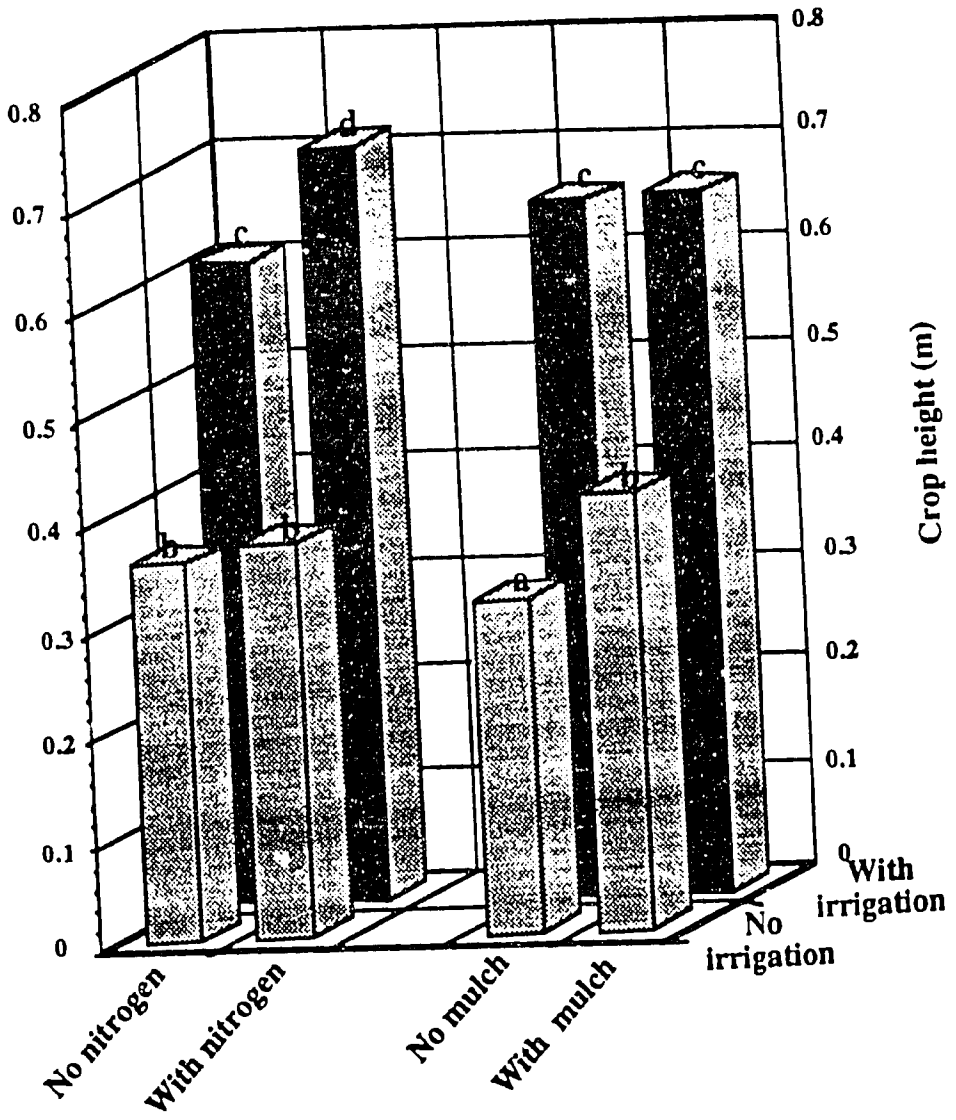

Figure 26. Effect of irrigation, nitrogen, and mulch on sorghum crop height on day 208 at the experiment site.

The interaction on day 208 indicated a significant increase in plant height with the application of irrigation. Nitrogen had little effect on dryland plots as compared to irrigated plots. This trend was reversed for mulch. Mulch had a greater effect among dryland plots as compared to irrigated plots. Therefore water conservation by mulch was the only source of additional water on dryland plots. This effect can be explained by the fact that water supply on the irrigated treatment was adequate, thereby reducing the effect of the mulch.

For all treatments the highest increase in vegetative growth with time occurred between day 213 and 237. Anthesis of crops in all treatments occurred between day 240 and 250, which was consistent with the photosensitivity threshold described in Fig. 18. A statistically significant interaction between irrigation and mulch was present on day 237 (Table 14a) when crops on mulch treatment were 10% shorter than those on irrigation/mulch treatment. As discussed earlier, application of mulch on dryland plots resulted in shallower root systems. Plants on these plots were more affected by the first dry spell reported in Table 10. On irrigated plots, mulch induced surface soil moisture conservation and caused better plant growth (Fig. 22). Detailed soil moisture profiles are discussed in the soil water changes section. The same type of response (interaction between irrigation and nitrogen) was present at the end of the growing season (Table 14b). Increase of plant height was smallest between day 248 and 278 (post anthesis period).

It was expected that each experimental factor would have statistically significant effects on crop height. However, nitrogen did not have any significant effect on plant height at any date. This was probably due to the relatively improved soil fertility (long fallow) mentioned earlier, and the interactions between the three factors. The treatment that yielded the tallest plants was irrigation/nitrogen/mulch. The combination of mulch with either nitrogen or irrigation had almost a similar effect.

Plant height is not always a good indicator of biomass production especially when it is a simple expression of the mean height of plants present in a given plot (empty hills were not taken into consideration in the measurement of crop height). The lack of a statistically significant difference in plant height between treatments does not imply a lack of a statistically significant differences in biomass production or LAI. Therefore, the two parameters are examined in the next sections.

5. Leaf area index (LAI)

Crop transpiration rate is a function of its leaf area. It can be an indirect way for treatments to affect water use. If a given treatment has a significant effect on LAI, it may induce a significant effect on crop transpiration and WUE. Also, as indicated in the Material and Methods section, LAI was an important input parameter in the ENWATBAL model. The LAI for the crop is given in Table 15.

Table 14a. Interaction between irrigation and mulch on sorghum height on day 237 at the experiment site.

	No mulch	With mulch
	m	
No irrigation	2.29 b†	2.10 a
With irrigation	2.22 a	2.26 b

† Values followed by different letters are statistically different (P = 0.05).

Table 14b. Interaction between irrigation nitrogen on sorghum height on day 278 at the experiment site.

	No mulch	With mulch
	m	
No nitrogen	2. 64 a	2.60 ab
With nitrogen	2.52 b	2.69 a

† Values followed by different letters are statistically different (P = 0.05).

Table 15. Main factor mean (n = 20) and treatment mean (n = 5) plant leaf area index (LAI) as effect by irrigation, nitrogen and mulch during the growing the season.

Parameter	Day of the year								
	208	213	218	229	237	248	258	268	278
	LAI								
EXPERIMENTAL FACTOR: MAIN EFFECT									
Irrigation (I)									
None	0.41a†	1.83a	1.97	3.60	4.47a	3.98	4.08	3.24	1.97
With	0.61b	2.19b	2.57	4.12	4.61b	3.75	3.91	3.34	1.89
Nitrogen (N)									
None	0.51	1.99	2.15	3.73	4.74a	3.74	4.05	3.06	1.76a
With	0.51	2.03	2.40	3.99	4.33b	3.98	3.93	3.52	2.10b
Mulch (M)									
None	0.50	2.09	2.42	4.08	4.46	3.66	4.05	3.31	1.92
With	0.52	1.94	2.13	3.65	4.62	4.06	3.94	3.27	1.94
Mean	0.51	2.01	2.27	3.86	4.45	3.86	3.99	3.29	1.93
CV (%)	32	23	30	22	15	23	21	28	25
TREATMENT MEAN									
Control	0.32	1.79	2.09	3.36	4.52	3.48	4.27	2.87	1.64
Mulch	0.39	1.74	1.31	3.47	4.63	3.97	4.01	3.11	1.93
Nitrogen	0.50	2.04	2.33	4.03	3.86	3.93	4.34	3.37	2.16
Nitrogen/mulch	0.24	1.75	2.14	3.54	4.40	4.54	3.68	3.59	2.14
Irrigation	0.62	2.35	2.52	4.53	4.13	3.55	3.57	3.00	1.77
I/M	0.59	2.09	2.66	3.57	4.69	3.96	4.35	3.24	1.70
I/N	0.69	2.17	2.72	4.39	4.22	3.70	4.01	3.99	2.10
I/N/M	0.73	2.16	2.39	4.00	4.21	3.77	3.70	3.13	2.00
LSD									
(5%)	0.21	0.61	0.88	1.12	0.87	1.14	1.10	1.19	0.63
(1%)	0.29	0.83	1.19	1.52	1.18	1.55	1.49	1.61	0.85

† Means within the same management factor followed by different letters are statistically significant (P = 0.05).

Leaf area index in all treatments ranged from less than 0.3 (day 208) to more than 4.6 (day 258). The highest leaf area index of all treatment occurred between day 237 and day 258. This period occurred shortly before anthesis. From observations made in the field, maximum soil coverage occurred when LAI was about 4 (around day 229). Individual plants had an average of 9 leaves with each leaf having a mean length of 1.4 m and mean maximum width of 0.05 m. Irrigation had the greatest effect on LAI from seeding up to day 218. After that date, nitrogen had the highest impact.

Fastest LAI increase occurred between day 213 and 237 paralleled plant height increase. The taller plants tended to have longer and wider leaves, hence higher LAI. Irrigation/mulch and mulch treatments caused the highest LAI. They also caused the earliest occurrence of maximum LAI. Maximum LAI occurred later in the nitrogen treatment.

There was no statistically significant effect of a main treatment throughout the growing period except for irrigation (day 208). Leaf area index tended to be lowest on plots with the combination of nitrogen and mulch. This can be attributed to a lower plant survival on those plots after the dry spells. Relatively high coefficient of variation (CV) values were induced by continuous leaf fall (senescence) during the growing season, especially after the vegetative growth period. After reaching its maximum value, the LAI of each treatment tended to decrease, while CV increased.

6. Dry matter production

Crop LAI affects crop water use efficiency (transpiration), but it also affects biomass production, hence photosynthesis. From a productivity point of view, increased biomass should be the result of improved crop water use efficiency. Before testing the first hypothesis of this study, it is appropriate to examine how the experimental factors affected biomass production. Above ground biomass production ranged from less than 12 kg ha^{-1} (day 197) to more than 7000 kg ha^{-1} at harvest (Table 16). Mean biomass production was 8733 kg ha^{-1}, which is a relatively good production level in this ecosystem according to INRAN (1988).

Irrigation had the most significant effect on biomass production. It caused statistically significantly higher values on all days except day 231. It also increased final biomass production by 31%. Nitrogen did not cause any statistically significant increase before day 231 when it became the only factor that had a significant effect. It also had a significant effect (14% increase) on final biomass production. Final biomass yield of treatments with no nutrient averaged 8178 kg ha^{-1} while yield of nutrient applied treatments averaged 9288 kg ha^{-1}. The average increase due to nutrient was 20%. Since this increase was statistically significant it increased the probability for accepting the hypothesis that WUE(ET) of the Sahelian agroecosystem can be improved by N input. However, no definite conclusion regarding the hypothesis could not be drawn at this point.

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Table 16. Main factor mean (n = 20) and treatment mean (n = 5) biomass production as effected by irrigation, nitrogen and mulch during the growing the season.

	Day of the year							
	197	208	218	231	237	248	258	278
	kg ha^{-1}							
EXPERIMENTAL FACTOR: MAIN EFFECT								
Irrigation (I)								
None	14a†	51a	113a	1251	2430a	3233a	4840a	7546
With	10b	89b	192b	1650	2801b	3502b	5188b	9921
Nitrogen (I)								
None	12	68	148	1212a	2483	3327	4533a	8178a
With	13	72	156	1689b	2748	3408	5494b	9288b
Mulch (M)								
None	13a	59a	130	1379	2465a	3324	5336	8413
With	11b	81b	174	1522	2276b	3411	4672	9053
Mean	12	70	152	1451	2615	3368	5314	8733
CV (%)	15	5	23	17	24	23	19	14
Interactions‡					NxM			IxNxM
TREATMENT MEAN								
Control	8	25	61	1016	2155	3037	3495	6269
Mulch	11	67	145	1399	2458	3036	4280	7538
Nitrogen	8	48	105	1448	2632	3190	4889	8125
Nitrogen/mulch	12	65	163	1551	2509	3217	4562	8250
Irrigation	13	73	139	1501	2475	3496	5178	9719
Irrigation/mulch	14	91	192	1141	2594	3625	5797	9188
Irrigation/nitrogen	14	88	193	1683	2475	3611	5741	9538
I/N/M1	16	103	218	1864	3465	3728	6169	11238
LSD								
(5%)	2	48	80	749	981	892	1020	517
(1%)	3	64	108	1016	1329	1209	1386	401

† Means within the same management factor followed by different letters are statistically significant (P = 0.05).

‡ Significant (P = 0.05) interactions where I is irrigation, N is nitrogen, and M is mulch.

Mulch had the least effect (8% increase) on final biomass production. This caused statistically significant effects on days 197, 208, and 237 suggesting that mulch tended to improve growth under relatively good soil moisture conditions. However, due to the shallow root system associated with mulch, plants were more vulnerable to extended dry spells.

This in addition to the statistically significant interaction between nitrogen and mulch on day 237 is illustrated in Table 17. Interactions between irrigation, nitrogen and mulch on final biomass production (Table 18) suggested that the effect of nitrogen was statistically significant and greater than that of mulch on both the irrigated and non- irrigated plots. Biomass increase due to mulch was greater on dryland than irrigated plots. Nitrogen treatment followed the same trend as mulch treatment. This suggests that regardless of irrigation, the addition of nitrogen had a greater impact than mulch. From a management standpoint, nitrogen should be the first choice when soil moisture conditions are favorable. mulch/nitrogen treatment can be disastrous when less favorable soil moisture conditions result in moisture stress. This is illustrated by the fact that nitrogen/mulch treatment produced less biomass than mulch and nitrogen treatments (Table 17). As mentioned earlier, this response is caused by a higher vulnerability (shallow rooting depth and poor survival) of crop on the nitrogen/mulch treatments. As suggested by the significant interaction between irrigation, nitrogen, and mulch (Table 18) the maximum yield was caused by combining irrigation, nitrogen, and mulch.

7. Yield components and grain yield

To understand how the effect of the different treatments on biomass and grain yield occurred it was essential to examine both yield and yield components. Since sorghum is grown primarily for its grain high harvest index it is a desirable yield component. There was no statistically significant differences in harvest index among main factor means (Table 19). The average increase was 3%. The only significant difference (P = 0.05) between treatments were those between the irrigation/mulch and control treatments, and between the irrigation/nitrogen/mulch and control treatments. This suggests that water was an important factor in improving the harvest index. The irrigation/mulch and irrigation/nitrogen/mulch treatments were not statistically different but had the highest harvest index values, suggesting a synergistic effect of irrigation, mulch, and nitrogen.

Increased yield may be caused by a higher number of heads per unit area, more fertile heads, a higher number of seeds per head, or heavier seeds. Number of heads per m^2 was significantly increased 10% by nitrogen, mulch and irrigation treatments. There was no significant difference among means of irrigated treatments. This was probably due to the fact that as mentioned earlier, statistical significance of irrigation treatment required greater mean square value compared to other experimental factors.

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Table 17. Interactive effect between nitrogen and mulch on biomass production on day 278 at the experiment site.

	No mulch	With mulch
	kg ha^{-1}	
No nitrogen	3037 a†	3618 b
With nitrogen	3612 b	3204 a

† Values followed by different letters are statistically different (P = 0.05).

Table 18. Interaction between irrigation, nitrogen, and mulch on final sorghum biomass production at the experiment site.

Treatment	Mean	LSD Rank
	kg ha^{-1}	
Control	6269	d†
Mulch	7538	cd
Nitrogen	8125	bc
Nitrogen/mulch	8250	bc
Irrigation	9719	ab
Irrigation/mulch	9188	b
Irrigation/nitrogen	9538	b
Irrigation/nitrogen/mulch	11238	a

† Treatment means followed by the same letters are not statistically different (P = 0.05).

Table 19. Main factor mean (n=20) and treatment mean (n=5) yield components and grain yield as affected by supplemental irrigation, nitrogen and mulch at the experiment site.

	Harvest Index	Heads m^{-2}	Fertile heads	Head mass	Seed mass	Seed $head^{-1}$	Grain yield
			%	g	mg		kg ha-1
EXPERIMENTAL FACTOR: MAIN EFFECT							
Irrigation (I)							
None	0.29	10	58	29a	22	1267a	2128a
With	0.31	11	66	36b	24	1563b	3008b
Nitrogen (N)							
None	0.29	10a†	60	30a	23	1289a	2328a
With	0.31	11b	63	35b	23	1541b	2805b
Mulch (M)							
None	0.29	10a	57a	32	23	1410	2363a
With	0.31	11b	65b	33	23	1420	2774b
Interactions‡			IxNxM				
Mean	0.30	10	61	32	23	1415	2568
CV (%)	18	12	17	22	6	21	17
TREATMENT MEAN							
Control	0.25	9	46	24	23	1072	1538
Mulch	0.29	9	63	31	23	1328	2106
Nitrogen	0.31	11	58	30	22	1361	2375
N/M	0.31	11	59	30	23	1307	2494
Irrigation	0.29	10	65	35	24	1483	2732
I/M	0.33	11	65	29	23	1274	2938
I/N	0.30	11	60	39	23	1725	2807
I/N/M	0.32	11	73	41	23	1770	3557
LSD							
(5%)	0.07	1	12	8	1.5	125	568
(1%)	0.10	2	16	11	2.1	169	769

† Means within the same management factor followed by different letters are statistically significant (P = 0.05).

‡ Significant (P = 0.05) interactions where I is water, F is nitrogen, and M is mulch.

Mulch was the only factor that significantly affected head fertility. Irrigation increased head fertility by 14%, compared to a 5% increase by nitrogen. There was also a significant interaction between Irrigation, Nutrient and Mulch (Table 20) that suggests a strong primary effect of irrigation and mulch, and a secondary effect of irrigation and nutrient.

The effect of the experimental factors on head mass and number of seeds per head were similar. This suggested that the increase of head mass was probably due to a higher number of seeds per head on irrigation or Nutrient treatments. This conclusion is supported by the lack of significant differences (P = 0.05) of seed mass across all factors and all means. Furthermore, this conclusion is consistent with the significant effect of irrigation and fertilizer on grain yield (Table 19). The significant effect of mulch on grain yield can be attributed to the significant increase of head fertility. Each experimental factor significantly increased grain yield, however, irrigation was the treatment with the strongest impact on grain yield. Irrigation/nutrient/mulch treatment was once again the best treatment. In general, crop response was most affected by irrigation followed by nutrient, then mulch. The next section examines how the treatments affected crop water use and tests hypothesis defined earlier.

E. Effect of mulch on the energy balance

1. Radiation balance

In the energy manipulation scheme described earlier, mulch was used to alter the soil energy balance. The effect of mulch on crop long wave emission (simulation results) is presented in Fig. 27a. A five day period, after day 202, was selected to illustrate the effect of mulch on soil energy balance. Mean maximum global sky radiation was 760 W m^{-2}, and sky long wave radiation was 480 W m^{-2}. Maximum radiation on all treatments occurred around noon. However, maximum long wave radiation emission from mulch treatment was about 200 W m^{-2} lower than Control treatment. As a result, net crop radiation balance of mulch treatment was 20 to 60 W m^{-2} lower than that of the control treatment (Fig. 28). Soil long wave radiation emission followed the same trend as the long wave radiation emission. But the difference between mulch and control treatments ranged from 150 to 100 W m^{-2}.

From the soil energy balance alteration standpoint, the most interesting effect of mulch was observed on the soil net radiation balance (Fig. 27b). Net soil radiation balance of Mulch treatment was consistently 60% lower than that of the control treatment. This provided evidence that the soil energy balance can be substantially reduced with mulch. However, in order to have an insight of its effect on soil water losses one should assess the effect of mulch on the heat and latent flux.

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Table 20. Interactive effect of irrigation, nitrogen, and mulch on percent fertile sorghum heads at the experiment site.

Treatment	Mean	LSD Separation
	%	
Control	46	c†
Mulch	63	ab
Nitrogen	58	bc
Nitrogen/mulch	59	bc
Irrigation	65	ab
Irrigation/mulch	65	ab
Irrigation/nitrogen	60	ab
Irrigation/nitrogen/mulch	73	a

† Treatment means followed by the same letters are not statistically different (P = 0.05).

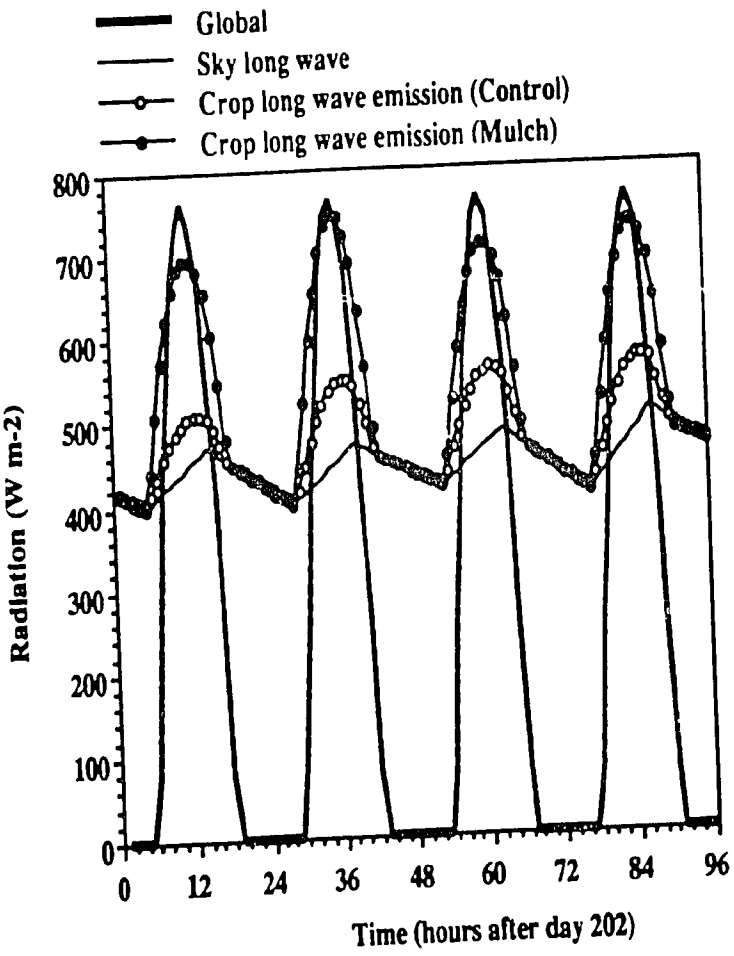

Figure 27a. Global radiation, sky long wave radiation, and the effect of mulch on crop long wave radiation emission 96 hours after 202 at the experiment site.

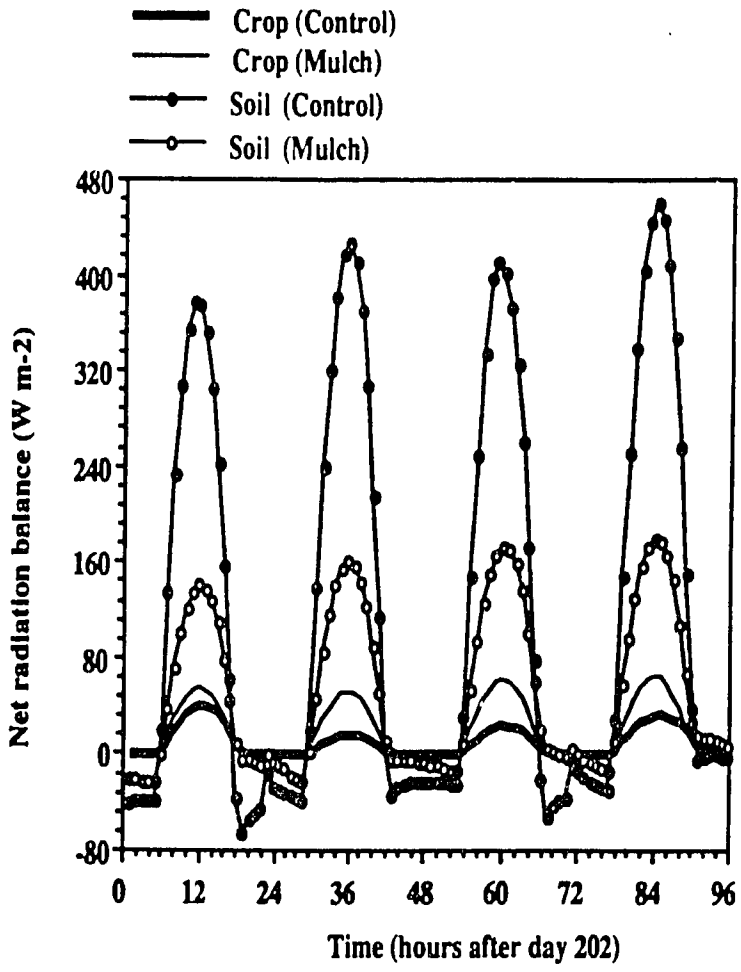

Figure 27b. Effect of mulch on soil and crop net radiation 96 hours after 202 at the experiment site.

2. **Heat fluxes**

The effect of mulch on sensible heat flux between the canopy and the air, the sensible heat flux between the soil and air, and the soil heat flux at the surface is illustrated in Fig. 28. As for the energy balance, daily fluctuations of these fluxes were substantially reduced by mulch treatment. Mulch reduced sensible heat flux between soil and air by 60 to 80 W m^{-2}, heat flux between canopy and air by -30 to -60 W m^{-2}, and soil heat flux at the surface by 40 to 160 W m^{-2}.

3. **Vapor fluxes**

The implications of the radiation and heat fluxes for water losses are presented in Fig. 29. When the soil is dry (time ranging from 0 to 24 hours) the maximum soil evaporative flux of mulch and control treatment were similar (70 - 80 W m^{-2}). Under wet soil conditions (note precipitation occurred on hour 24), this difference tended to increase, ranging from 120 to 200 W m^{-2}. Fluctuations between maximum soil evaporation flux, during wet and dry days, were lesser with the mulch. This indicates that mulch substantially reduced soil evaporation. The net amount of water losses are discussed later in the water balance section.

Crop transpiration rate was less affected by precipitation. Daily changes of mulch treatment were regular compared to those of the control. Crop transpiration of control treatment tended to be greater than the mulch under dry soil conditions and less under wet conditions. This could be caused by the fact that surface moisture is conserved by mulch and is available for crop uptake and transpiration a considerable period of time following precipitation. In addition, the higher heat transfer in the canopy of the control treatment may induce higher transpiration rates under dry conditions. High soil evaporation flux following precipitation may also increase air vapor pressure, thereby reducing crop transpiration (Fig. 29).

D. Soil water dynamics

Even though alteration of the energy balance affects soil water balance, the latter, and particularly crop water use, depends largely on the dynamics (supply frequency, changes with time and depth) of soil water. It is appropriate to characterize soil water dynamics in order to better relate the water balance to crop growth and yield on the one hand, and better evaluate the water balance manipulation parameters on the other hand. For this purpose wetting front, and changes of soil moisture are presented.

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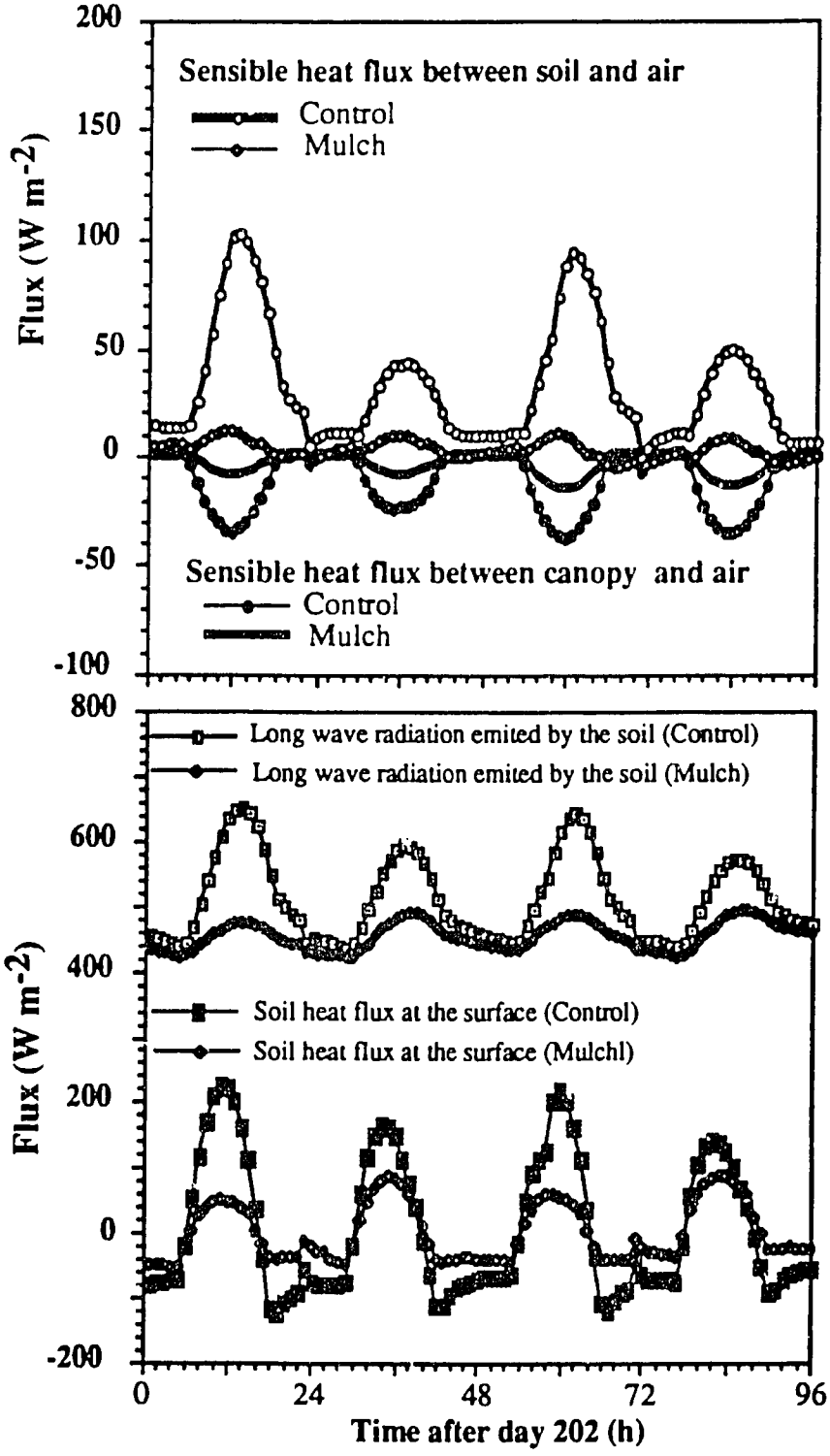

Figure 28. Effect of mulch on sensible heat fluxes, soil long wave radiation emission, and soil heat flux at the surface.

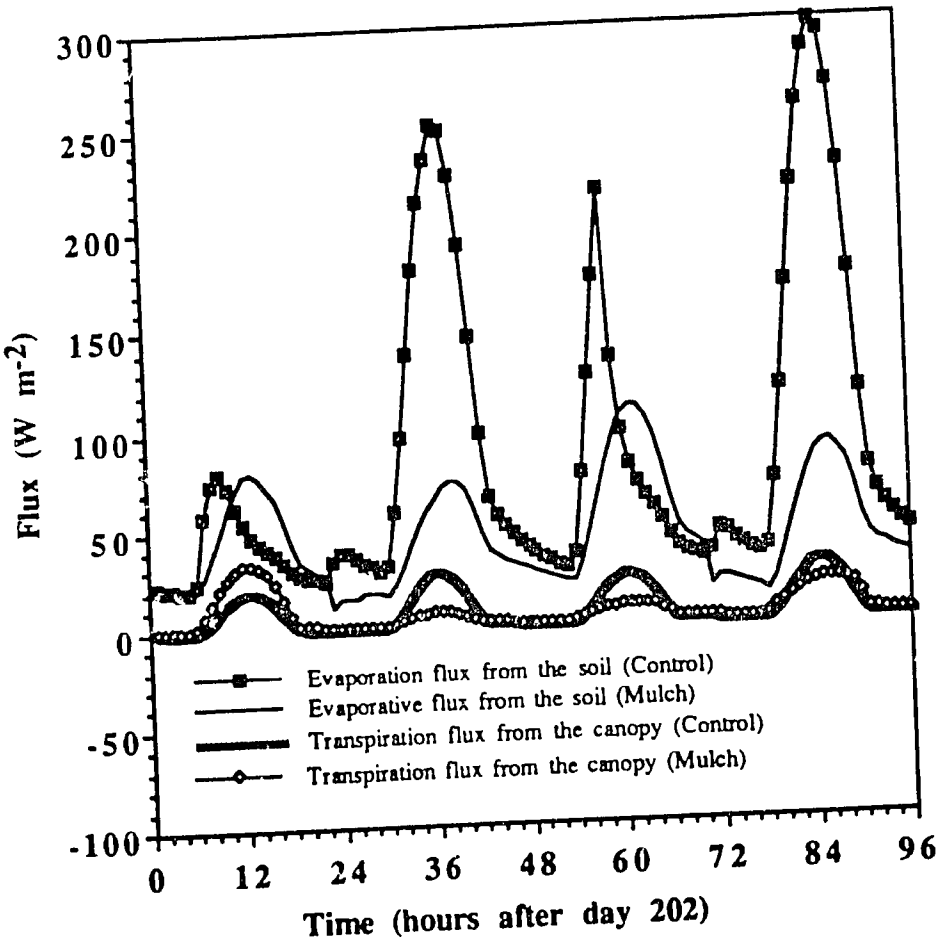

Figure 29. Effect of mulch on sensible heat flux between soil and air, sensible heat between canopy and air, long wave radiation emission by the soil, and soil heat flux at the surface 96 hours after day 202 at the experiment site.

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1. Wetting front

Initial soil moisture content at the experiment site was less than 0.05 $m^3 m^{-3}$ (Fig. 30) therefore, roots could not develop throughout the entire soil profile. Root penetration in the soil depth was primarily limited by the maximum wetting front. Before day 230, except on the fertilized and mulched plots, there was no difference between non-irrigated and irrigated plots in the penetration of the front.

Without fertilizer the wetting front of the irrigated plots tended to reach the maximum depth about 30 days earlier than the non-irrigated plots (Fig. 31). The delay on fertilized plots was longer than the delay on the front penetration which was about 1.1 m depth. This was probably due to the fact that nutrient availability in the upper soil layer increased root activity and induced higher water uptake as compared to unfertilized plots. This conclusion was supported by the increased plant evapotranspiration discussed later. The maximum wetting front at the end of the growing period on non-irrigated plots were 0.1 m shallower compared to non-mulched plots, where the front reached 1.2 m about 30 days earlier.

The maximum wetting front during the growth period (day 180 to 273) for all treatments were limited to 1.2 m. This limitation was caused by the low hydraulic conductivity of the soil horizon (0.9 - 1.2 m) as discussed earlier. This is consistent with the final root distribution. This limit was reached around day 240 for all treatments.

2. Soil moisture changes

Changes of surface soil moisture are important for the water balance and are primarily due to evaporation. Since one of the purposes of mulch was to control these losses it is appropriate to examine the effect of mulch on soil evaporation. Results indicate that soil evaporation rate, during the growing season, was lower on mulched compared to non-mulched plots (Fig. 32). This effect was greater during the first part of the season when crop LAI was low. It provides an answer to the hypothesis that soil evaporation can be controlled by crop residue mulch.

Changes of soil moisture in the root zone of the control treatment are presented in Fig. 33. Most changes occurred in the top two (0 - 0.30 m and 0.30 - 0.60 m) layers, suggesting that most of the water dynamics and root water uptake occurred in these layers. High variability was caused by the thickness of each layer (0.30 m) and the relatively slow downward water flow.

On dryland plots mulch tended to reduce variability in the surface layers and increase variations in the deep layers of mulch treatment (Fig. 34). This was an indication that the infiltration rate and the overall downward water movement in the top soil were improved by mulch (reduced soil evaporation, and protection of surface soil from raindrop impact). However, this effect on deep soil

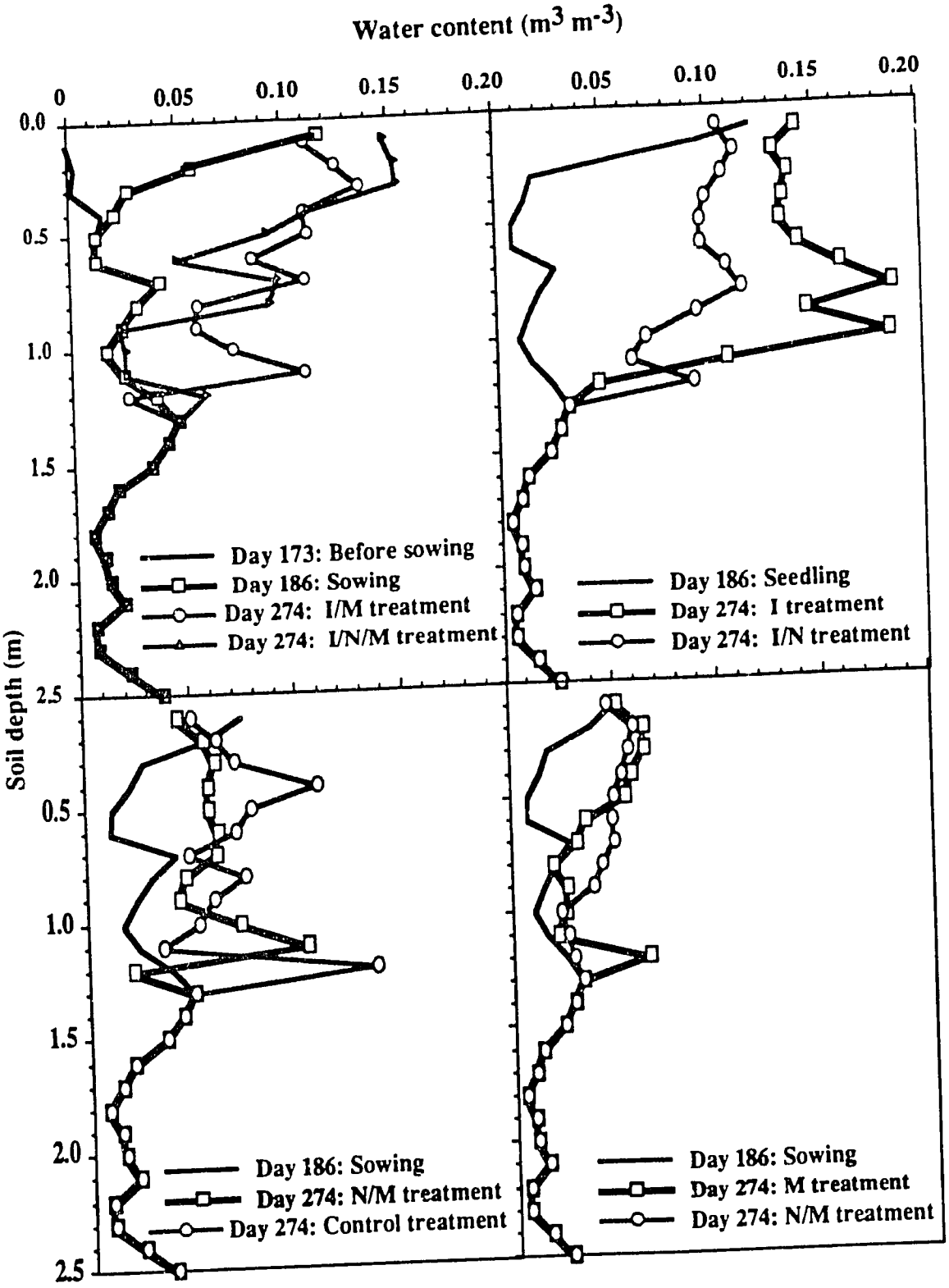

Figure 30. Soil moisture profile of the different treatments on day 173, 186, and 274.

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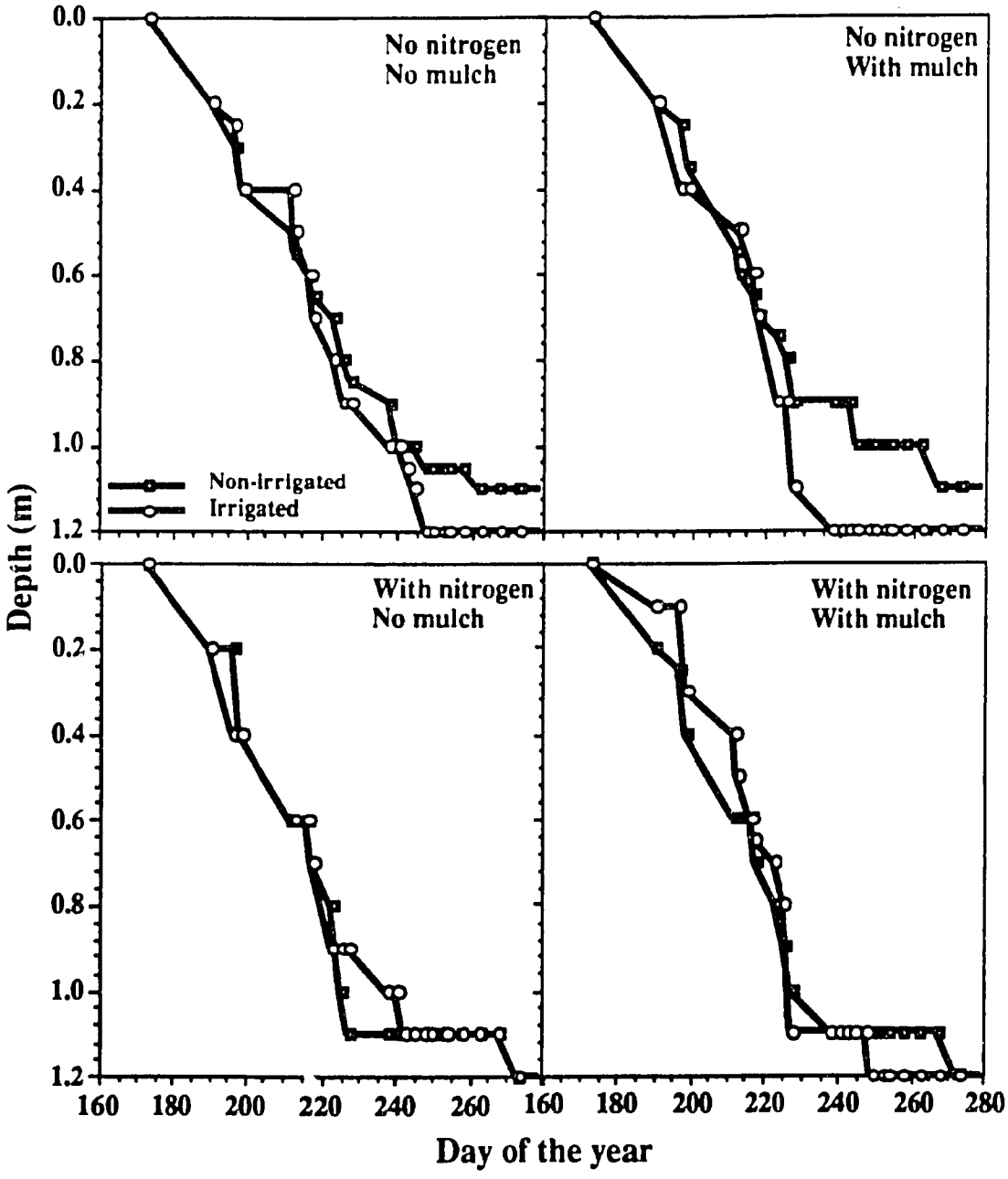

Figure 31. Maximum wetting front in the soil of the different management systems at the experiment site.

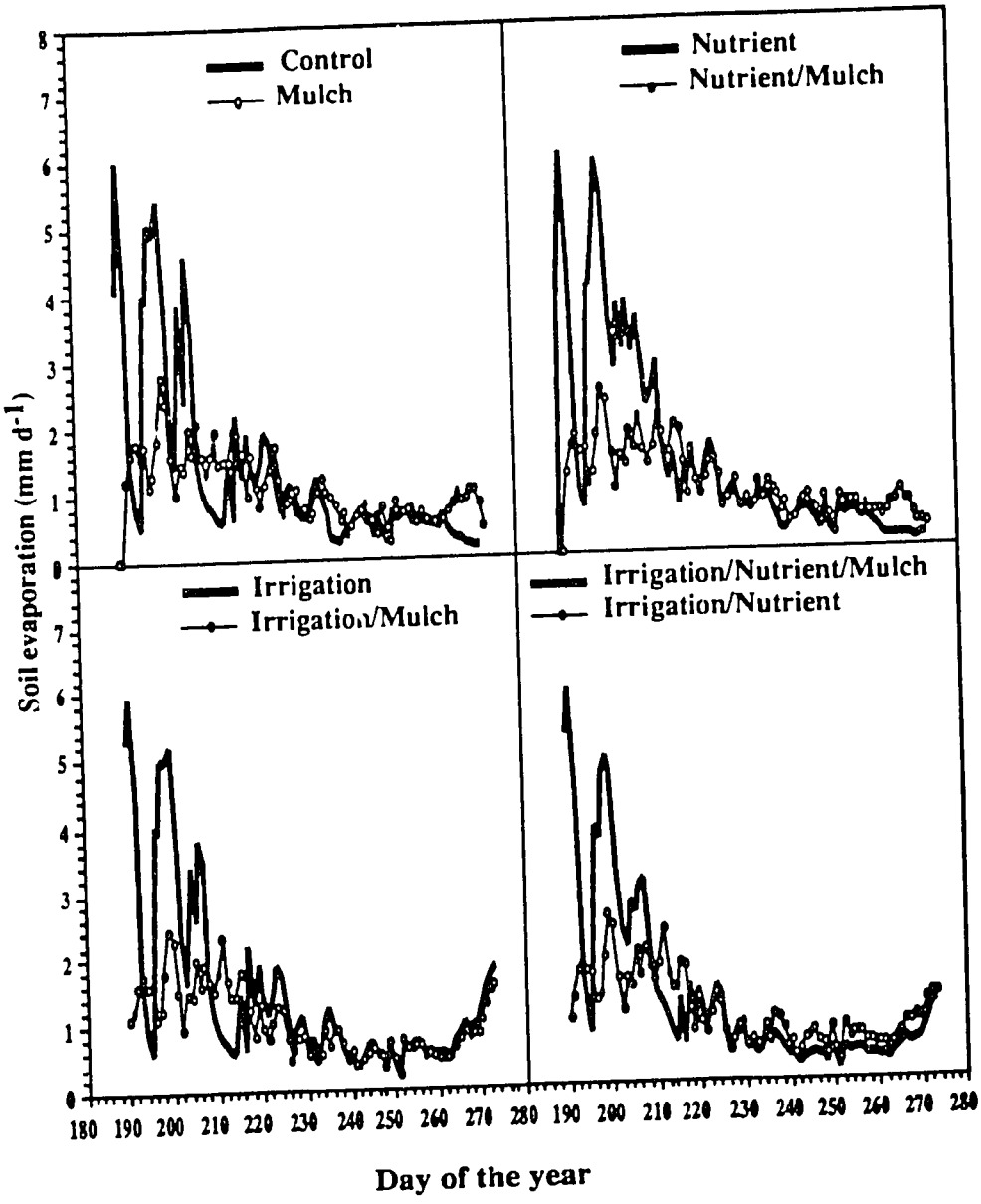

Figure 32. Soil evaporation (simulated) as affected by the different treatments during the growing season at the experiment site.

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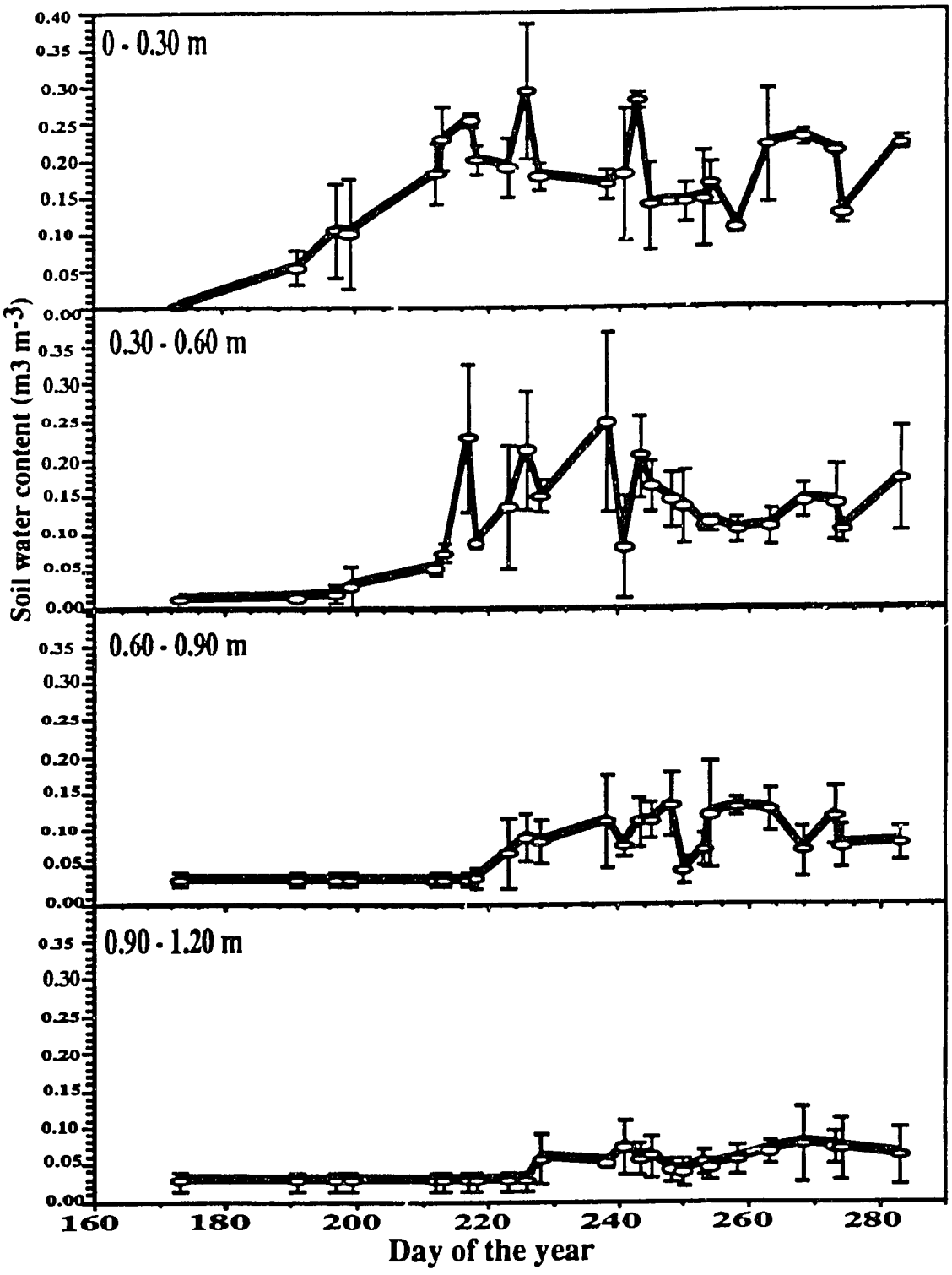

Figure 33. Mean soil water content in the different soil layers during the growing season in the control treatment. Vertical bar is one standard deviation of the mean (n=3).

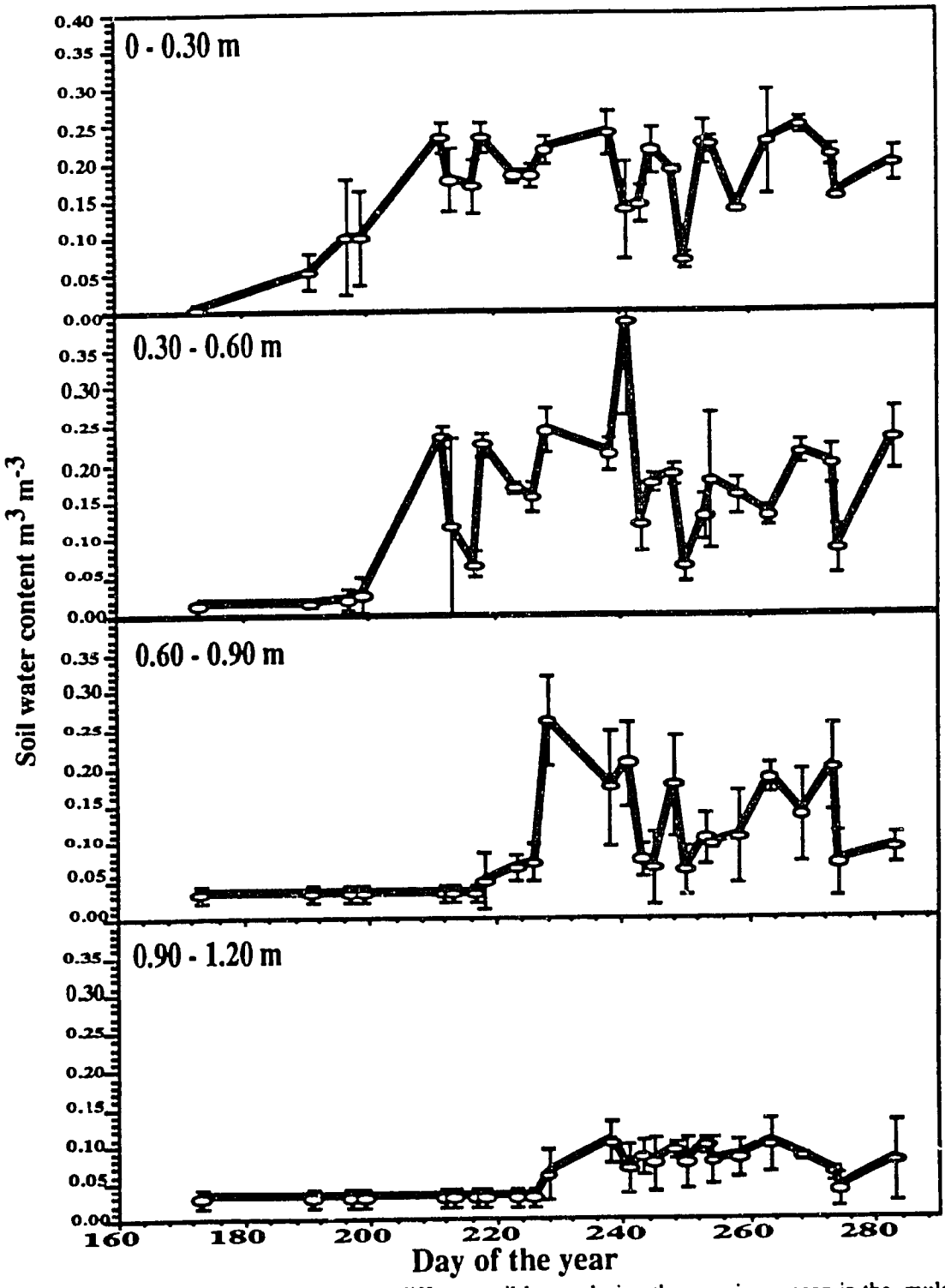

Figure 34. Mean soil water content in the different soil layers during the growing season in the mulch treatment. Vertical bar is one standard deviation of the mean (n=3).

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layers was greater at the end of the growing season. Changes of soil water content in the 0.60-0.90 soil layer ranged from 0.03 to 0.15 m3 m-3 and did not occur before day 220.

In the depest layer (0.90 - 1.20 m, changes did not occur before day 230. In addition, changes were very small indicating that the maximum wetting front barely reached the bottom of that layer. This coupled with root distribution data, suggests that changes in this layer were primarily caused by drainage rather than root extraction.

Changes of soil moisture in the top two layers of nutrient treatment and nutrient/mulch (Figs. 35 and 36) were similar to those of control and mulch treatments. Changes in the two deepest layers of treatment nutrients and the Nutrient/Mulch treatments were greater. The most prominent of all changes was in the 0.90 - 1.20 m layer of nutrient/mulch treatment. This can be explained by the fact that mulch tended to conserve more surface soil moisture (Fig. 22, page 73) and therefore caused shallow rooting and probably more moisture withdrawal from the surface layers. This is supported by the root distribution data discussed earlier. Soil moisture was predominantly withdrawn from the surface soil by the crop roots.

Changes of soil moisture in the deep soil layers of irrigated treatments (Figs. 37-40) were lower than expected. Changes were very low in the deepest layer except for the control treatment. In the top layer, Irrigation increased the surface soil moisture content. This confirmed the conclusion drawn earlier suggesting that irrigation induced intensive but shallow rooting. Roots were deeper in non-irrigated treatments (figs. 26-29). In the treatments were no rooting occurred in the 0.90 to 1.20 m layer (mulch, irrigation/mulch, nutrient, irrigation/nutrient/mulch treatments) changes of soil moisture content in the deep layer can be attributed primarily to unsaturated water flow (drainage). These losses are assessed in the next section.

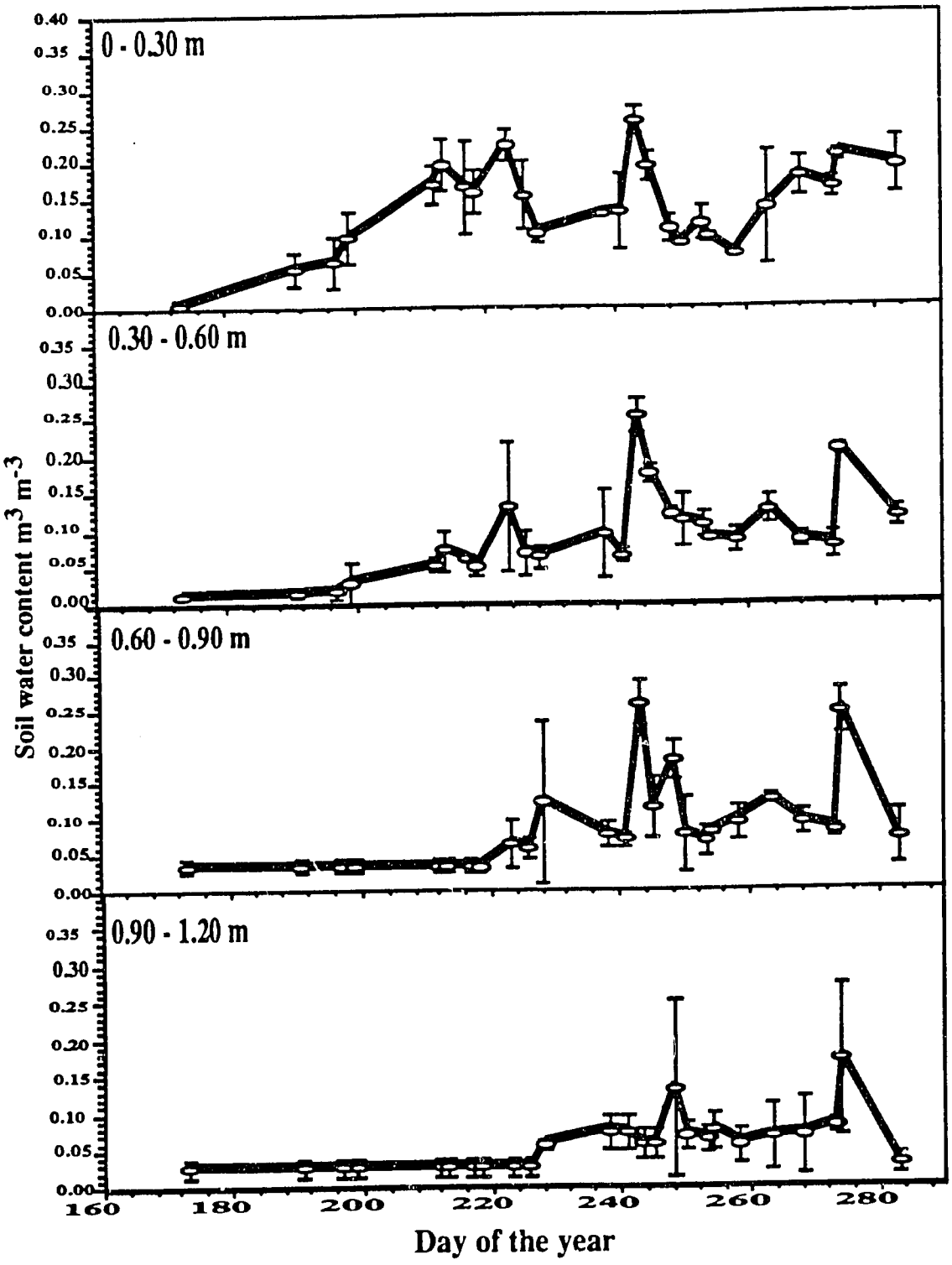

Figure 35. Mean soil water content in the different soil layers during the growing season in the nutrient treatment. Vertical bar is one standard deviation of the mean (n=3).

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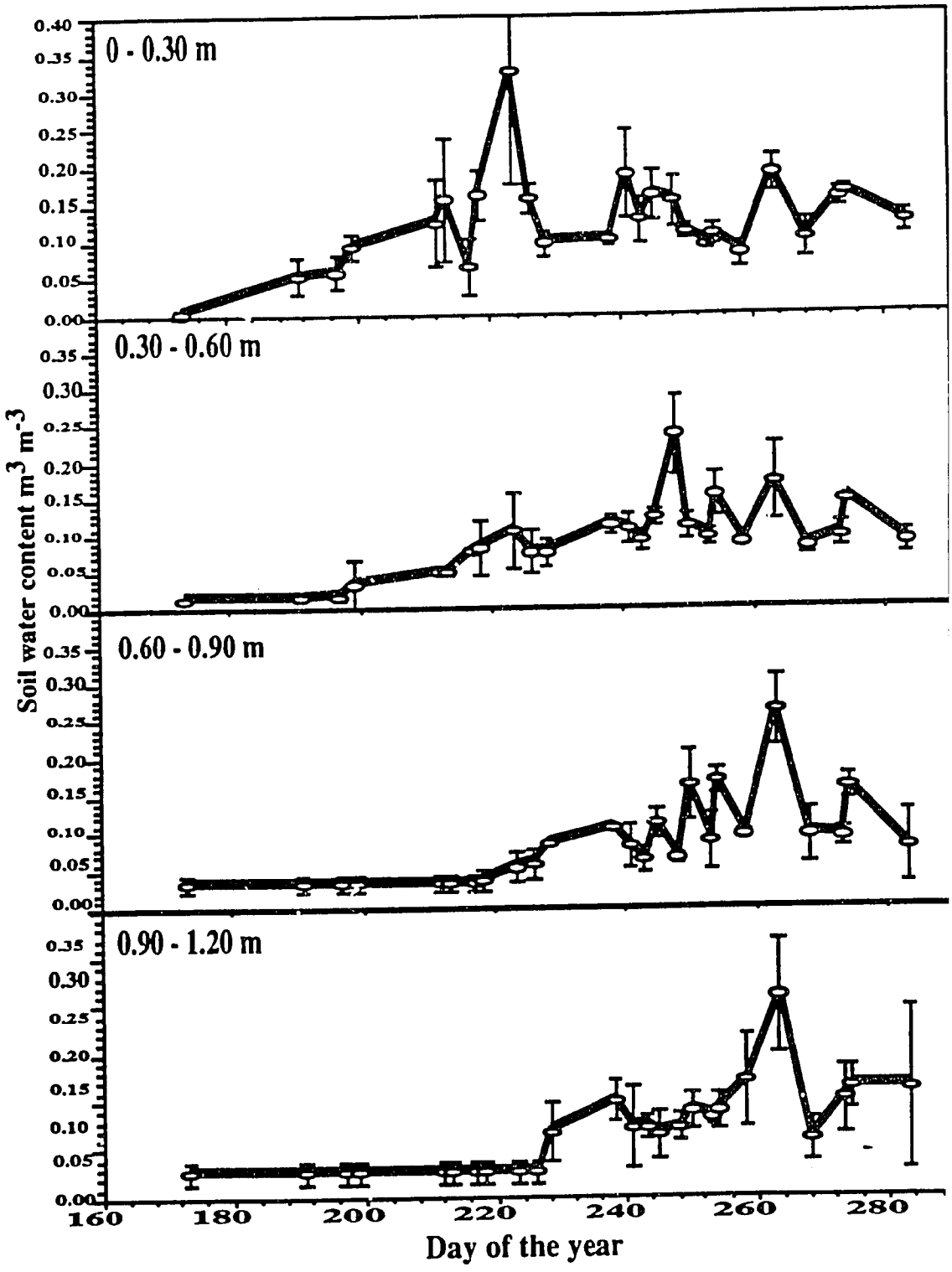

Figure 36. Mean soil water content in the different soil layers during the growing season in the nutrients/mulch treatment. Vertical bar is one standard deviation of the mean (n=3).

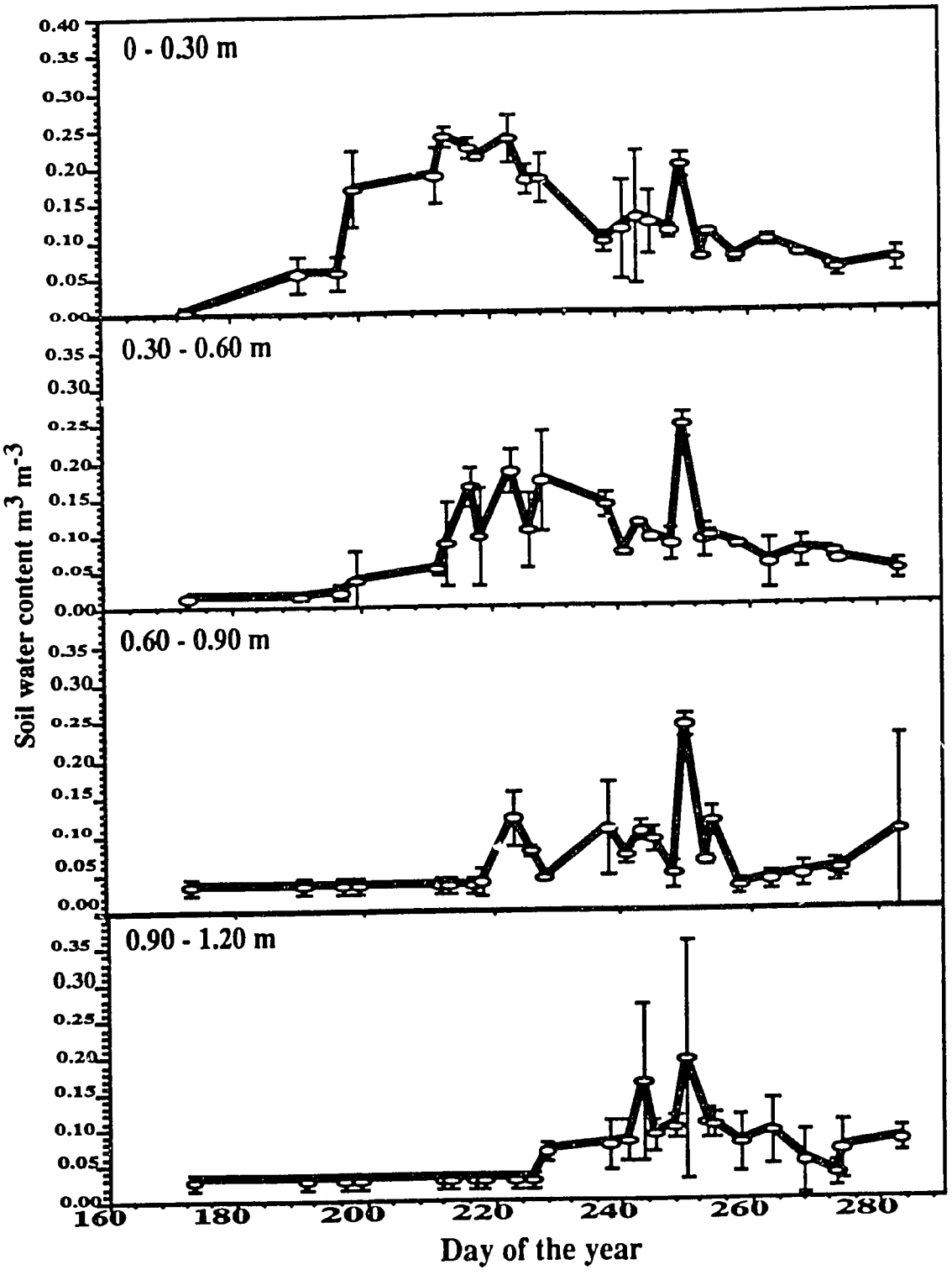

Figure 37. Mean soil water content in the different soil layers during the growing season in the Irrigation treatment. Vertical bar is one standard deviation of the mean (n=3).

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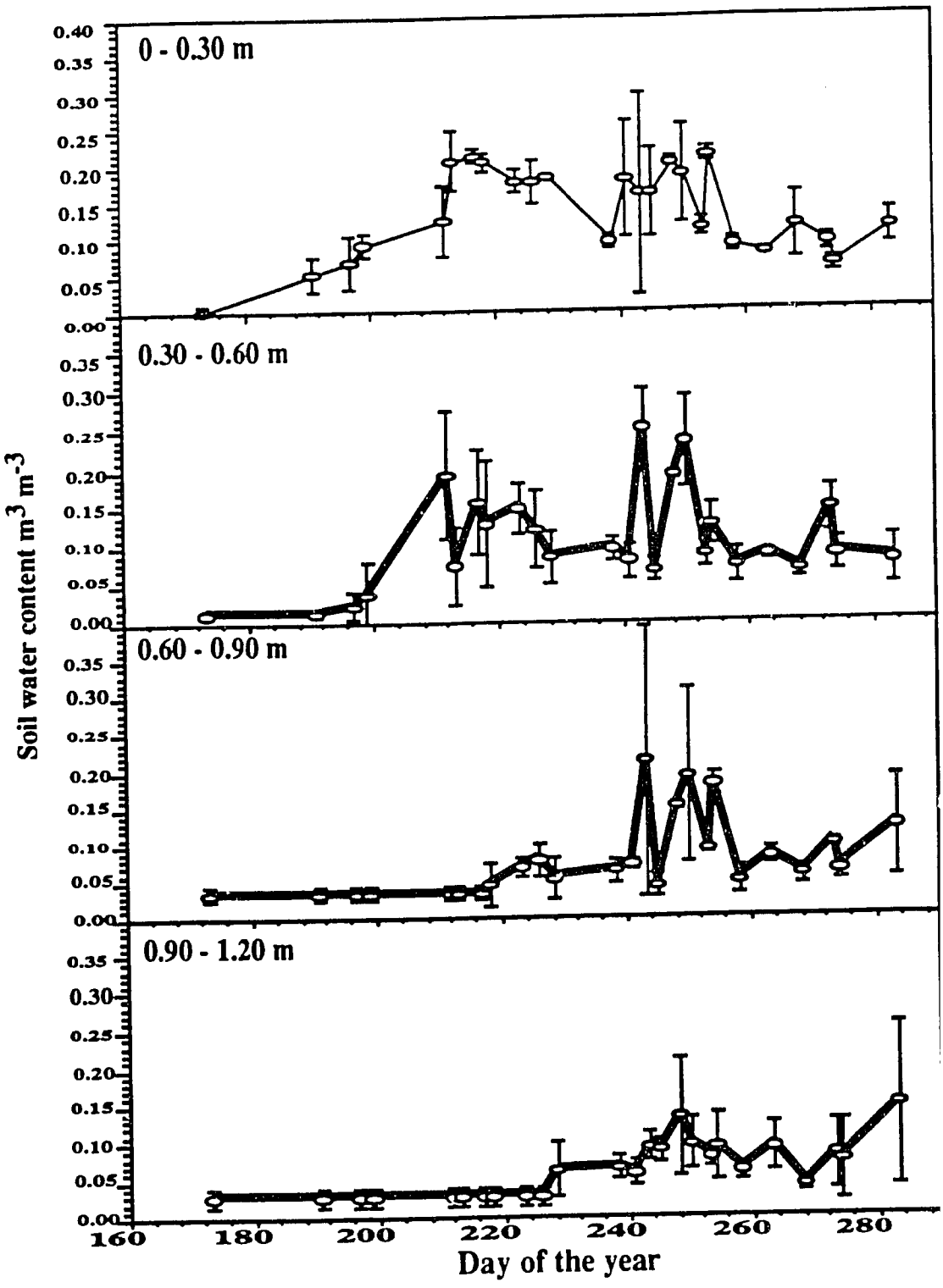

Figure 38. Mean soil water content in the different soil layers during the growing season in the irrigation/mulch treatment. Vertical bar is one standard deviation of the mean (n=3).

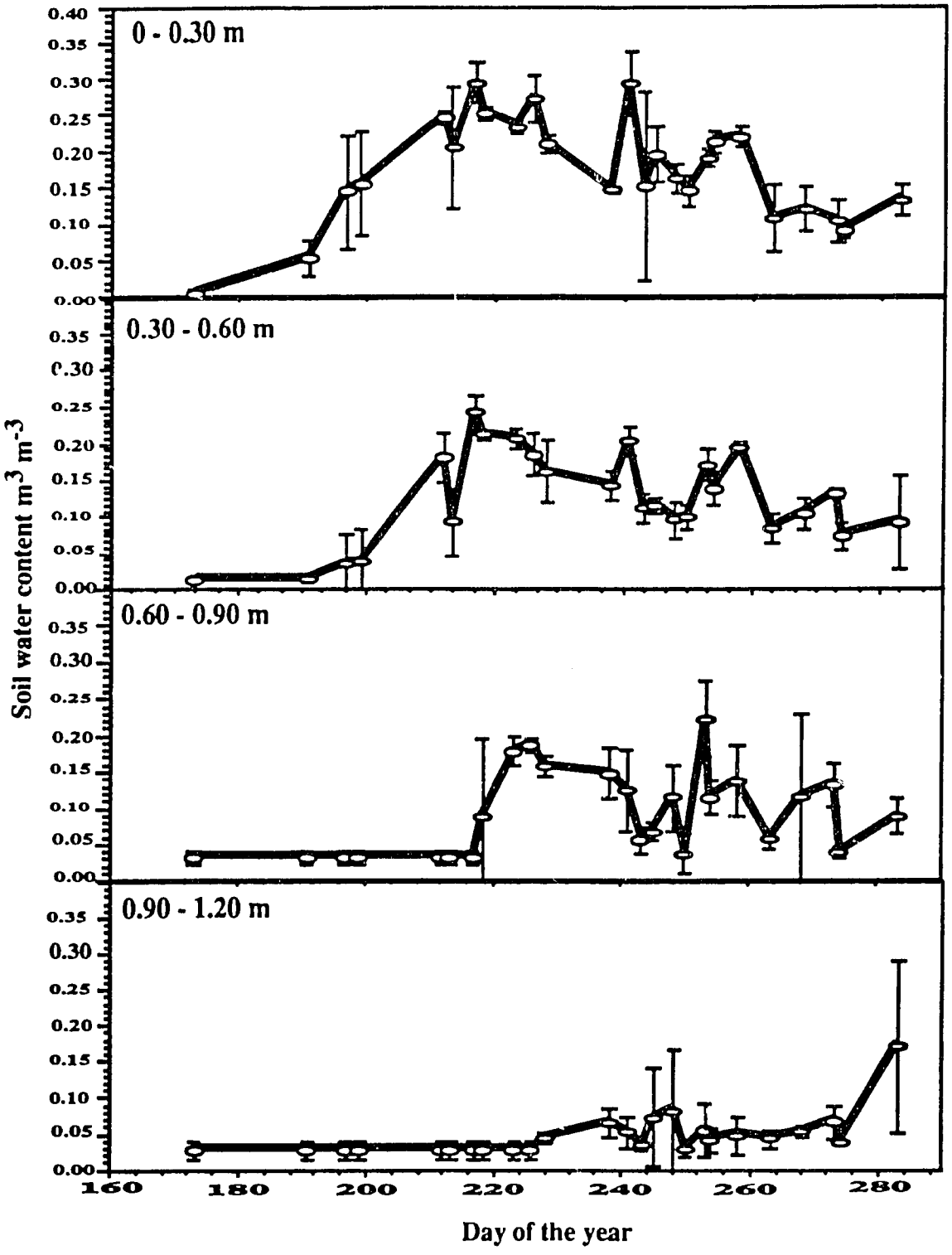

Figure 39. Mean soil water content in the different soil layers during the growing season in the irrigation/nutrients treatment. Vertical bar is one standard deviation of the mean (n=3).

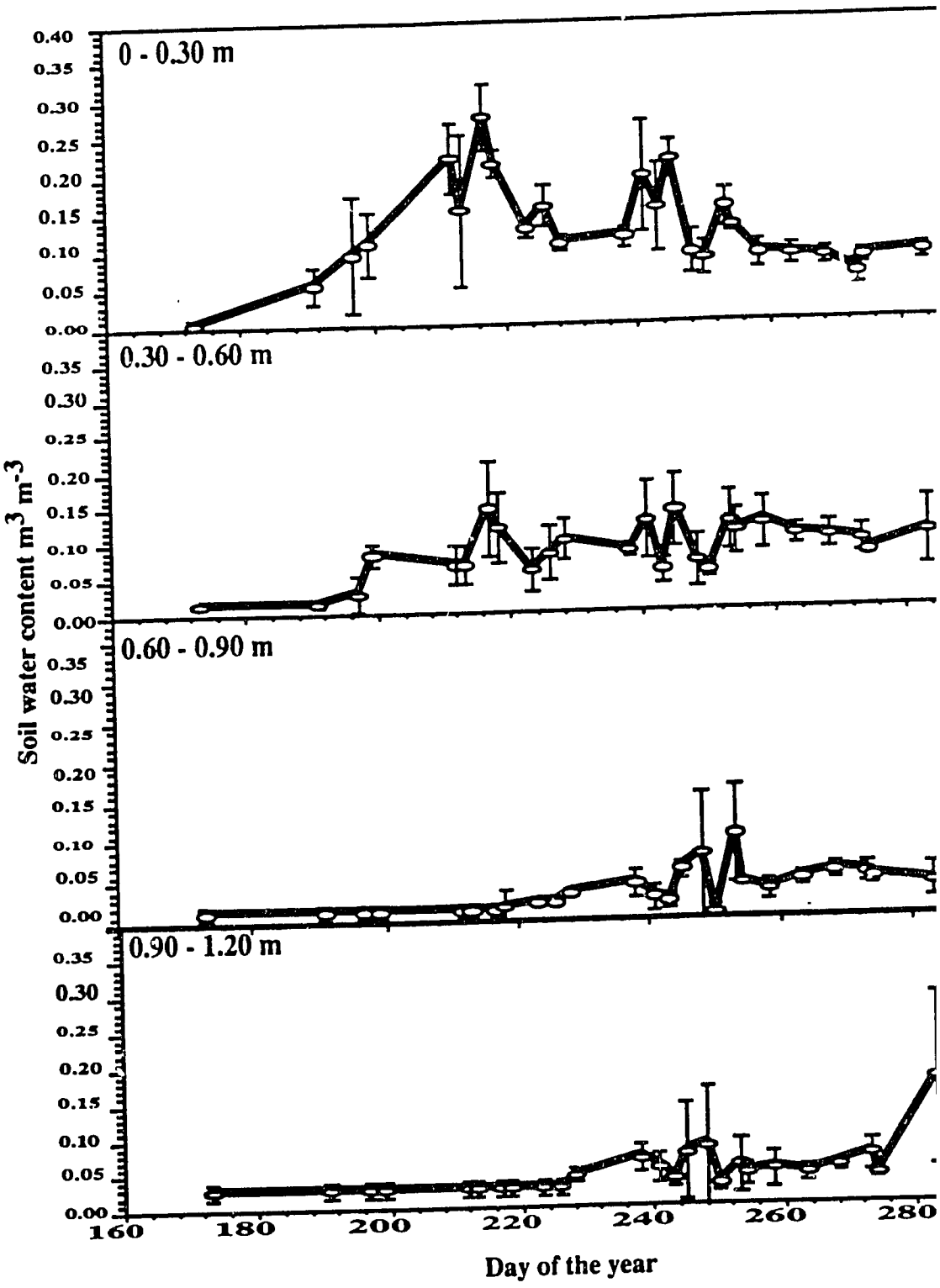

Figure 40. Mean soil water content in the different soil layers during the growing season in th irrigation/nutrients/mulch treatment. Vertical bar is one standard deviation of the mean (n=3).

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Most changes of soil water content in all treatments occurred in the top two layers, indicating that most of the soil water dynamics occurred in these layers. This is supported by the root distribution results discussed earlier. Changes of soil moisture content in the deepest soil layers (0.90 - 1.20 m) of the non-irrigated treatments ranged from 0.03 to 0.10 m^3 m^{-3}. On the irrigated treatments changes ranged from 0.05 to 0.15 m3 m-3 and occurred after day 270 for the Irrigation/Nutrient and the irrigation/nutrient/mulch treatments. For the irrigation and irrigation/mulch treatments, the relatively faster penetration of the wetting front mentioned earlier induced earlier changes (day 230) compared to the other irrigated treatments.

Soil water content determinations were made every 0.10 m. Changes in water content in the deep soil (0.90 - 1.20 m) were primarily indicative of drainage. Changes of soil moisture in these layers did not occur before day 230 for any treatment. The nitrogen/mulch treatment caused the highest variations in the deepest layer. This was probably due to the fact that mulch and fertilizer caused greater root growth in the surface and therefore limited water extraction from the deepest layer.

E. Water balance

1. Seasonal water balance

Results on the seasonal water balance of the root zone (1.20 m) during the crop growth period (day 191 to 274) are summarized in Tables 21a and 21b. Precipitation and irrigation were 283 and 100 mm respectively. Therefore, total water input for dryland and irrigated treatments was 283 and 383 mm, respectively.

c. Runoff and drainage

As indicated earlier, a protective ridge was built aroung each individual plot to prevent runoff and run-on. No runoff or run-on occrured in either plot during the growing season; runoff was zero for all treatments.

No drainage loss occurred on the control treatment which is consistent with the root distribution and the wetting front discussed earlier, and the conclusion that most of the water dynamic occurred on the top soil. Drainage losses of all treatments was low. The maximum loss was 6 mm, which was less than 1% of the seasonal rainfall. Drainage losses can therefore considered to be minor compared to the other terms of the water balance.

b. Changes of soil moisture content with time

Initial soil moisture was higher on irrigated treatments (mean of 45 mm) compared to dryland treatments (mean of 36 mm). This difference was greater at the end of the season where mean cumulative soil water content for irrigated and dryland treatments was 140 and 62 mm respectively. These differences

Table21a. Seasonal water balance of the different treatments as defined by Eq. 34.

Treatment	P_R	IR	Soil moisture			D_A	ET	ET/Buget
			Initial	Final	D_S			
	mm							%
Control	283	0	35	65	30	0	253	89
Nitrogen (N)	283	0	35	73	28	4	240	85
Mulch (M)	283	0	39	45	6	6	271	96
N/M	283	0	34	63	29	6	250	88
Irrigation (I)	283	100	44	142	98	4	281	99
I/M	283	100	46	159	113	6	263	93
I/N	283	100	43	131	88	3	292	103
I/N/M	283	100	47	126	79	6	298	105

Table 21b. Water usage (relative to the water budget) by E and T for the different treatments.

Treatment	Component	
	E	T
	% of total water budget	
Control	38	51
Mulch (M)	37	58
Nitrogen (N)	33	63
N/M	30	58
Irrigation (I)†	34	39
I/N	25	44
I/N	33	43
I/N/M	26	51

† Budget is irrigation plus rainfall

were due to the water input on irrigated treatments.

d. Evapotranspiration (ET)

Evapotranspiration of the different treatments ranged from 240 (Nutrient) to 298 mm (irrigation/nutrient/mulch) representing 85 to 105% of the seasonal rainfall, respectively. Mean ET for dryland and irrigated treatments was 254 and 284 respectively.

The effect of the different treatments on ET is shown on Fig. 41. Values under irrigation , mulch, or nutrient indicate increase over no irrigation, no mulch, and no nitrogen respectively. Where irrigation is attached to an arrow under mulch or nutrient it indicates a comparison between the two parameters with irrigation compared to dryland (unattached arrow). Mulch reduced ET in both irrigated and non-irrigated treatments. The effect was greater on dryland treatments (-7 compared to -3%). This can be attributed to the high transpiration caused by mulch on irrigated treatments (+2%) compared to dryland treatments (+16%). As discussed earlier, with mulch, soil evaporation losses are reduced, therefore a relatively higher amounts of water is available for crop transpiration. Overall, mulch reduced ET by 5%.

Unlike mulch, nutrient increased ET. Relative increase for non-irrigated and irrigated treatments were 6 and 9% respectively. The effect of nitrogen on T was greater compared to that on E (Fig. 41). Increase of ET due to nutrient can be attributed to higher T values caused by better crop growth; higher LAI during the vegetative growth stage, particularly prior to day 248 (see Table 15). The effect of irrigation on ET was the greatest of all experimental factors. ET increase was 11%, indicating that rainfall supply was below crop ET demand.

e. Evaporation (E) and transpiration (T)

Soil evaporation accounted for 35% of the water budget on non-irrigated treatments and 30% on the irrigated treatments (Table 21b). This suggests that an important part of the water budget is loss by soil evaporation that may cause inefficient crop water use. Mulch reduced evaporation by 19 % on dryland treatments and 24% on irrigated treatments (Fig. 41). The effect of nitrogen on E was minor and erratic (3% decrease with no irrigation and 2% increase with irrigation). Overall, irrigation increased E by 24%.

Overall, soil evaporation accounted for 33% and T for 51% of the water budget. It is interesting to notice that even though irrigation caused a 24% increase of evaporation, transpiration increased only by 5%. Proportion of the budget used as transpiration on dryland and irrigated treatments was 58 and 44%, respectively. On dryland treatments, the difference between E and T was 23%. On irrigated treatments this difference was 14%. The usage of a relatively higher proportion of the water budget for transpiration on dryland treatments was an indication that crop on dryland treatments may have used water more efficiently. Therefore, one could expect WUE(T) of irrigated treatments to be higher compared to

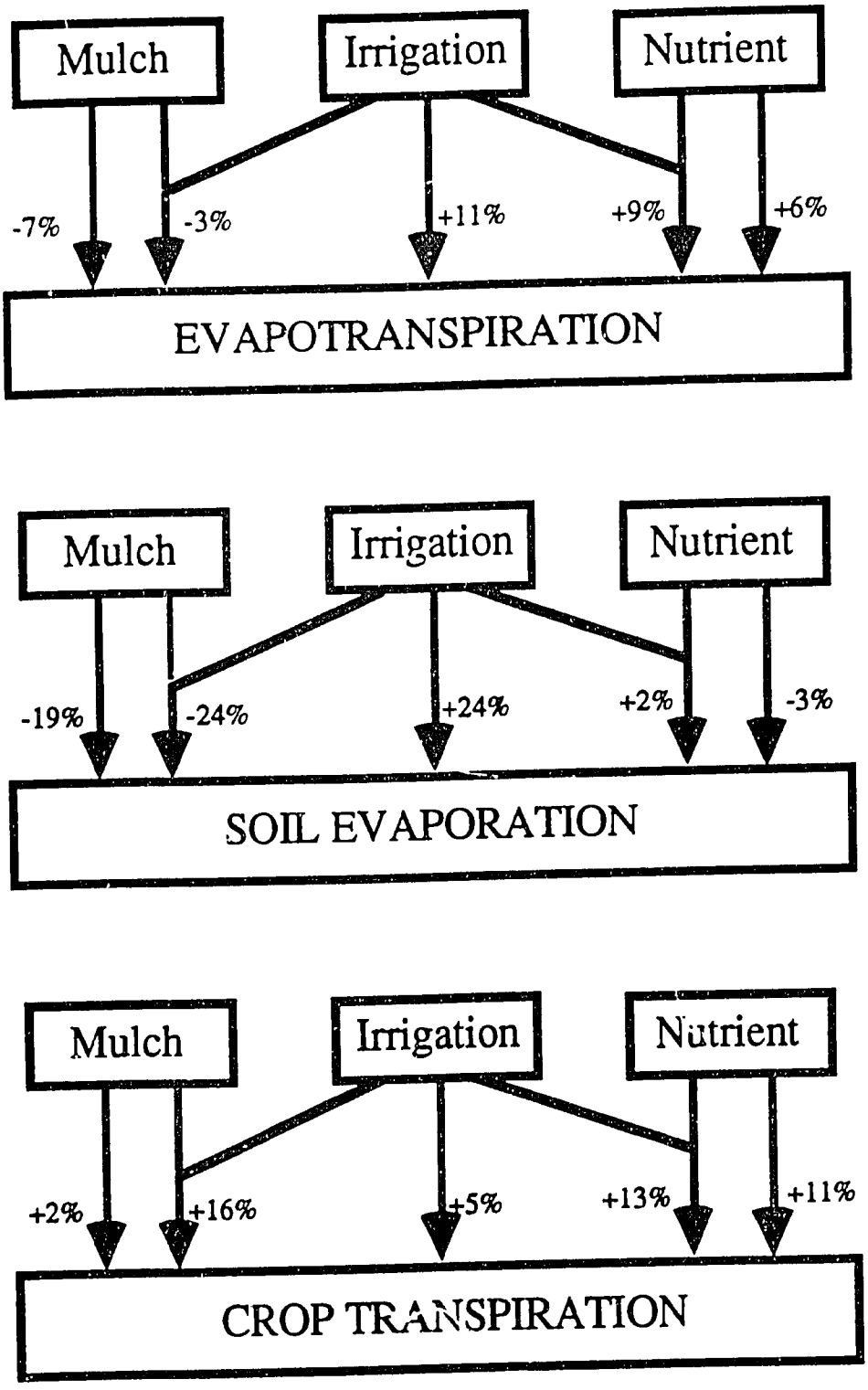


Figure 41. Relative effect of the experimental factors on ET, E, and T at the experiment site.

the dryland treatments. However, no conclusion can be drawn at this point. This question is addressed in the crop water use efficiency section where statistical analyse are presented.

The effects of each experimental factor on the water balance is discussed in terms of the ET. To test the study hypothesis detailed assessments of the effects of those experimental factors on E, T, and crop water use are required. One of the difficulties in assessing crop water use efficiency is need for separating soil evaporation from ET. In addition to integrating the soil-plant-atmosphere water relationships the model also accomplishes this task.

2. Experimental factors and crop water use

It has been demonstrated that mulch can be used to reduce soil evaporation. However, the efficiency and the extent to which this manipulation takes place should be evaluated by looking at relevant water balance components of the total seasonal water balance. Evaporation loss was greater on irrigated plots compared to dryland plots. This was due to the more frequent water availability at the soil surface (following each irrigation). Nutrient had little effect on water loss by evaporation (Fig. 42). This figure shows main and interactive effects of the three experimental factors on the water balance components (downward arrow) and biomass production (upward arrow). Horizontal arrows represents interactive effects. On dryland plots 57% of the water supply was transpired by crops. The amount of water transpired on irrigated plots was 40% of rainfall. This suggest that about 100 mm water was lost by soil evaporation. In terms of water management and conservation, effective reduction of water losses by evaporation could save an amount of water is in the same magnitude (100 mm) as the net seasonal irrigation input. It can be concluded that in terms of crop water use an effective evaporation suppressant system could potentially yield the same benefits as supplemental irrigation.

From a practical stabdpoint, results suggest that yields can be increased with nitrogen, without irrigation and less than 300 mm of rainfall. Results of the relative response to the manipulation scheme are summarized in Fig. 42. and are in agreement with those of Krishna, 1980. Based on these results it can be concluded that there is evidence to accept the general hypothesis that the water balance of the Sahelian agroecosystem can be manipulated with irrigation, mulch and nitrogen.

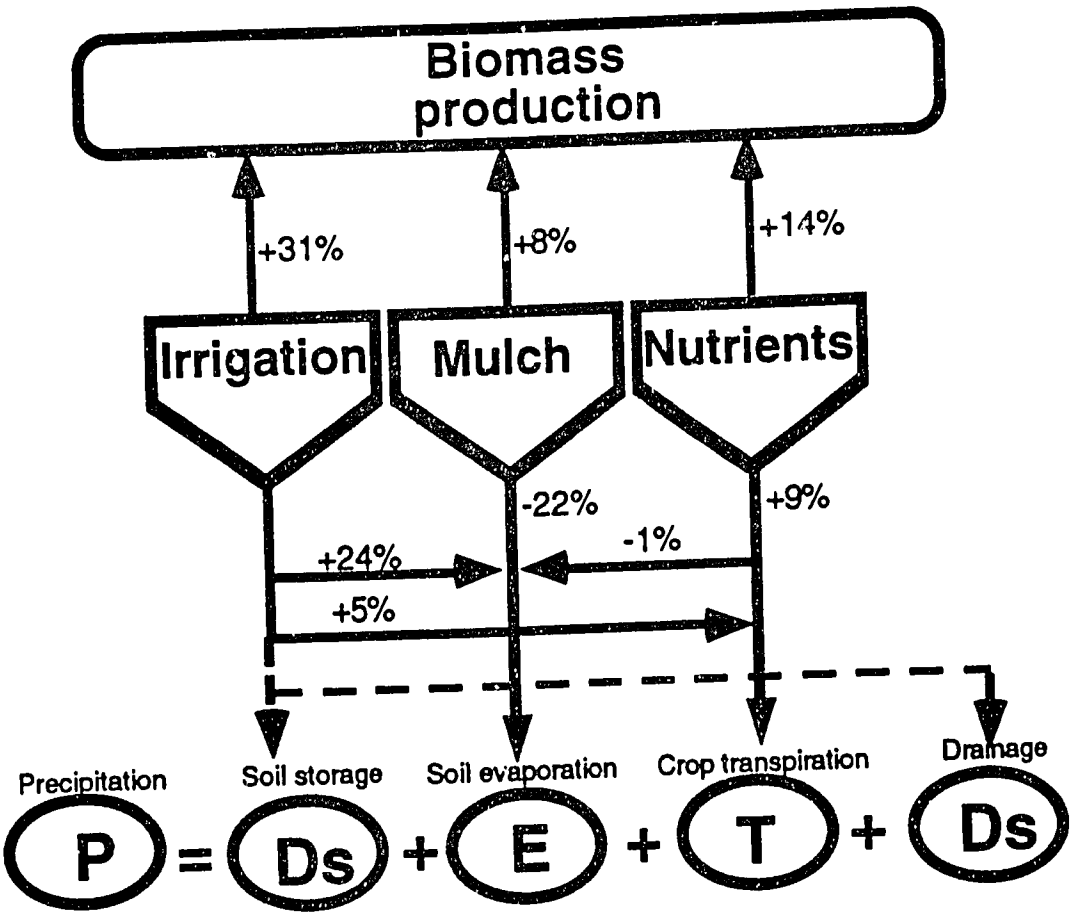


Figure 42. Relative global response to the water balance manipulation.

F. Modeling of evapotranspiration, evaporation, and transpiration

1. Pertinent considerations

The ENWATBAL model was used to predict ET, T and E. Soil properties (water retention and hydraulic conductivity functions) were presented in the soil hydrologic properties section and were the same for all treatments. However, initial soil moisture and temperature profiles were specific to each level of irrigation. For each treatment, LAI, and rooting depths (maximum and optimum) were determined from results presented earlier in the crop growth experiment section. Detailed input data are presented in Appendix C.

Crop LAI is an important parameter in the ENWATBAL model. Crop leaves senescence and fall occurred in all plots towards the end of the season. Before the crop completely matured about one third of plant leaves falled down. This resulted in random variability in LAI measurements. Another consequence of leaf fall was the partial mulching of the soil surface. This simulated the effect of the mulch treatment. Therefore, changes of LAI toward the end of the season was a cause for concern.

2. Results

a. Drainage and runoff

Results on drainage evaluation according to Eq. 32 are presented in Table 22. As indicated earlier, a protective ridge was built around each individual plot to prevent runoff and runon. This fact was well predicted by the simulation model using water detention capacity parameter of 0.20 m. Neither drainage nor runoff losses was predicted for any treatment which was consistent with the drainage values discussed earlier.

b. Evapotranspiration

There was a good agreement between simulated and measured ET for all treatments (Table 23). Mean measured ET for dryland treatments was 254 mm compared to 257 mm from the simulation. On irrigated treatments means measured and predicted ET was 284 and 274, mm respectively. The differences between the two determinations ranged from 2 to 11 mm (Table 23). The overall mean error for ET prediction was 7.5 mm. This represented 3-5% of the total, which is the accuracy limit suggested by Lascano et al. (1987). This provides evidence that the model can accurately predict ET for different management systems of the Sahelian agroecosystem.

Table 22. Simulated and computed seasonal water loss by drainage and runoff.

Treatment	ΔZ	$\Delta\theta$	D_A†	D_{AS}	Runoff‡
	m	$m^3\ m^{-3}$	mm		
Control	0.00	0.05	0	0	0
Mulch	0.20	0.03	6	0	0
Nitrogen	0.10	0.04	4	0	0
Nitrogen/mulch	0.20	0.03	6	0	0
Irrigation	0.20	0.02	4	0	0
Irrigation/Mulch	0.20	0.03	6	0	0
Irrigation/nitrogen	0.10	0.03	3	0	0
Irrigation/nitrogen/mulch	0.20	0.03	6	0	0

† Computed from soil moisture and root data.
‡ Simulated and computed

Table 23. Simulation of evaporation, transpiration, and evapotranspiration of the different treatments and associated errors.

Treatment	Evaporation			Transpiration			Evapotranspiration		
	E	ES†	Error	T	TS‡	Error	ET	ETS¶	Error
	mm		%	mm		%	mm		%
	108	112	-4	145	146	-1	253	258	-2
Mulch (M)	77	87	-13	163	155	5	240	242	-1
Nitrogen (N)	94	115	-22	177	167	-6	271	282	-4
N/M	86	82	5	164	163	1	250	245	2
Irrigation (I)	130	121	7	151	149	1	281	270	4
I/M	94	82	13	169	177	-5	263	259	2
I/N	128	103	20	164	180	-10	292	283	3
I/N/M	101	85	16	197	200	-2	298	285	4

† Calculated evaporation
‡ Calculated transpiration
¶ Calculated evapotranspiration

e. Evaporation

One of the reasons for using the model was to separate evaporation and transpiration. The separation of these components are summarized in Table 23. The error associated with E was relatively greater compared to ET and T. Nevertheless, predicted values were close to measured; error for E simulation ranged from -4 (nitrogenutrient/mulch) to -21 mm (nitrogen). That of T from -1 (nitrogen/mulch) to -17 (irrigation/nitrogen).

Since the determination of E and T was based on measured E (Eq. 32) in which E is a key parameter, it is essential to compare measured and simulated E. Cumulative values of simulated and measured E are presented in Fig. 43. In most cases, there was a close agreement between simulated and measured values, particularly in the early part of the growing season (prior to day 240). Two distinct trends were observed: that of the mulched and that of the non-mulched treatments. Soil evaporation from mulched treatments was consistently lower which is consistant with the energy and water balance results presented earlier.

Most predicted values were whithin 5 to 10% percent error from the measured values. The prediction of E for the control and the mulch treatment was consistent. The greatest difference between measured and predicted values occurred on the nitrogen treatment. Possible causes for that discrepancy could include: the leaf drop and the lower crop survival. Measured values suggested that there was very little evaporation after day 250. About 10 mm rainfall occured after that date indicating tha measurements on this treatment tended to underestimate evaporation. Therefore, one may speculate tha predicted value are closer to real values.

In general, predicted final values on irrigated treatments were lower than measured value particularly on the irrigation/nitrogen and irrigation/nitrogen/mulch treatments. This could have bee caused by evaporation losses from the irrigation on day 269 when crops were almost mature.

3. Conclusions

The evapotranspiration components of the different treatments were adequately predicted by th model. In most cases, predicted values were within 5 to 10% error of measured values. The erro associated with the simulation estimation did not follow any particular trend. Soil evaporatio measurements were based on micro-lysimeters which requires soil disturbance and disturbance of mul during measurements. Root activity within the lysimeter was also excluded. Therefore, changes of so moisture within the lysimeter were relatively different from those of the field. Inaccuracies in th measurement of soil evaporation affected the computation of crop transpiration (Eq. 34). Fie measurement from mini-lysimeters suggested that evaporation tended to stop four to five days followi the rain second stage of the Richie model (Ritchie, 1972) (with incomplete crop cover, as described Hillel, 1980), particularly on non-mulched plots. All these factors may have contributed to the errors.

Table 24. Crop water use efficiency (WUE) of the different treatments at the experiment site.

Parameter	Component					
	WUE(ET)	WUE(T)	WUE(ET)grain	WUE(T)grain	WUE(R)	WUE(R+I)
	g kg^{-1}					
EXPERIMENTAL FACTOR: MAIN EFFECT						
Irrigation (I)						
None	2.98	4.64	0.84a	1.30a	2.52	2.52
With	3.62	6.24	1.10b	1.90b	3.31	2.22
Nitrogen (N)						
None	3.14a†	5.21	0.89a	1.48a	2.73a	2.21a
With	3.46b	5.68	1.05b	1.72b	3.10b	2.53b
Mulch (M)						
None	3.05a	5.29	0.85a	1.48a	2.80	2.27
With	3.55b	5.60	1.09b	1.72b	3.02	2.46
Interactions	IxNxM	NxM			IxNxM	IxNxM
Mean	3.30	5.44	0.97	1.60	2.91	2.37
CV(%)	13	14	16	18	14	14
TREATMENT MEAN						
Control	2.48	4.33	0.61	1.06	2.09	2.09
Mulch (M)	3.14	4.62	0.88	1.29	2.51	2.51
Nitrogen (N)	3.00	4.59	0.88	1.34	2.71	2.71
N/M	3.30	5.03	1.00	1.52	2.75	2.75
Irrigation (I)	3.46	6.44	0.97	1.81	3.24	2.17
I/M	3.49	5.44	1.12	1.74	3.06	2.05
I/N	3.26	5.82	0.96	1.71	3.18	2.13
I/N/M	4.28	7.26	1.36	2.32	3.75	2.51

† Means within the same experimental factor level followed by different letters are statistical significant (P = 0.05).

Results suggested that ENWATBAL can be used to predict crop transpirational water in the Sahelian agroecosystems. It also provides a good insight on crop water use from the energy balance. Therefore, it is an appropriate means for testing hypotheses on crop water use studies in the Sahel.

G. Crop water use efficiency and hypotheses

The hypothesis of this study were defined as follows: (1) sorghum WUE(ET) can be improved by nutrient input, (2) WUE(ET) can be improved by supplemental irrigation, and (3) WUE(T) can be improved by mulch. These hypotheses are examined in this section.

1. Effect of nutrient on WUE(ET)

The effect of the different treatments on crop WUE(ET) is presented in Table 24. Nitrogen caused a statistically significant increase of WUE(ET). The increase was 13% on non-irrigated treatments and 9% on irrigated treatments. This provides evidence upon which the first hypotheses is accepted. Therefore, it can be concluded that nitrogen is a limiting factor for sorghum efficient water use in the Sahelian agroecosystem. Addition of nitrogen improved WUE(ET) on non-irrigated and irrigated treatments, indicating that the rate of biomass production increase per unit water evapotranspired was higher with nitrogen.

A significant interaction between the three factors (Fig. 44) indicates that WUE(ET) tended to be higher on irrigated plots. All the treatments can be ranged into 4 statistically different groups; (1) the control, (2) the nitrogen, (3) the irrigation/nitrogen/mulch, and (4) the others. The WUE(ET) of all combinations of irrigation and mulch treatments was significantly improved WUE(ET) compared to the Control. The irrigation/nitrogen/mulch treatment caused the highest WUE(ET).

This interaction indicated that mulch increased WUE(ET) with the addition of nutrient on all non-irrigated treatments where the increase was lesser on mulched compared to non-mulched treatments. This could be due, as indicated earlier, to the increased transpiration caused by both mulch and nitrogen.

The effect of nitrogen on WUE(ET) of irrigated treatments was affected by mulch. Nitrogen decreased WUE(ET) on non-mulched treatments but increased WUE(ET) on mulched treatments (Fig. 44). This could be explained by the fact that ET losses are high when irrigation or nitrogen is applied: due to more water availability and more plant growth. The WUE(ET) of the irrigation/nitrogen and irrigation/mulch ("no mulch/nitrogen" and "mulch/no nitrogen" on Fig. 43) were about the same, but were lower than that of the Irrigation treatment (no mulch/no nitrogen and irrigation on Fig. 43).

2. Effect of supplemental irrigation on WUE(ET)

Even though irrigation increased WUE(ET) 22% (Fig. 45) it did not cause any statistically significant main effect (Table 24). Therefore, the second hypothesis should be rejected. The interaction presented in Fig. 45 indicated that irrigation in some cases may significantly increase WUE(ET). These results imply that it can not be concluded that in general irrigation improves WUE(ET). Irrigation may be used to offset the effects of drought and improve yields.

3. Effect of mulch on WUE(T)

Crop WUE(T) response was more complex compared to WUE(ET). All experimental factors increased WUE(T) but no increase was statistically significant (Table 24). Therefore, the third hypothesis should be rejected. Two significant interactions were present: one between Irrigation, Nutrient, and Mulch, and another between Nutrient and Mulch.

The interaction between irrigation, nitrogen, and mulch (Fig 46) indicates that mulch significantly increased WUE(T) of the irrigation/nitrogen treatment and increased WUE(T) on dryland treatments. On irrigated plots, the magnitude of the response was greater, and the trend different. Addition of mulch to Irrigation treatment (no mulch/no nitrogen treatment on Fig. 46) decreased WUE(T) while addition of mulch to the nitrogen treatment (no mulch/nitrogen) increased WUE(T). The decrease of WUE(T) caused by mulch on the irrigation treatment could be attributed to the low (6%) biomass increase and the high (24%) transpiration increase caused by the addition of mulch.

Based on the interaction discussed above, the second hypothesis should be accepted only for the irrigation/nutrient treatment. The interaction between mulch and nitrogen (Fig. 47) indicated that overall, mulch caused significant increases of WUE(T) only when nutrient is applied. This conclusion is consistent with the previous ones indicating that nitrogen is limiting to efficient water use in the agroecosystem. Therefore, as concluded by Kanemasu et al. (1982) water use efficiency can not be improved by evaporation control, or irrigation without adding nitrogen.

4. Grain water use efficiency

Results on grain water use efficiency are presented in Table 24. All experimental factors significantly increased grain evapotranspirational water use efficiency (WUE(ET)grain) indicating that they all contributed individually to crop grain production efficiency. Irrigation had the greatest impact on grain water use effeciency. It increased WUE(ET) grain 31% and WUE(T) grain 46% (Fig. 48). This indicated that irrigation provided enough supplemental water to insure good crop vegetative growth and reproduction.

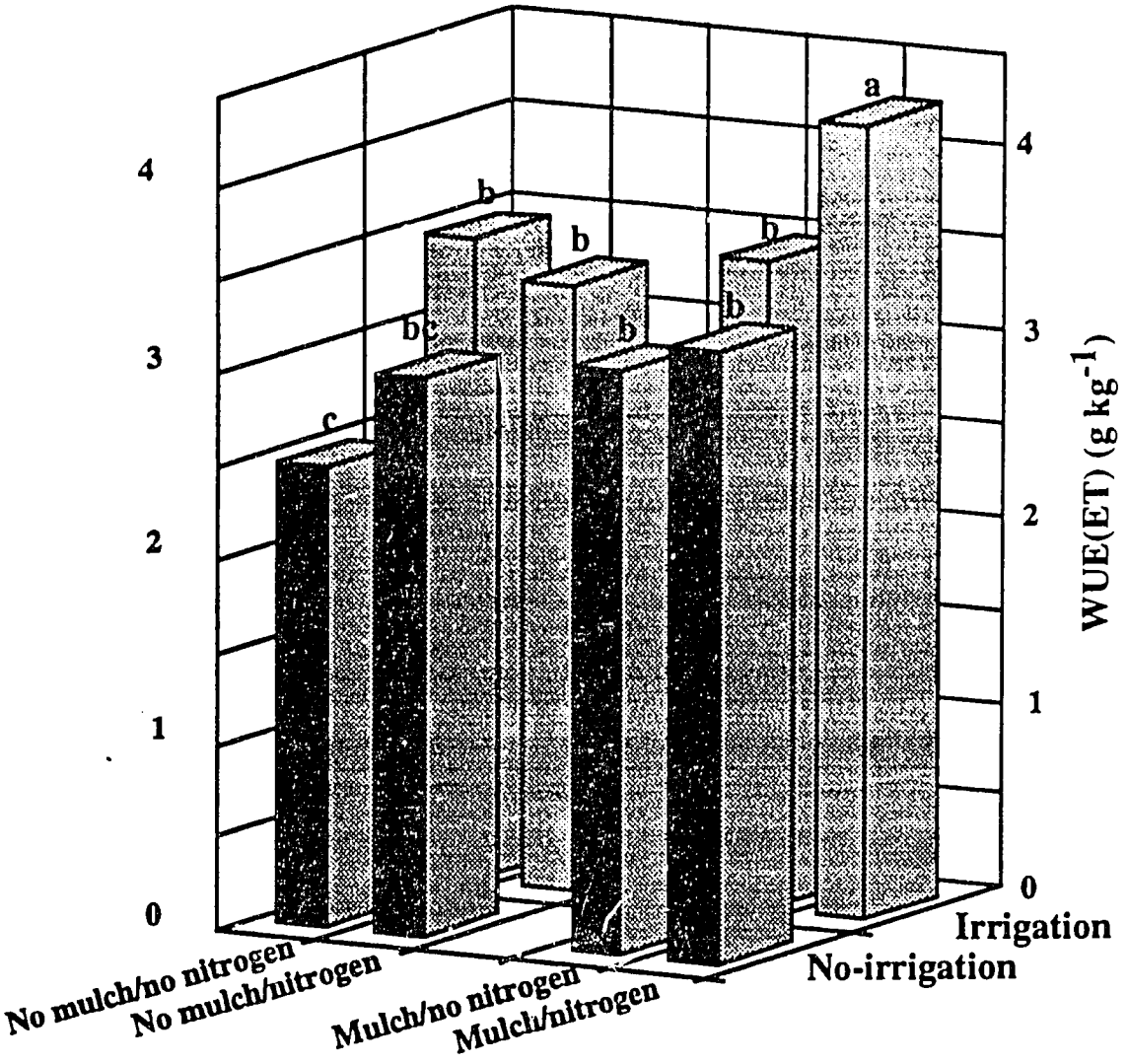
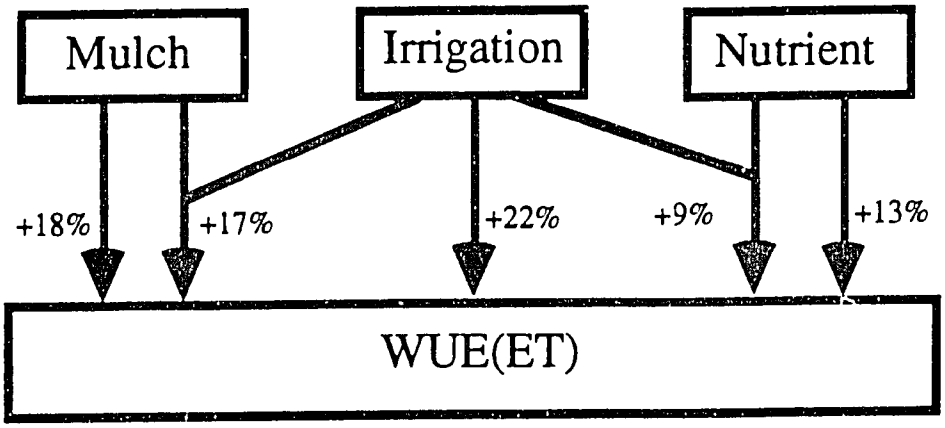


Figure 44. Interaction between irrigation, nitrogen, and mulch on crop WUE(ET). Bars capped with different letters are statistically (P=0.05) different.



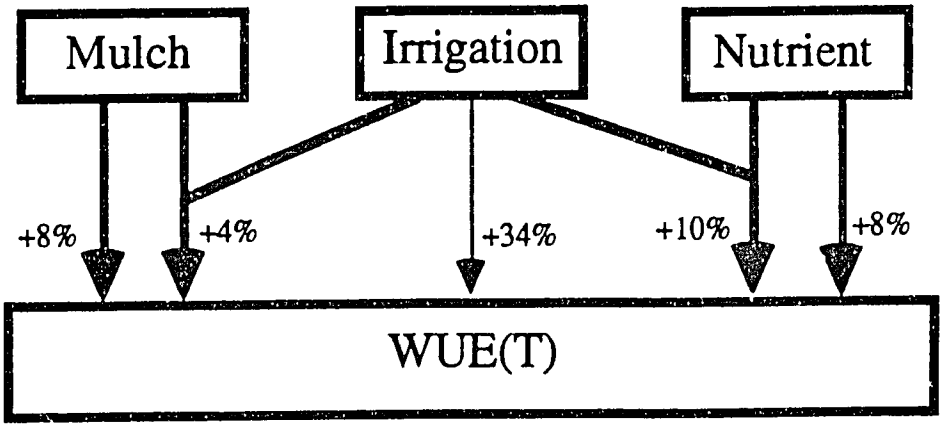


Figure 45. Relative effect of the experimental factors on sorghum biomass WUE(ET) and WUE(T) at the experiment sites.

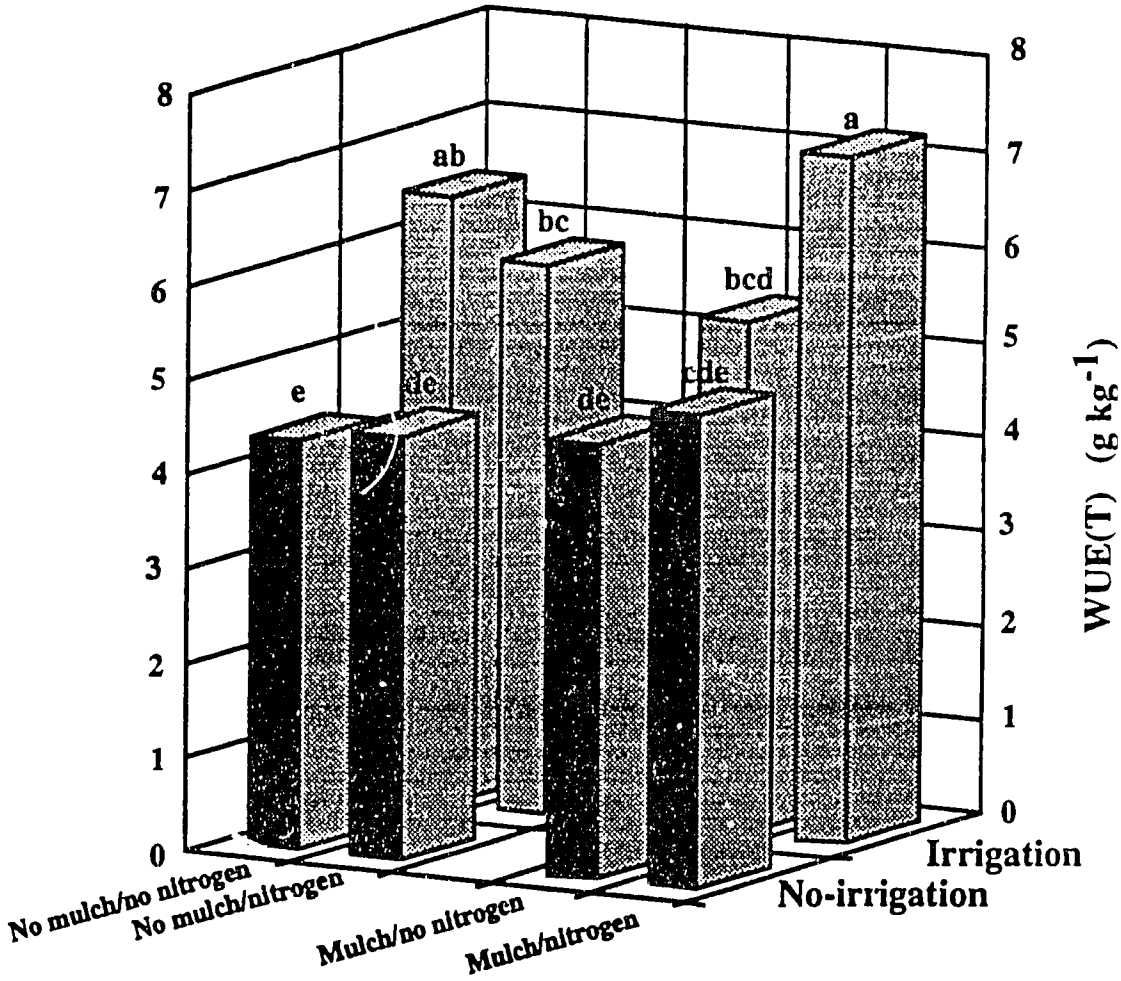


Figure 46. Interaction between irrigation, nitrogen, and mulch on crop WUE(T). Bars capped with different letters are statistically (P=0.05) different.

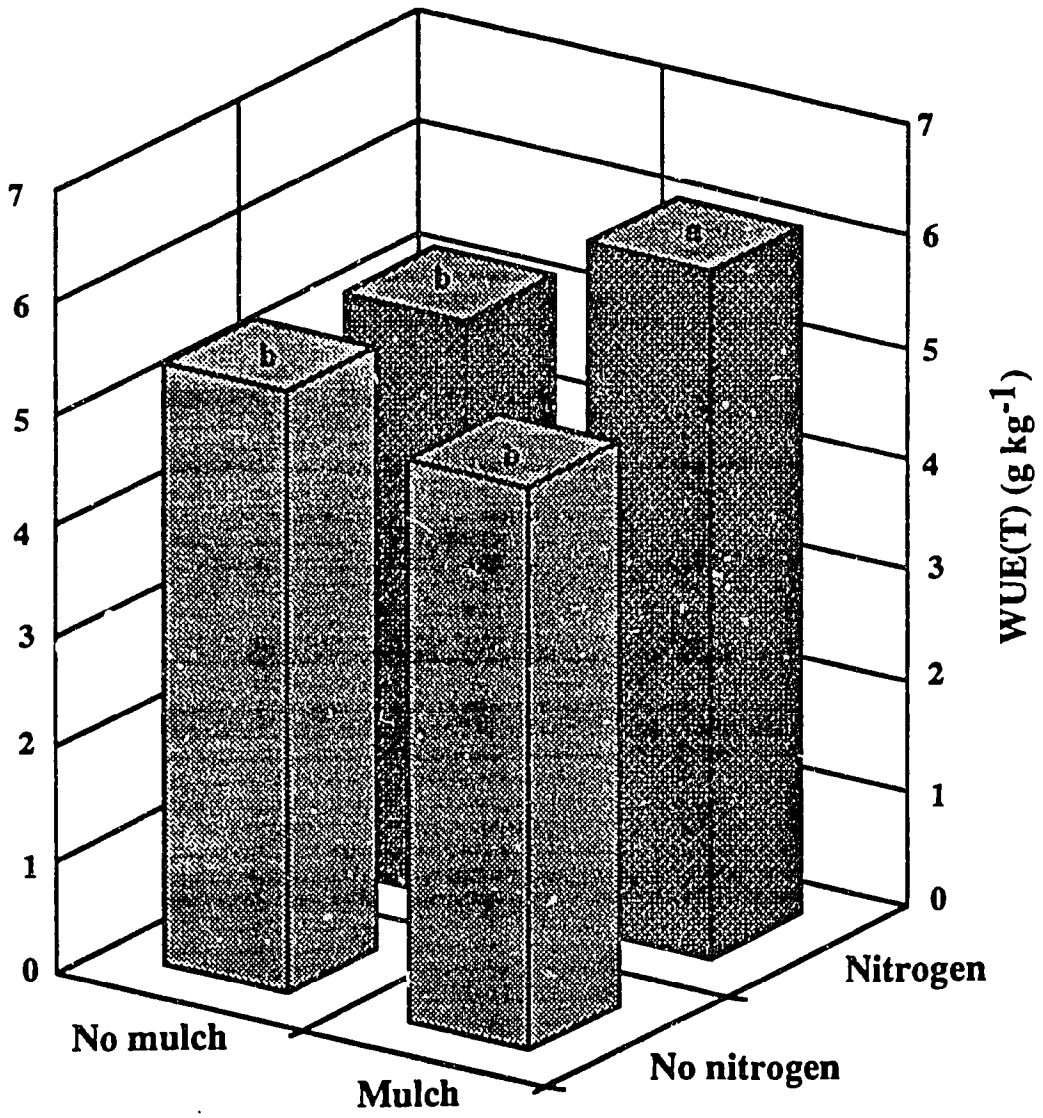
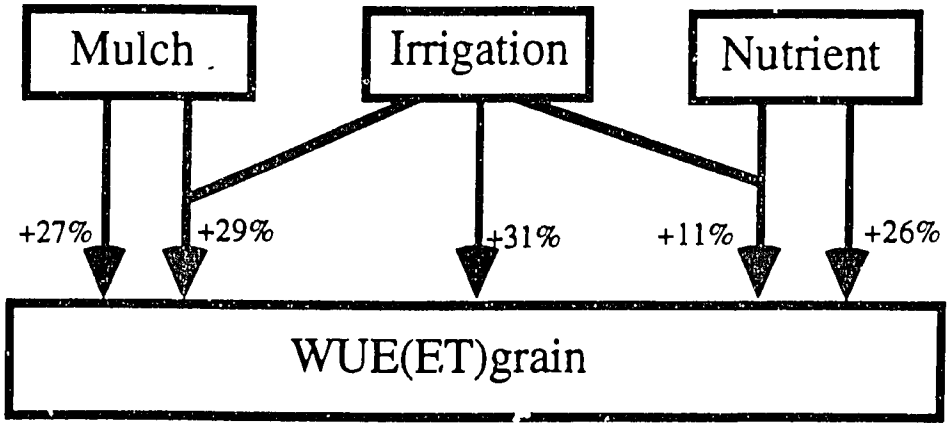


Figure 47. Interaction between nitrogen, and mulch on crop WUE(T). Bars capped with different letters are statistically (P=0.05) different.



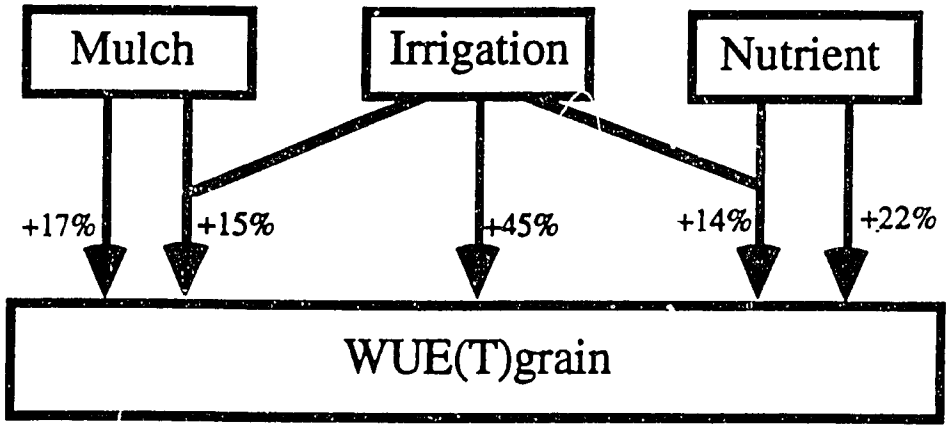


Figure 48. Relative effect of the experimental factors on sorghum grain WUE(ET) and WUE(T) at the experiment sites.

Nitrogen increased WUE(ET)grain 18% which was lower compared to the effect of mulch (28% increase). The higher effect of mulch on WUE(ET)grain can be attributed to the reduction of soil evaporation losses discussed earlier. This is supported by the fact that effect of nitrogen and mulch on WUE(T)grain was similar (16% increase). This implies that in terms of management for improved grain production mulch played a more important role compared to its role in biomass production.

5. Rainfall and total water use efficiency

In analyzing the efficiency of a given system, one must not fail to consider the global scheme. Since the main challenge in Sahelian agriculture is to use rainfall efficiently it is appropriate to give analysis results with respect to Sahelian global system. Water use efficiency is analyzed with respect to the seasonal rainfall. Each treatment was considered as a given set of inputs and WUE(R) refers to how this set of inputs influences crop seasonal rainfall use. It has also been shown in the literature review that drought may limit crop production in the Sahel. When inputs such as water harvesting and supplemental irrigation are used to offset the effect of drought from they are net inputs (in the form of water) that modifies the total water budget and crop water use efficiency. Therefore, treatments should also be analyzed in terms of the total water buget. The WUE (R+I) term used in this section evaluates treatments effectiveness with respect to the total water budget provided.

Irrigation increased (31%) WUE(R) and decreased (12%) WUE(R+I). This may indicate three facts: (1) that the amount of irrigation exceeded the minimum additional amount of water required to reach maximum WUE(R), (2) that moisture stress (drought) did not cause massive crop losses, and (3) that some of the irrigation water was not used.

Nitrogen was the only factor that significantly increased WUE(R) and WUE(R+I) (Table 24). It increased both parameters by 14%. Interactions between thr three factors indicates that nitrogen and mulch increased WUE(R) with or without irrigation. This increase was greater on non-irrigated treaments. This indicates again the importance of nitrogen for efficient crop water use, and also that in order to improve total water use efficiency any water input should be coupled with nitrogen input if the natural supply is not adequate.

The effect of mulch on WUE(R) and WUE(R+I) was similar to that of nitrogen but was half (8% compared to 16%) of that of nitrogen. Since mulch reduces soil evaporation losses increase of WUE(R+I) indicates that one of the reasons for reduced WUE(R+I) with irrigation is water loss by soil evaporation.

VIII. CONCLUSIONS

The Sahelian agroecosystem selected for this study was characterized by alluvial soils and a short growing season during which precipitation exceeded potential evapotranspiration. Sorghum is commonly grown on these alluvial soils (Entisols and Inceptisols) in which intensive solar irradiance occurs and evaporation is a major component of soil water loss. The occurrence of two major dry spells during the growing season resulted in significant variability in the soil water supply which was desirable for this study. Soil fertility and hydrological characteristics of alluvial soils of the study site, were relatively better than those of upland sandy dunes where millet is commonly grown. Water movement between 0.90 and 1.2 m depth was restricted by a sealed soil layer which slowed water movement and limited effective (90%) rooting to the top 0.9 m depth.

Irrigation improved biomass yield, increased ET and T water use efficiency and induced the greatest water use efficiency values except for WUE(R+I). This suggests that increase of biomass production caused by additional irrigation tended to be of the linear type rather than exponential. The most significant improvement from irrigation was on rainfall use efficiency (WUE(R). This indicated that rainfall was below the optimum level.

Nitrogen had the greatest overall statistical impact on crop water use efficiency, particularly on dryland plots. It significantly increased WUE(ET), WUE(ET)grain, WUE(T)grain, WUE(R), and WUE(R+I). Transpirational water use efficiency was also increased but the increase was not statistically significant.

Mulch significantly increased WUE(ET). Increase of WUE(T) due to mulch was not significant, suggesting that it increased plant transpiration. Irrigation and nitrogen were involved in all interactions, suggesting that they were the most important factors increasing water use efficiency although, many interactions involved all three factors.

Biomass production was limited predominantly by soil evaporation (less available water) that induced severe water stress during drought periods. The second production limiting factor was nitrogen. Mulch tended to promote a shallow crop rooting. Since soil evaporation losses occurred from the surface 0.9 m the shallow rooted crop was more vulnerable to dry spells when irrigation was not supplied.

Soil evaporation accounts for a major part (40 - 50%) of the total water losses. The irrigation water supply was equivalent to seasonal water loss by evaporation. This implies that if a reduction in the soil evaporation is provided, it could have the same effect as irrigation. During the season mulch caused to a significant (33%) reduction in evaporation. Practical means for reducing soil evaporation includes: crop residue or waste mulch; high LAI; and soil sealing or crusting between planting rows. This study suggests that controlling soil evaporation could be a major contribution to the problem of

drought. Future studies should focus on identifying the best form of evaporation control and heat dissipation alternatives, for the physical, environmental, and socio-economical context of the Sahel.

Results from the water balance study suggest that soil water balance can be manipulated with nitrogen, mulch and irrigation. This manipulation can be used to manipulate crop water use efficiency. All experimental factors affected crop water use effiency but at different levels and interactively in most cases. For the specific study hypothesis it can be concluded that: (1) nitrogen significantly improved WUE(ET), (2) supplemental irrigation significantly improved water use efficiency only when no other input is made or both mulch and nitrogen were applied, (3) mulch improved WUE(T) only when irrigation and nutrient were applied.

The ENWATBAL model accurately predicted crop water use (ET, E, and T). Therefore it is appropriate for Sahelian agroecosystems crop water studies analyses and could be used as a practical tool for predicting soil water balance for different seasonal rainfall distribution and cropping systems as well as different weather scenarios.

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APPENDIX A. SOIL PROFILES DESCRIPTIONS

Table A1. Soil description of profile A.

Horizon	Depth	Description†
	(cm)	
A1	0-15	Dark brown‡ (10 YR 3/3) when moist, sandy loam; moderate medium to fine sub angular blocky; friable; clear smooth boundary; pH 7.5
A2	15-32	Dark brown (10 YR 3/3) moist, loam; massive; friable; abrupt smooth boundary; pH 7.5
C1	32-57	Yellowish brown (10 YR 5/4) clay loam; grayish brown (10 YR 5/2) moist; massive to weak sub angular blocky; friable; abrupt wavy boundary; pH 7.5
C2	57-65	Very pale brown (10 YR 7/4) loamy fine sand, yellowish brown (10 YR 5/4) moist; massive; slightly hard; abrupt broken boundary; pH 7.5
C3	65-88	Light brownish gray (10 YR 6/2) clay loam, grayish brown (10 YR 5/2) moist; massive to weak medium to coarse sub angular blocky with litting; abrupt wavy boundary; pH 7.7
C4	88-102	Pink (7.5 YR 7/4) fine sand, light brown (7.5 YR 6/4) moist; massive; slightly hard; abrupt wavy boundary; pH 8.5
C5	102-141	Variegated gray (10 YR 5/1) and grayish brown (10 YR 5/2) clay; respectively dark gray (10 YR 4/1) and dark grayish brown (10 YR 4/2) moist; moderate medium to fine sub angular blocky; very hard; abrupt smooth boundary; pH 8.3
C6	141-193	Variegated pale brown (10 YR 6/3) and brownish yellow (10 YR 6/6) sandy loam; respectively brown (10 YR 5/3) and yellowish brown (10 YR 5/4) moist; massive; hard; clear smooth boundary; pH 8.8
C7	193-248	Light brownish gray (10 YR 6/2) loamy sand; dark grayish brown (10 YR 4/2) moist; massive; hard; pH 8.8

† Details of site location and collectors are the same as those presented in Table 6 (page 43)

‡ Colors are for dry soil unless otherwise indicated.

Table A2. Soil description of profile C.

Horizon	Depth	Description†
	(cm)	
A1	0-16	Yellowish brown‡ (10 YR 5/4) sandy loam, dark brown (10 YR 3/3) when moist; moderate medium sub angular blocky; slightly hard; clear smooth boundary; pH 8.0
A2	16-39	Yellowish brown (10 YR 5/4) sandy clay loam, dark brown (10 YR 3/3) moist; weak coarse sub angular blocky; hard to very hard; abrupt wavy boundary; pH 8.5
C1	39-57	Light brown (10 YR 6/4) loam; brown to dark brown (10 YR 4/3) moist; weak course sub angular blocky; hard to very hard; abrupt wavy boundary; pH 8.3
C2	57-86	Pink (10 YR 7/4) sand, yellowish brown (10 YR 5/4) moist; massive and weak coarse sub angular blocky; soft to slightly hard; abrupt wavy boundary; pH 8.2
C3	85-134	Variegated pale brown (10 YR 6/3), pink (10 YR 7/4) and strong brown (7.5 YR 5/8) loam; respectively brown (10 YR 5/3), very pale brown (10 YR 7/4) and strong brown (7.5 YR 5/6) moist; massive; hard; abrupt wavy boundary; pH 8.2
C4	134-183	Variegated brown (7.5 YR 5/4) and gray (10 YR 5/1) clay loam; respectively brown to dark brown (7.5 YR 4/4) and dark gray (10 YR 4/1) moist; massive; hard to very hard; clear smooth boundary; pH 8.6
C5	183-206	Variegated light brownish gray (10 YR 6/2) and yellowish brown (10 YR 5/4) sandy loam; respectively gray (10 YR 5/1) and dark yellowish brown (10 YR 4/4) moist; massive; hard to very hard; abrupt smooth boundary; pH 8.7
C6	206-222	Variegated light gray (10 YR 7/1), pale brown (10 YR 6/3) and yellowish brown (10 YR 5/6) sandy loam; respectively light gray to gray (10 YR 6/1) brown (10 YR 5/3) and dark yellowish brown (10 YR 4/4) moist; massive; soft to slightly hard; abrupt smooth boundary; pH 8.6
C7	222-251	Variegated light gray to gray (10 YR 6/1), yellowish brown (10 YR 5/4) and (10 YR 5/6) clay loam; respectively gray (10 YR 5/1), dark gray (10 YR 4/1) and yellowish brown (10 YR 5/6) moist; massive; very hard; pH 8.3

† Details of site location and collectors are the same as those presen . in Table 6 (page 43)

‡ Colors are for dry soil unless otherwise indicated.

APPENDIX B. CHEMICAL EVALUATION OF IRRIGATION WATER

Table B1. Laboratory analysis.

Parameter	Unit		
Element	Meq l^{-1}	mg kg^{-1}	Other
Calcium	0.41	8.20	
Magnesium	0.16	2.00	
Sodium	1.39	32.00	
Potassium	0.13	5.00	
Bi-carbonate	1.08	66.12	
Sulfate	0.32	15.60	
Chloride	0.25	9.00	
Boron		0.02	
Nitrate		6.10	
Zinc		0.01	
Total cations	2.09	47.2	
Total anions	1.66	90.72	
Sodium adsorption ratio (SAR)			2.58 $mole^{0.5}\ l^{-0.5}$
Soluble salt percentage (SSP)			66.48 %
pH			7.20
Hardness			0.67 grain $gallon^{-1}$
Electrical conductivity			0.226 dS m^{-1}

Table B2. Hazards associated with irrigation water as suggested by USDA (1954).

Parameter	Threshold	Hazard
Sorghum (*Sorghum bicolor*)		
Electrical conductivity	6.8 dS m^{-1}	16% yield reduction
Specific conductivity	23 dS m^{-1}	Salinity hazard
Boron concentration	6 - 10 ppm	Boron toxicity hazards
	0.02	Very slight boron hazards
SAR	2.58	Low salinity hazards
Cowpea (*Vigna ungulata*)		
Electrical conductivity	4.9 dS m^{-1}	12% yield reduction
Specific conductivity	23 dS m^{-1}	Salinity hazard
Boron concentration	0.50 - 0.75 ppm	Boron toxicity hazards
	0.02	Very slight boron hazards
SAR	2.58	Low salinity hazards

APPENDIX C. MEAN SQUARES FROM ANALYSIS OF VARIANCE

Table C1. Mean square associated with plant height.

Source	df†	Day of the year					
		197	208	213	218	229	237
		m					
Replication	4	0.000	0.061	0.039	0.045	0.449	0.206
Irrigation (I)	1	0.003**	0.130*	0.204*	0.339*	1.384	0.029
Error 1	1	0.000	0.007	0.018	0.024	0.301	0.070
Nutrients (N)	1	0.000	0.000	0.005	0.001	0.002	0.078
IxN	1	0.000	0.003	0.001	0.000	0.044	0.068
Mulch (M)	1	0.002*	0.001	0.040	0.102*	0.050	0.057
IxM	1	0.000	0.010	0.002	0.014	0.000	0.158*
NxM	1	0.000	0.001	0.001	0.001	0.050	0.002
IxNxM	1	0.000	0.019*	0.002	0.042	0.079	0.099
Error 2	24	0.000	0.004	0.015	0.018	0.050	0.030

† Degrees of freedom
* significant at the 5% probability level
** significant at the 1% probability level

Table C1 (Cont.').

Source	df†	Day of the year			
		248	258	268	278
		m			
Replication	4	0.136	0.104	0.101	0.010
Irrigation (I)	1	0.262	0.002	0.133	0.023
Error 1	4	0.061	0.265	0.052	0.044
Nutrients (N)	1	0.000	0.004	0.070	0.002
IxN	1	0.000	0.071	0.000	0.003
Mulch (M)	1	0.017	0.056	0.015	0.038
IxM	1	0.002	0.014	0.001	0.000
NxM	1	0.014	0.000	0.000	0.107*
IxNxM	1	0.003	0.127	0.059	0.006
Error 2	24	0.032	0.041	0.018	0.021

† Degrees of freedom
* significant at the 5% probability level

Table C2. Mean square associated with plant LAI.

Source	df†	Day of the year					
		197	208	213	218	229	237
		$m^2 m^{-2}$					
Replication	4	0.000	0.294	0.279	0.289	1.427	2.530
Irrigation (I)	1	0.001	0.873*	1.321*	3.660	2.730	0.713
Error 1	4	0.000	0.060	0.071	1.282	3.099	0.894
Nutrients (N)	1	0.000	0.038	0.013	0.625	0.658	3.036*
IxN	1	0.000	0.020	0.080	0.835	0.131	1.246
Mulch (M)	1	0.003**	0.021	0.230	0.847	1.836	0.396
IxM	1	0.000	0.029	0.004	0.376	0.583	0.062
NxM	1	0.000	0.042	0.000	0.011	0.001	0.042
IxNxM	1	0.000	0.097	0.150	0.708	0.850	1.260
Error 2	24	0.000	0.026	0.219	0.454	0.738	0.448

† Degrees of freedom
* significant at the 5% probability level
** significant at the 1% probability level

Table C2 (Cont.').

Source	df†	Day of the year			
		248	258	268	278
		$m^2 m^{-2}$			
Replication	4	1.078	0.633	0.491	4.510*
Irrigation (I)	1	0.545	0.291	0.105	0.055
Error 1	4	1.051	2.493	1.405	0.380
Nutrients (N)	1	0.593	0.138	2.158	1.176*
IxN	1	0.689	0.002	0.007	0.007
Mulch (M)	1	1.556	0.124	0.018	0.006
IxM	1	0.236	1.215	0.732	0.125
NxM	1	0.030	1.418	0.776	0.069
IxNxM	1	0.136	0.291	0.743	0.052
Error 2	24	0.763	0.713	0.829	0.231

† Degrees of freedom
* significant at the 5% probability level

Table C3. Mean square associated with plant biomass production.

Source	df†	Day of the year		
		197	208	218
		kg ha $^{-1}$		
Replication	4	17.150	2246.688	9016.288
Irrigation (I)	1	176.400**	13987.600*	62094.400*
Error 1	4	12.650	1751.787	6785.337
Nutrients (N)	1	6.400	211.600	756.900
IxN	1	10.000	360.000	1166.400
Mulch (M)	1	48.400	5198.400	18835.600
IxM	1	10.000	490.000	2340.900
NxM	1	0.000	3.600	14.400
IxNxM	1	0.400	1638.400	6708.100
Error 2	24	3.450	1326.438	5311.696

† Degrees of freedom
* significant at the 5% probability level
** significant at the 1% probability level

Table C3 (Cont').

Source	df†	Day of the year		
		231	237	248
		kg ha $^{-1}$		
Replication	4	166995.212	589393.713	11233631.150
Irrigation (I)	1	24950.025	47059.600	1213128.900*
Error 1	4	1093192.337	1804293.537*	5988555.650
Nutrients (N)	1	1683871.225*	64641.600	9235210.650
IxN	1	46172.025	37088.100	3290169.600
Mulch (M)	1	5405.625	2447280.900*	4679928.100
IxM	1	178890.625	23328.900	3736876.900
NxM	1	17766.225	74995.600	1060153.600
IxNxM	1	5085.025	30030.400	4626720.400
Error 2	24	309901.708	666979.292	6102289.767

† Degrees of freedom
* significant at the 5% probability level

Table C3 (Cont').

Source	df†	Day of the year	
		258	278
		kg ha $^{-1}$	
Replication	4	1876.900	2583559.900
Irrigation (I)	1	13509700.400*	56408625.025
Error 1	4	8960417.900	13595304.275
Nutrients (N)	1	22861440.000*	12308793.025**
IxN	1	4675824.400	306775.225
Mulch (M)	1	875568.100	4104324.225
IxM	1	6676524.100	31528.225
NxM	1	822542.400	739024.225
IxNxM	1	3886275.600	7120828.225*
Error 2	24	4145154.600	1569712.171

† Degrees of freedom
* significant at the 5% probability level
** significant at the 1% probability level

Table C4. Mean square associated with yield components.

Source	df†	Grain Yield	Harvest index	Head m^{-2}
		(Kg ha^{-1})		
Replication	4	309102.663	0.003	1 150
Irrigation (I)	1	7740480.400*	0.004	4.900*
Error 1	4	223895.837	0.009	1.775
Nutrients (N)	1	2302080.400*	0.004	8.100*
IxN	1	176358.400	0.003	6.400
Mulch (M)	1	1688388.100*	0.006	3.600
IxM	1	45024.100	0.000	0.100
NxM	1	5522.500	0.002	0.100
IxNxM	1	617522.500	0.000	0.400
Error 2	24	189182.250	0.003	1.596

† Degrees of freedom
* significant at the 5% probability level

Table. C4 (Cont'.).

Source	df†	Fertile heads	Bad heads	Head weight
		%		g
Replication	4	69.912	43.100	52.212
Irrigation (I)	1	792.100	08.900	497.025*
Error 1	4	156.162	29.400	30.212
Nutrients (N)	1	78.400	22.500	275.625*
IxN	1	22.500	2.500	65.025
Mulch (M)	1	577.600*	220.900*	1.225
IxM	1	22.500	52.900	87.025
NxM	1	3.600	0.100	2.025
IxNxM	1	562.500*	22.500	126.025
Error 2	24	112.288	32.650	51.013

† Degrees of freedom
* significant at the 5% probability level

Table C4 (Cont'.).

Source	df†	Seed mass	Grain head^{-1}	Seeds head^{-1}	Seeds m^{-2}
		g	kg kg^{-1}	#	
Replication	4	10.350	0.007	105859.337	5824.400
Irrigation (I)	1	0.400	0.004	877048.225*	118048.225**
Error 1	4	13.60	0.005	103825.788	5329.350
Nutrients (N)	1	0.40	0.000	632271.025*	49350.625**
IxN	1	0.10	0.001	138180.025	8910.225
Mulch (M)	1	0.10	0.008	32890.225	32890.225**
IxM	1	3.60	0.005	83814.025	2265.025
NxM	1	1.60	0.004	1863.225	7.225
IxNxM	1	0.90	0.007	197824.225	3591.025
Error 2	24	47.80	0.005	91002.979	3516.892

† Degrees of freedom
* significant at the 5% probability level
** significant at the 1% probability level

Table C5a. Mean square associated with biomass water use efficiency.

Source	df†	WUE(ET)	WUE(T)	WUE(R)	WUE(R+I)
		g kg^{-1}			
Replication	4	0.397	1.377	0.319	0.140
Irrigation (A)	1	4.147	25.440	6.265	0.897
Error 1	4	1.800	4.868	1.512	0.937
Nutrients (B)	1	1.018*	2.209	1.380**	1.021**
AB	1	0.005	0.180	0.034	0.122
Mulch (C)	1	2.540*	0.876	0.456	0.333
AC	1	0.005	0.055	0.004	0.027
BC	1	0.240	4.186	0.084	0.009
ABC	1	1.122*	3.306	0.792**	0.482*
Error 2	24	0.194	0.606	0.174	0.106

† Degrees of freedom
* significant at the 5% probability level
** significant at the 1% probability level

Table C5b. Mean square associated with grain water use efficiency.

Source	df†	WUE(ET)	WUE(T)
		g kg^{-1}	
Replication	4	0.041	0.124
Irrigation (A)	1	0.686**	3.487**
Error 1	4	0.029	0.090
Nutrients (B)	1	0.237**	0.608*
AB	1	0.017	0.001
Mulch (C)	1	0.552**	0.559*
AC	1	0.014	0.009
BC	1	0.008	0.239
ABC	1	0.102	0.333
Error 2	24	0.025	0.082

† Degrees of freedom
* significant at the 5% probability level
** significant at the 1% probability level

Table C6. Mean square associated with plant stand and survival.

Source	df†	Stand	Survival
		%	
Replication	4	101.600	64.131
Irrigation (A)	1	10336.225**	6347.880**
Error 1	4	97.225	41.100
Nutrients (B)	1	9.025	23.870
AB	1	3.025	25.440
Mulch (C)	1	3.025	12.432
AC	1	3.025	6.806
BC	1	65.025	98.282
ABC	1	70.225	17.030
Error 2	24	59.246	29.494

† Degrees of freedom
* significant at the 5% probability level
** significant at the 1% probability level

Table C7. Mean square associated with surface soil pH, N, and P content.

Source	df†	pH	N	P
			g kg^{-1}	
Replication	4	0.055	0.002	0.000
Irrigation (A)	1	0.036	0.002	0.000
Error 1	4	0.048	0.001	0.000
Nutrients (B)	1	0.009	0.001	0.000
AB	1	0.025	0.002	0.000
Mulch (C)	1	0.001	0.001	0.000
AC	1	0.009	0.000	0.000
BC	1	0.036	0.002	0.000
ABC	1	0.016	0.000	0.000
Error 2	24	0.092	0.001	0.000

APPENDIX D. INPUT DATA FOR THE ENWATBAL MODEL

Table D1. Weather and crop input data for the control treatment.

Day	HG	Tmax	Tmin	TDmax	TDmin	U	LAI	RD	Rmax	Pair
#	MJ m^{-2}	____	____	°C	____	m s^{-1}		m	m	kPa
190	24.04	30	25	23.59	12.38	2.33	0.00	0.00	0.00	87.3
191	23.97	33	22	24.40	17.86	1.86	0.01	0.03	0.05	87.3
192	20.30	34	21	28.07	20.87	1.80	0.03	0.05	0.10	87.3
193	20.31	29	21	26.08	18.40	2.75	0.04	0.10	0.18	87.3
194	20.32	29	21	23.59	18.52	1.65	0.06	0.15	0.23	87.3
195	20.33	32	22	23.86	19.30	1.65	0.08	0.20	0.27	87.3
196	20.27	26	19	23.60	16.60	1.65	0.10	0.20	0.31	87.3
197	20.34	30	21	24.05	19.20	0.89	0.11	0.25	0.35	87.3
198	20.35	30	20	24.95	19.58	2.30	0.13	0.30	0.40	87.3
199	20.35	28	20	23.12	16.44	4.60	0.15	0.30	0.40	87.3
200	20.36	29	22	23.01	20.42	4.60	0.17	0.35	0.41	87.3
201	17.71	29	21	24.28	19.80	1.93	0.18	0.35	0.41	87.3
202	22.37	25	21	23.55	20.22	0.58	0.20	0.36	0.42	87.3
203	22.37	28	19	23.86	18.02	1.68	0.22	0.36	0.42	87.3
204	22.37	29	19	23.59	18.02	0.97	0.24	0.36	0.45	87.3
205	22.37	31	21	24.40	20.07	1.87	0.25	0.37	0.43	87.3
206	22.37	32	20	26.60	19.00	1.59	0.27	0.40	0.44	87.3
207	22.37	31	24	25.20	23.12	1.91	0.31	0.40	0.45	87.3
208	22.36	28	20	23.83	17.11	1.28	0.44	0.40	0.46	87.3
209	22.36	28	21	24.73	20.26	0.92	0.57	0.42	0.47	87.3
210	22.35	31	23	24.35	19.82	0.91	0.70	0.42	0.47	87.3
211	22.28	33	22	25.83	21.36	1.88	0.84	0.42	0.48	87.3
212	19.57	28	21	26.30	19.09	1.23	0.98	0.45	0.50	87.3
213	19.57	29	20	24.85	18.90	0.93	1.12	0.45	0.55	87.3
214	19.56	31	22	28.07	20.30	0.84	1.28	0.47	0.55	87.3
215	19.55	31	24	24.73	21.11	1.28	1.43	0.49	0.56	87.3
216	19.54	31	19	24.26	18.02	1.48	1.58	0.51	0.58	87.3
217	19.53	29	19	25.83	18.13	2.19	1.73	0.51	0.60	87.3
218	19.52	31	23	26.95	22.05	0.46	1.88	0.52	0.65	87.3
219	19.51	32	23	25.83	20.55	1.33	2.04	0.53	0.66	87.3
220	19.49	26	21	24.94	19.58	1.34	2.19	0.55	0.67	87.3
221	19.48	30.	21	26.08	18.35	0.69	2.33	0.58	0.68	87.3
222	20.96	32	22	26.21	19.60	1.02	2.48	0.58	0.69	87.3
223	20.94	32	24	25.96	21.35	1.81	2.63	0.65	0.70	87.3
224	20.93	32	24	26.30	21.35	1.70	2.77	0.65	0.73	87.3
225	20.91	30	22	28.69	16.12	1.15	2.90	0.65	0.77	87.3
226	20.89	24	20	23.10	18.02	0.48	3.04	0.68	0.80	87.3
227	20.87	29	21	28.00	18.54	0.95	3.17	0.72	0.82	87.3
228	20.85	31	23	26.95	19.38	1.09	3.29	0.75	0.85	87.3
229	20.83	30	20	26.60	18.90	1.47	3.41	0.75	0.86	87.3
230	13.52	29	20	26.08	17.82	0.91	3.53	0.76	0.87	87.3
231	20.78	27	21	25.15	16.17	1.00	3.63	0.78	0.87	87.3
232	20.75	32	21	28.79	17.83	0.67	3.74	0.80	0.88	87.3
233	20.73	34	23	29.36	18.31	0.63	3.83	0.81	0.88	87.3
234	20.70	33	24	27.37	21.03	1.40	3.92	0.82	0.88	87.3
235	20.67	32	23	28.69	13.38	0.81	3.01	0.82	0.89	87.3

Table D1 (Cont'.).

Day	HG	Tmax	Tmin	TDmax	TDmin	U	LAI	RD	Rmax	Pair
#	MJ m^{-2}			°C		m s^{-1}		m	m	kPa
236	20.65	33	24	26.03	17.99	1.45	4.08	0.83	0.89	87.3
237	20.62	32	23	27.14	18.39	1.42	4.15	0.83	0.89	87.3
238	20.58	30	22	26.00	21.00	1.37	4.22	0.83	0.90	87.3
239	20.55	27	23	24.95	21.11	0.70	4.27	0.83	0.95	87.3
240	19.21	32	22	30.00	21.00	1.19	4.32	0.84	0.97	87.3
241	20.49	27	23	25.00	21.00	0.66	4.36	0.84	1.00	87.3
242	17.79	32	22	30.00	19.00	0.69	4.39	0.84	1.00	87.3
243	19.98	30	22	26.00	21.00	1.00	4.41	0.84	1.00	87.3
244	20.87	29	22	30.00	20.00	1.47	4.43	0.84	1.00	87.3
245	20.83	33	27	27.00	24.00	1.35	4.44	0.85	1.00	87.3
246	20.83	32	22	30.33	22.00	0.92	4.44	0.85	1.05	87.3
247	20.76	32	21	27.42	19.02	0.94	4.43	0.85	1.05	87.3
248	20.72	30	22	23.59	19.25	0.25	4.41	0.85	1.05	87.3
249	20.68	29	22	27.42	17.16	1.39	4.39	0.85	1.05	87.3
250	20.63	33	22	30.39	18.91	0.84	4.36	0.85	1.05	87.3
251	20.59	31	21	24.60	20.25	0.04	4.32	0.85	1.05	87.3
252	20.55	32	23	23.82	16.44	1.21	4.27	0.85	1.05	87.3
253	20.44	33	21	24.95	19.22	0.84	4.22	0.86	1.05	87.3
254	15.22	34	22	24.05	12.07	1.00	5.16	0.90	1.05	87.3
255	15.19	34	22	24.26	15.21	1.14	4.09	0.90	1.05	87.3
256	15.15	33	22	24.05	17.44	1.17	4.01	0.90	1.05	87.3
257	15.12	35	20	23.02	10.07	0.65	3.93	0.90	1.05	87.3
258	15.08	35	19	22.70	9.26	0.90	3.81	0.90	1.05	87.3
259	15.04	36	20	22.63	5.57	0.66	3.75	0.90	1.05	87.3
260	15.01	33	20	22.63	12.43	0.60	3.65	0.91	1.05	87.3
261	14.97	28	21	22.50	4.44	0.63	3.54	0.91	1.05	87.3
262	14.93	31	23	26.30	2.25	0.47	3.43	0.91	1.05	87.3
263	14.89	33	22	25.80	1.14	0.54	3.31	0.92	1.10	87.3
264	19.25	28	21	24.90	1.45	0.63	3.19	0.94	1.10	87.3
265	19.20	29	20	26.80	11.20	0.73	3.06	0.95	1.10	87.3
266	19.14	31	22	30.00	13.00	0.86	2.93	0.96	1.10	87.3
267	19.09	31	24	26.40	1.42	0.56	2.80	1.00	1.10	87.3
268	19.04	36	22	25.90	6.55	0.60	2.66	1.00	1.10	87.3
269	18.98	35	21	30.20	13.50	0.68	2.52	1.00	1.10	87.3
270	18.92	36	19	35.90	9.84	0.68	2.38	1.00	1.10	87.3
271	18.86	36	18	29.10	3.6	0.87	2.24	1.00	1.10	87.3
272	18.80	33	23	27.00	4.76	1.04	2.10	1.00	1.10	87.3
273	18.56	32	20	27.90	12.90	1.35	1.95	1.00	1.10	87.3
274	18.23	33	20	32.50	8.18	0.87	1.81	1.00	1.10	87.3

Table D2. Weather and crop input data for mulch treatment.

Day	HG	Tmax	Tmin	TDmax	TDmin	U	LAI	PD	Rmax	Pair
#	MJ m^{-2}	____	____	°C	____	$m\ s^{-1}$		m	m	kPa
190	24.04	30	25	23.59	12.38	2.33	0.01	0.00	0.00	87.3
191	23.97	33	22	24.40	17.86	1.86	0.01	0.03	0.05	87.3
192	20.30	34	21	28.07	20.87	1.80	0.02	0.05	0.10	87.3
193	20.31	29	21	26.08	18.40	2.75	0.03	0.10	0.18	87.3
194	20.32	29	21	23.59	18.52	1.65	0.05	0.15	0.23	87.3
195	20.33	32	22	23.86	19.60	1.65	0.07	0.20	0.27	87.3
196	20.27	26	19	23.60	16.60	1.65	0.09	0.20	0.31	87.3
197	20.34	30	21	24.05	19.20	0.89	0.12	0.25	0.35	87.3
198	20.35	30	20	24.95	19.58	2.30	0.16	0.30	0.40	87.3
199	20.35	28	20	23.12	16.44	4.60	0.19	0.30	0.40	87.3
200	20.36	29	22	23.01	20.42	4.60	0.24	0.35	0.41	87.3
201	17.71	29	21	24.28	19.80	1.93	0.28	0.35	0.41	87.3
202	22.37	25	21	23.55	20.22	0.58	0.33	0.36	0.42	87.3
203	22.37	28	19	23.86	18.02	1.68	0.39	0.36	0.42	87.3
204	22.37	29	19	23.59	18.02	0.97	0.45	0.36	0.45	87.3
205	22.37	31	21	24.40	20.07	1.87	0.51	0.37	0.43	87.3
206	22.37	32	20	26.60	19.00	1.59	0.58	0.40	0.44	87.3
207	22.37	31	24	25.20	23.12	1.91	0.65	0.40	0.45	87.3
208	22.36	28	20	23.83	17.11	1.28	0.73	0.40	0.46	87.3
209	22.36	28	21	24.73	20.26	0.92	0.75	0.42	0.47	87.3
210	22.35	31	23	24.35	19.82	0.91	0.79	0.42	0.47	87.3
211	22.28	33	22	25.83	21.36	1.88	0.81	0.42	0.48	87.3
212	19.57	28	21	26.30	19.09	1.23	0.98	0.45	0.50	87.3
213	19.57	29	20	24.85	18.90	0.93	1.12	0.45	0.55	87.3
214	19.56	31	22	28.07	20.30	0.84	1.28	0.47	0.55	87.3
215	19.55	31	24	24.73	21.11	1.28	1.43	0.49	0.56	87.3
216	19.54	31	19	24.26	18.02	1.48	1.58	0.51	0.58	87.3
217	19.53	29	19	25.83	18.13	2.19	1.73	0.51	0.60	87.3
218	19.52	31	23	26.95	22.05	0.46	1.88	0.52	0.65	87.3
219	19.51	32	23	25.83	20.55	1.33	2.04	0.53	0.66	87.3
220	19.49	26	21	24.94	19.58	1.34	2.19	0.55	0.67	87.3
221	19.48	30	21	26.08	18.35	0.69	2.33	0.58	0.68	87.3
222	20.96	32	22	26.21	19.60	1.02	2.48	0.58	0.69	87.3
223	20.94	32	24	25.96	21.35	1.81	2.63	0.65	0.70	87.3
224	20.93	32	24	26.30	21.35	1.70	2.77	0.65	0.73	87.3
225	20.91	30	22	28.69	16.12	1.15	2.90	0.65	0.77	87.3
226	20.89	24	20	23.10	18.02	0.48	3.04	0.68	0.80	87.3
227	20.87	29	21	28.00	18.54	0.95	3.17	0.72	0.82	87.3
228	20.85	31	23	26.95	19.38	1.09	3.29	0.75	0.85	87.3
229	20.83	30	20	26.60	18.90	1.47	3.41	0.75	0.86	87.3
230	13.52	29	20	26.08	17.82	0.91	3.53	0.76	0.87	87.3
231	20.78	27	21	25.15	16.17	1.00	3.63	0.78	0.87	87.3

Table D2. (Cont'.).

	HG	Tmax	Tmin	TDmax	TDmin	U	LAI	RD	Rmax	Pair
#	MJ m^{-2}			°C		m s^{-1}		m	m	kPa
232	20.75	32	21	28.79	17.83	0.67	3.74	0.80	0.88	87.3
233	20.73	34	23	29.36	18.31	0.63	3.83	0.81	0.88	87.3
234	20.70	33	24	27.37	21.03	1.40	3.92	0.82	0.88	87.3
235	20.67	32	23	28.69	13.38	0.81	3.01	0.82	0.89	87.3
236	20.65	33	24	26.03	17.99	1.45	4.08	0.83	0.89	87.3
237	20.62	32	23	27.14	18.39	1.42	4.15	0.83	0.89	87.3
238	20.58	30	22	26.00	21.00	1.37	4.22	0.83	0.90	87.3
239	20.55	27	23	24.95	21.11	0.70	4.27	0.83	0.95	87.3
240	19.21	32	22	30.00	21.00	1.19	4.32	0.84	0.97	87.3
241	20.49	27	23	25.00	21.00	0.66	4.36	0.84	1.00	87.3
242	17.79	32	22	30.00	19.00	0.69	4.39	0.84	1.00	87.3
243	19.98	30	22	26.00	21.00	1.00	4.41	0.84	1.00	87.3
244	20.87	29	22	30.00	20.00	1.47	4.43	0.84	1.00	87.3
245	20.83	33	27	27.00	24.00	1.35	4.44	0.85	1.00	87.3
246	20.83	32	22	30.33	22.00	0.92	4.44	0.85	1.05	87.3
247	20.76	32	21	27.42	19.02	0.94	4.43	0.85	1.05	87.3
248	20.72	30	22	23.59	19.25	0.25	4.41	0.85	1.05	87.3
249	20.68	29	22	27.42	17.16	1.39	4.36	0.85	1.05	87.3
250	20.63	33	22	30.39	18.91	0.84	4.32	0.85	1.05	87.3
251	20.59	31	21	24.60	20.25	0.04	4.27	0.85	1.05	87.3
252	20.55	32	23	23.82	16.44	1.21	4.22	0.86	1.05	87.3
253	20.44	33	21	24.95	19.22	0.84	4.16	0.90	1.05	87.3
254	15.22	34	22	24.05	12.07	1.00	4.09	0.90	1.05	87.3
255	15.19	34	22	24.26	15.21	1.14	4.01	0.90	1.05	87.3
256	15.15	33	22	24.05	17.44	1.17	3.93	0.90	1.05	87.3
257	15.12	35	20	23.02	10.07	0.65	3.75	0.90	1.05	87.3
258	15.08	35	19	22.70	9.26	0.90	3.65	0.91	1.05	87.3
259	15.04	36	20	22.63	5.57	0.66	3.54	0.91	1.05	87.3
260	15.01	33	20	22.63	12.43	0.60	3.43	0.91	1.05	87.3
261	14.97	28	21	22.50	4.44	0.63	3.31	0.92	1.10	87.3
262	14.93	31	23	26.30	2.25	0.47	3.19	0.94	1.10	87.3
263	14.89	33	22	25.80	1.14	0.54	3.06	0.95	1.10	87.3
264	19.25	28	21	24.90	1.45	0.63	2.93	0.96	1.10	87.3
265	19.20	29	20	26.80	11.20	0.73	3.06	0.95	1.10	87.3
266	19.14	31	22	30.00	13.00	0.86	2.93	0.96	1.10	87.3
267	19.09	31	24	26.40	1.42	0.56	2.80	1.00	1.10	87.3
268	19.04	36	22	25.90	6.55	0.60	2.66	1.00	1.10	87.3
269	18.98	35	21	30.20	13.50	0.68	2.52	1.00	1.10	87.3
270	18.92	36	19	35.90	9.84	0.68	2.38	1.00	1.10	87.3
271	18.86	36	18	29.10	3.6	0.87	2.24	1.00	1.10	87.3
272	18.80	33	23	27.00	4.76	1.04	2.10	1.00	1.10	87.3
273	18.56	32	20	27.90	12.90	1.35	1.95	1.00	1.10	87.3
274	18.23	33	20	32.50	8.18	0.8[illegible]	1.81	1.00	1.10	87.3

Table D3. Weather and crop input data for nitrogen treatment.

Day	HG	Tmax	Tmin	TDmax	TDmin	U	LAI	RD	Rmax	Pair
#	MJ m^{-2}			°C		m s^{-1}		m	m	kPa
190	24.04	30	25	23.59	12.38	2.33	0.05	0.00	0.00	87.3
191	23.97	33	22	24.40	17.86	1.86	0.01	0.00	0.00	87.3
192	20.30	34	21	28.07	20.87	1.80	0.03	0.00	0.03	87.3
193	20.31	29	21	26.08	18.40	2.75	0.04	0.05	0.10	87.3
194	20.32	29	21	23.59	18.52	1.65	0.06	0.06	0.10	87.3
195	20.33	32	22	23.86	19.60	1.65	0.08	0.07	0.11	87.3
196	20.27	26	19	23.60	16.60	1.65	0.10	0.08	0.12	87.3
197	20.34	30	21	24.05	19.20	0.89	0.11	0.08	0.13	87.3
198	20.35	30	20	24.95	19.58	2.30	0.13	0.09	0.14	87.3
199	20.35	28	20	23.12	16.44	4.60	0.16	0.10	0.15	87.3
200	20.36	29	22	23.01	20.42	4.60	0.22	0.11	0.16	87.3
201	17.71	29	21	24.28	19.80	1.93	0.30	0.12	0.17	87.3
202	22.37	25	21	23.55	20.22	0.58	0.38	0.13	0.18	87.3
203	22.37	28	19	23.86	18.02	1.68	0.47	0.13	0.19	87.3
204	22.37	29	19	23.59	18.02	0.97	0.57	0.14	0.19	87.3
205	22.37	31	21	24.40	20.07	1.87	0.67	0.15	0.20	87.3
206	22.37	32	20	26.60	19.00	1.59	0.78	0.16	0.21	87.3
207	22.37	31	24	25.20	23.12	1.91	0.90	0.18	0.22	87.3
208	22.36	28	20	23.83	17.11	1.28	1.02	0.18	0.23	87.3
209	22.36	28	21	24.73	20.26	0.92	1.14	0.18	0.24	87.3
210	22.35	31	23	24.35	19.82	0.91	1.27	0.19	0.25	87.3
211	22.28	33	22	25.83	21.36	1.88	1.40	0.20	0.26	87.3
212	19.57	28	21	26.30	19.09	1.23	1.53	0.21	0.27	87.3
213	19.57	29	20	24.85	18.90	0.93	1.66	0.21	0.28	87.3
214	19.56	31	22	28.07	20.30	0.84	1.80	0.23	0.30	87.3
215	19.55	31	24	24.73	21.11	1.28	1.94	0.24	0.32	87.3
216	19.54	31	19	24.26	18.02	1.48	20.7	0.26	0.34	87.3
217	19.53	29	19	25.83	18.13	2.19	2.21	0.27	0.35	87.3
218	19.52	31	23	26.95	22.05	0.46	2.34	0.29	0.37	87.3
219	19.51	32	23	25.83	20.55	1.33	2.48	0.30	0.39	87.3
220	19.49	26	21	24.94	19.58	1.34	2.61	0.32	0.41	87.3
221	19.48	30.	21	26.08	18.35	0.69	2.75	0.33	0.43	87.3
222	20.96	32	22	26.21	19.60	1.02	2.88	0.35	0.45	87.3
223	20.94	32	24	25.96	21.35	1.81	3.00	0.36	0.47	87.3
224	20.93	32	24	26.30	21.35	1.70	3.13	0.38	0.48	87.3
225	20.91	30	22	28.69	16.12	1.15	3.25	0.39	0.50	87.3
226	20.89	24	20	23.10	18.02	0.48	3.37	0.41	0.52	87.3
227	20.87	29	21	28.00	18.54	0.95	3.48	0.42	0.54	87.3
228	20.85	31	23	26.95	19.38	1.09	3.59	0.44	0.56	87.3
229	20.83	30	20	26.60	18.90	1.47	3.70	0.45	0.58	87.3
230	13.52	29	20	26.08	17.82	0.91	3.80	0.47	0.60	87.3
231	20.78	27	21	25.15	16.17	1.00	3.90	0.48	0.62	87.3

Table D3. (Cont'.).

#	HG	Tmax	Tmin	TDmax	TDmin	U	LAI	RD	Rmax	Pair
	MJ m^{-2}	____	____	°C	____	$m\ s^{-1}$		m	m	kPa
232	20.75	32	21	28.79	17.83	0.67	3.80	0.46	0.58	87.3
233	20.73	34	23	29.36	18.31	0.63	3.89	0.48	0.59	87.3
234	20.70	33	24	27.37	21.03	1.40	3.97	0.49	0.61	87.3
235	20.67	32	23	28.69	13.38	0.81	4.05	0.51	0.62	87.3
236	20.65	33	24	26.03	17.99	1.45	4.12	0.52	0.64	87.3
237	20.62	32	23	27.14	18.39	1.42	4.19	0.53	0.65	87.3
238	20.58	30	22	26.00	21.00	1.37	4.25	0.55	0.66	87.3
239	20.55	27	23	24.95	21.11	0.70	4.30	0.56	0.68	87.3
240	19.21	32	22	30.00	21.00	1.19	4.34	0.58	0.69	87.3
241	20.49	27	23	25.00	21.00	0.66	4.38	0.59	0.71	87.3
242	17.79	32	22	30.00	19.00	0.69	4.41	0.60	0.72	87.3
243	19.98	30	22	26.00	21.00	1.00	4.43	0.62	0.74	87.3
244	20.87	29	22	30.00	20.00	1.47	4.64	0.68	0.86	87.3
245	20.83	33	27	27.00	24.00	1.35	4.66	0.69	0.88	87.3
246	20.83	32	22	30.33	22.00	0.92	4.66	0.71	0.89	87.3
247	20.76	32	21	27.42	19.02	0.94	4.66	0.71	0.91	87.3
248	20.72	30	22	23.59	19.25	0.25	4.66	0.71	0.91	87.3
249	20.68	29	22	27.42	17.16	1.39	4.65	0.71	0.92	87.3
250	20.63	33	22	30.39	18.91	0.84	4.63	0.71	0.92	87.3
251	20.59	31	21	24.60	20.25	0.04	4.60	0.71	0.92	87.3
252	20.55	32	23	23.82	16.44	1.21	4.57	0.71	0.92	87.3
253	20.44	33	21	24.95	19.22	0.84	4.53	0.71	0.92	87.3
254	15.22	34	22	24.05	12.07	1.00	4.49	0.72	0.92	87.3
255	15.19	34	22	24.26	15.21	1.14	4.44	0.72	0.92	87.3
256	15.15	33	22	24.05	17.44	1.17	4.38	0.72	0.92	87.3
257	15.12	35	20	23.02	10.07	0.65	4.32	0.72	0.93	87.3
258	15.08	35	19	22.70	9.26	0.90	4.26	0.72	0.93	87.3
259	15.04	36	20	22.63	5.57	0.66	4.19	0.72	0.93	87.3
260	15.01	33	20	22.63	12.43	0.60	4.11	0.72	0.93	87.3
261	14.97	28	21	22.50	4.44	0.63	4.03	0.73	0.93	87.3
262	14.93	31	23	26.30	2.25	0.47	3.94	0.73	0.93	87.3
263	14.89	33	22	25.80	1.14	0.54	3.85	0.73	0.93	87.3
264	19.25	28	21	24.90	1.45	0.63	3.76	0.73	0.94	87.3
265	19.20	29	20	26.80	11.20	0.73	3.66	0.73	0.94	87.3
266	19.14	31	22	30.00	13.00	0.86	3.56	0.73	0.94	87.3
267	19.09	31	24	26.40	1.42	0.56	3.45	0.73	0.94	87.3
268	19.04	36	22	25.90	6.55	0.60	3.35	0.74	0.94	87.3
269	18.98	35	21	30.20	13.50	0.68	3.24	0.74	0.94	87.3
270	18.92	36	19	35.90	9.84	0.68	3.12	0.74	0.94	87.3
271	18.86	36	18	29.10	3.6	0.87	3.01	0.74	0.94	87.3
272	18.80	33	23	27.00	4.76	1.04	2.90	0.74	0.95	87.3
273	18.56	32	20	27.90	12.90	1.35	2.78	0.74	0.95	87.3
274	18.23	33	20	32.50	8.18	0.87	2.66	0.74	0.95	87.3
275	18.17	33	22	31.30	13.30	0.63	2.55	0.74	0.95	87.3
276	18.00	36	20	37.92	8.18	1.08	2.43	0.74	0.95	87.3
277	17.98	37	20	26.46	1.68	0.65	2.32	0.75	0.95	87.3
278	17.75	36	17	19.78	3.31	0.90	2.20	0.75	0.95	87.3

Table D4. Weather and crop input data for nitrogen/mulched treatment.

Day	HG	Tmax	Tmin	TDmax	TDmin	U	LAI	RD	Rmax	Pair
#	MJ m^{-2}	____	____	°C	____	$m\ s^{-1}$		m	m	kPa
190	24.04	30	25	23.59	12.38	2.33	0.05	0.00	0.00	87.3
191	23.97	33	22	24.40	17.86	1.86	0.01	0.00	0.03	87.3
192	20.30	34	21	28.07	20.87	1.80	0.03	0.00	0.05	87.3
193	20.31	29	21	26.08	18.40	2.75	0.04	0.02	0.08	87.3
194	20.32	29	21	23.59	18.52	1.65	0.06	0.06	0.10	87.3
195	20.33	32	22	23.86	19.60	1.65	0.08	0.07	0.11	87.3
196	20.27	26	19	23.60	16.60	1.65	0.10	0.08	0.12	87.3
197	20.34	30	21	24.05	19.20	0.89	0.11	0.08	0.13	87.3
198	20.35	30	20	24.95	19.58	2.30	0.13	0.09	0.14	87.3
199	20.35	28	20	23.12	16.44	4.60	0.15	0.10	0.16	87.3
200	20.36	29	22	23.01	20.42	4.60	0.17	0.11	0.17	87.3
201	17.71	29	21	24.28	19.80	1.93	0.18	0.11	0.18	87.3
202	22.37	25	21	23.55	20.22	0.58	0.20	0.12	0.19	87.3
203	22.37	28	19	23.86	18.02	1.68	0.22	0.13	0.20	87.3
204	22.37	29	19	23.59	18.02	0.97	0.24	0.14	0.21	87.3
205	22.37	31	21	24.40	20.07	1.87	0.27	0.15	0.22	87.3
206	22.37	32	20	26.60	19.00	1.59	0.31	0.15	0.23	87.3
207	22.37	31	24	25.20	23.12	1.91	0.43	0.16	0.24	87.3
208	22.36	28	20	23.83	17.11	1.28	1.56	0.17	0.26	87.3
209	22.36	28	21	24.73	20.26	0.92	1.69	0.18	0.27	87.3
210	22.35	31	23	24.35	19.82	0.91	1.82	0.18	0.28	87.3
211	22.28	33	22	25.83	21.36	1.88	1.96	0.19	0.29	87.3
212	19.57	28	21	26.30	19.09	1.23	1.11	0.20	0.30	87.3
213	19.57	29	20	24.85	18.90	0.93	1.25	0.20	0.31	87.3
214	19.56	31	22	28.07	20.30	0.84	1.40	0.21	0.32	87.3
215	19.55	31	24	24.73	21.11	1.28	1.55	0.23	0.34	87.3
216	19.54	31	19	24.26	18.02	1.48	1.70	0.24	0.35	87.3
217	19.53	29	19	25.83	18.13	2.19	1.85	0.26	0.37	87.3
218	19.52	31	23	26.95	22.05	0.46	2.00	0.27	0.38	87.3
219	19.51	32	23	25.83	20.55	1.33	2.15	0.28	0.40	87.3
220	19.49	26	21	24.94	19.58	1.34	2.30	0.30	0.41	87.3
221	19.48	30.	21	26.08	18.35	0.69	2.44	0.31	0.42	87.3
222	20.96	32	22	26.21	19.60	1.02	2.58	0.33	0.44	87.3
223	20.94	32	24	25.96	21.35	1.81	2.73	0.34	0.45	87.3
224	20.93	32	24	26.30	21.35	1.70	2.86	0.35	0.47	87.3
225	20.91	30	22	28.69	16.12	1.15	3.00	0.37	0.48	87.3
226	20.89	24	20	23.10	18.02	0.48	3.12	0.38	0.49	87.3
227	20.87	29	21	28.00	18.54	0.95	3.25	0.39	0.51	87.3
228	20.85	31	23	26.95	19.38	1.09	3.37	0.41	0.52	87.3
229	20.83	30	20	26.60	18.90	1.47	3.48	0.42	0.54	87.3
230	13.52	29	20	26.08	17.82	0.91	3.59	0.44	0.55	87.3
231	20.78	27	21	25.15	16.17	1.00	3.70	0.45	0.57	87.3

Table D4. Cont'

Day	HG	Tmax	Tmin	TDmax	TDmin	U	LAI	RD	Rmax	Pair
#	MJ m^{-2}	____	____	°C	____	m s^{-1}		m	m	kPa
232	20.75	32	21	28.79	17.83	0.67	3.80	0.46	0.58	87.3
233	20.73	34	23	29.36	18.31	0.63	3.89	0.48	0.59	87.3
234	20.70	33	24	27.37	21.03	1.40	3.97	0.49	0.61	87.3
235	20.67	32	23	28.69	13.38	0.81	4.05	0.51	0.62	87.3
236	20.65	33	24	26.03	17.99	1.45	4.12	0.52	0.64	87.3
237	20.62	32	23	27.14	18.39	1.42	4.19	0.53	0.65	87.3
238	20.58	30	22	26.00	21.00	1.37	4.25	0.55	0.66	87.3
239	20.55	27	23	24.95	21.11	0.70	4.30	0.56	0.68	87.3
240	19.21	32	22	30.00	21.00	1.19	4.34	0.58	0.69	87.3
241	20.49	27	23	25.00	21.00	0.66	4.38	0.59	0.71	87.3
242	17.79	32	22	30.00	19.00	0.69	4.41	0.60	0.72	87.3
243	19.98	30	22	26.00	21.00	1.00	4.43	0.62	0.74	87.3
244	20.87	29	22	30.00	20.00	1.47	4.44	0.63	0.75	87.3
245	20.83	33	27	27.00	24.00	1.35	4.45	0.64	0.76	87.3
246	20.83	32	22	30.33	22.00	0.92	4.45	0.66	0.78	87.3
247	20.76	32	21	27.42	19.02	0.94	4.44	0.66	0.78	87.3
248	20.72	30	22	23.59	19.25	0.25	4.43	0.66	0.78	87.3
249	20.68	29	22	27.42	17.16	1.39	4.41	0.66	0.78	87.3
250	20.63	33	22	30.39	18.91	0.84	4.38	0.66	0.78	87.3
251	20.59	31	21	24.60	20.25	0.04	4.35	0.66	0.78	87.3
252	20.55	32	23	23.82	16.44	1.21	4.31	0.67	0.78	87.3
253	20.44	33	21	24.95	19.22	0.84	4.26	0.67	0.79	87.3
254	15.22	34	22	24.05	12.07	1.00	4.21	0.67	0.79	87.3
255	15.19	34	22	24.26	15.21	1.14	4.15	0.67	0.79	87.3
256	15.15	33	22	24.05	17.44	1.17	4.08	0.67	0.79	87.3
257	15.12	35	20	23.02	10.07	0.65	4.01	0.67	0.79	87.3
258	15.08	35	19	22.70	9.26	0.90	3.94	0.67	0.79	87.3
259	15.04	36	20	22.63	5.57	0.66	3.86	0.67	0.79	87.3
260	15.01	33	20	22.63	12.43	0.60	3.78	0.67	0.79	87.3
261	14.97	28	21	22.50	4.44	0.63	3.69	0.68	0.79	87.3
262	14.93	31	23	26.30	2.25	0.47	3.60	0.68	0.80	87.3
263	14.89	33	22	25.80	1.14	0.54	3.51	0.68	0.80	87.3
264	19.25	28	21	24.90	1.45	0.63	3.41	0.68	0.80	87.3
265	19.20	29	20	26.80	11.20	0.73	3.32	0.68	0.80	87.3
266	19.14	31	22	30.00	13.00	0.86	3.22	0.68	0.80	87.3
267	19.09	31	24	26.40	1.42	0.56	3.12	0.68	0.80	87.3
268	19.04	36	22	25.90	6.55	0.60	3.02	0.68	0.80	87.3
269	18.98	35	21	30.20	13.50	0.68	2.92	0.69	0.80	87.3
270	18.92	36	19	35.90	9.84	0.68	2.82	0.69	0.80	87.3
271	18.86	36	18	29.10	3.6	0.87	2.72	0.69	0.81	87.3
272	18.80	33	23	27.00	4.76	1.04	2.62	0.69	0.81	87.3
273	18.56	32	20	27.90	12.90	1.35	2.53	0.69	0.81	87.3
274	18.23	33	20	32.50	8.18	0.87	2.44	0.69	0.81	87.3
275	18.17	33	22	31.30	13.30	0.63	2.35	0.69	0.81	87.3
276	18.00	36	20	37.92	8.18	1.08	2.27	0.69	0.81	87.3
277	17.98	37	20	26.46	1.68	0.65	2.19	0.69	0.81	87.3
278	17.75	36	17	19.78	3.31	0.90	2.12	0.69	0.81	87.3

Table D5. Weather and crop input data for the irrigation treatment.

Day	HG	Tmax	Tmin	TDmax	TDmin	U	LAI	RD	Rmax	Pair
#	MJ m^{-2}	____	____	°C	____	m s^{-1}		m	m	kPa
190	24.04	30	25	23.59	12.38	2.33	0.05	0.00	0.00	87.3
191	23.97	33	22	24.40	17.86	1.86	0.01	0.02	0.05	87.3
192	20.30	34	21	28.07	20.87	1.80	0.03	0.05	0.10	87.3
193	20.31	29	21	26.08	18.40	2.75	0.04	0.06	0.11	87.3
194	20.32	29	21	23.59	18.52	1.65	0.06	0.07	0.13	87.3
195	20.33	32	22	23.86	19.60	1.65	0.08	0.08	0.14	87.3
196	20.27	26	19	23.60	16.60	1.65	0.10	0.09	0.15	87.3
197	20.34	30	21	24.05	19.20	0.89	0.11	0.09	0.16	87.3
198	20.35	30	20	24.95	19.58	2.30	0.13	0.10	0.18	87.3
199	20.35	28	20	23.12	16.44	4.60	0.15	0.11	0.19	87.3
200	20.36	29	22	23.01	20.42	4.60	0.17	0.12	0.20	87.3
201	17.71	29	21	24.28	19.80	1.93	0.18	0.13	0.21	87.3
202	22.37	25	21	23.55	20.22	0.58	0.20	0.14	0.23	87.3
203	22.37	28	19	23.86	18.02	1.68	0.22	0.15	0.24	87.3
204	22.37	29	19	23.59	18.02	0.97	0.24	0.16	0.25	87.3
205	22.37	31	21	24.40	20.87	1.87	0.29	0.17	0.25	87.3
206	22.37	32	20	26.60	19.00	1.59	0.35	0.28	0.25	87.3
207	22.37	31	24	25.20	23.12	1.91	0.48	0.29	0.26	87.3
208	22.36	28	20	23.83	17.11	1.28	0.62	0.30	0.26	87.3
209	22.36	28	21	24.73	20.26	0.92	0.76	0.31	0.27	87.3
210	22.35	31	23	24.35	19.82	0.91	0.91	0.33	0.28	87.3
211	22.28	33	22	25.83	21.36	1.88	1.06	0.34	0.29	87.3
212	19.57	28	21	26.30	19.09	1.23	1.21	0.35	0.30	87.3
213	19.57	29	20	24.85	18.90	0.93	1.36	0.35	0.31	87.3
214	19.56	31	22	28.07	20.30	0.84	1.52	0.36	0.32	87.3
215	19.55	31	24	24.73	21.11	1.28	1.67	0.38	0.34	87.3
216	19.54	31	19	24.26	18.02	1.48	1.82	0.39	0.35	87.3
217	19.53	29	19	25.83	18.13	2.19	1.98	0.40	0.37	87.3
218	19.52	31	23	26.95	22.05	0.46	2.13	0.42	0.38	87.3
219	19.51	32	23	25.83	20.55	1.33	2.27	0.43	0.40	87.3
220	19.49	26	21	24.94	19.58	1.34	2.42	0.44	0.41	87.3
221	19.48	30.	21	26.08	18.35	0.69	2.56	0.46	0.42	87.3
222	20.96	32	22	26.21	19.60	1.02	2.70	0.47	0.44	87.3
223	20.94	32	24	25.96	21.35	1.81	2.83	0.48	0.45	87.3
224	20.93	32	24	26.30	21.35	1.70	2.96	0.50	0.47	87.3
225	20.91	30	22	28.69	16.12	1.15	3.08	0.51	0.48	87.3
226	20.89	24	20	23.10	18.02	0.48	3.20	0.52	0.49	87.3
227	20.87	29	21	28.00	18.54	0.95	3.31	0.54	0.51	87.3
228	20.85	31	23	26.95	19.38	1.09	3.42	0.55	0.52	87.3
229	20.83	30	20	26.60	18.90	1.47	3.52	0.56	0.54	87.3
230	13.52	29	20	26.08	17.82	0.91	3.61	0.58	0.55	87.3
231	20.78	27	21	25.15	16.17	1.00	3.70	0.59	0.57	87.3

Table D5. (Cont'.).

Day	HG	Tmax	Tmin	TDmax	TDmin	U	LAI	RD	Rmax	Pair
#	MJ m^{-2}	____	____	°C	____	$m\ s^{-1}$		m	m	kPa
232	20.75	32	21	28.79	17.83	0.67	3.77	0.60	0.58	87.3
233	20.73	34	23	29.36	18.31	0.63	3.84	0.62	0.59	87.3
234	20.70	33	24	27.37	21.03	1.40	3.91	0.63	0.61	87.3
235	20.67	32	23	28.69	13.38	0.81	3.96	0.64	0.62	87.3
236	20.65	33	24	26.03	17.99	1.45	4.01	0.66	0.64	87.3
237	20.62	32	23	27.14	18.39	1.42	4.05	0.67	0.65	87.3
238	20.58	30	22	26.00	21.00	1.37	4.08	0.68	0.66	87.3
239	20.55	27	23	24.95	21.11	0.70	4.10	0.70	0.68	87.3
240	19.21	32	22	30.00	21.00	1.19	4.11	0.71	0.69	87.3
241	20.49	27	23	25.00	21.00	0.66	4.12	0.72	0.71	87.3
242	17.79	32	22	30.00	19.00	0.69	4.12	0.74	0.72	87.3
243	19.98	30	22	26.00	21.00	1.00	4.11	0.75	0.74	87.3
244	20.87	29	22	30.00	20.00	1.47	4.09	0.76	0.75	87.3
245	20.83	33	27	27.00	24.00	1.35	4.06	0.78	0.76	87.3
246	20.83	32	22	30.33	22.00	0.92	4.03	0.79	0.78	87.3
247	20.76	32	21	27.42	19.02	0.94	3.99	0.79	0.78	87.3
248	20.72	30	22	23.59	19.25	0.25	3.94	0.79	0.78	87.3
249	20.68	29	22	27.42	17.16	1.39	3.88	0.79	0.76	87.3
250	20.63	33	22	30.39	18.91	0.84	3.82	0.80	0.78	87.3
251	20.59	31	21	24.60	20.25	0.04	3.75	0.80	0.78	87.3
252	20.55	32	23	23.82	16.44	1.21	3.67	0.80	0.78	87.3
253	20.44	33	21	24.95	19.22	0.84	3.59	0.80	0.79	87.3
254	15.22	34	22	24.05	12.07	1.00	3.50	0.80	0.79	87.3
255	15.19	34	22	24.26	15.21	1.14	3.41	0.80	0.79	87.3
256	15.15	33	22	24.05	17.44	1.17	3.31	0.80	0.79	87.3
257	15.12	35	20	23.02	10.07	0.65	3.21	0.81	0.79	87.3
258	15.08	35	19	22.70	9.26	0.90	3.11	0.81	0.79	87.3
259	15.04	36	20	22.63	5.57	0.66	3.00	0.81	0.79	87.3
260	15.01	33	20	22.63	12.43	0.60	2.88	0.81	0.79	87.3
261	14.97	28	21	22.50	4.44	0.63	2.77	0.81	0.79	87.3
262	14.93	31	23	26.30	2.25	0.47	2.65	0.81	0.80	87.3
263	14.89	33	22	25.80	1.14	0.54	2.54	0.81	0.80	87.3
264	19.25	28	21	24.90	1.45	0.63	2.42	0.81	0.80	87.3
265	19.20	29	20	26.80	11.20	0.73	2.30	0.82	0.80	87.3
266	19.14	31	22	30.00	13.00	0.86	2.18	0.82	0.80	87.3
267	19.09	31	24	26.40	1.42	0.56	2.06	0.82	0.80	87.3
268	19.04	36	22	25.90	6.55	0.60	1.95	0.82	0.80	87.3
269	18.98	35	21	30.20	13.50	0.68	1.84	0.82	0.80	87.3
270	18.92	36	19	35.90	9.84	0.68	1.73	0.82	0.80	87.3
271	18.86	36	18	29.10	3.6	0.87	1.63	0.82	0.81	87.3
272	18.80	33	23	27.00	4.76	1.04	1.53	0.83	0.81	87.3
273	18.56	32	20	27.90	12.90	1.35	1.44	0.83	0.81	87.3
274	18.23	33	20	32.50	8.18	0.87	1.35	0.83	0.81	87.3
275	18.17	33	22	31.30	13.30	0.63	1.28	0.83	0.81	87.3
276	18.00	36	20	37.92	8.18	1.08	1.21	0.83	0.81	87.3
277	17.98	37	20	26.46	1.68	0.65	1.15	0.83	0.81	87.3
278	17.75	36	17	19.78	3.31	0.90	1.10	0.83	0.81	87.3

Table D6. Weather and crop input data for the irrigation/mulched treatment.

Day	HG	Tmax	Tmin	TDmax	TDmin	U	LAI	RD	Rmax	Pair
#	MJ m^{-2}	____	____	°C	____	$m\ s^{-1}$		m	m	kPa
190	24.04	30	25	23.59	12.38	2.33	0.05	0.00	0.00	87.3
191	23.97	33	22	24.40	17.86	1.86	0.01	0.02	0.05	87.3
192	20.30	34	21	28.07	20.87	1.80	0.03	0.05	0.10	87.3
193	20.31	29	21	26.08	18.40	2.75	0.04	0.06	0.11	87.3
194	20.32	29	21	23.59	18.52	1.65	0.06	0.06	0.12	87.3
195	20.33	32	22	23.86	19.60	1.65	0.08	0.07	0.13	87.3
196	20.27	26	19	23.60	16.60	1.65	0.10	0.08	0.14	87.3
197	20.34	30	21	24.05	19.20	0.89	0.11	0.08	0.16	87.3
198	20.35	30	20	24.95	19.58	2.30	0.13	0.09	0.17	87.3
199	20.35	28	20	23.12	16.44	4.60	0.15	0.10	0.18	87.3
200	20.36	29	22	23.01	20.42	4.60	0.17	0.10	0.19	87.3
201	17.71	29	21	24.28	19.80	1.93	0.18	0.11	0.20	87.3
202	22.37	25	21	23.55	20.22	0.58	0.20	0.12	0.21	87.3
203	22.37	28	19	23.86	18.02	1.68	0.25	0.13	0.22	87.3
204	22.37	29	19	23.59	18.02	0.97	0.35	0.13	0.23	87.3
205	22.37	31	21	24.40	20.87	1.87	0.46	0.14	0.24	87.3
206	22.37	32	20	26.60	19.00	1.59	0.57	0.15	0.25	87.3
207	22.37	31	24	25.20	23.12	1.91	0.69	0.15	0.27	87.3
208	22.36	28	20	23.83	17.11	1.28	0.82	0.16	0.28	87.3
209	22.36	28	21	24.73	20.26	0.92	0.95	0.17	0.29	87.3
210	22.35	31	23	24.35	19.82	0.91	1.08	0.17	0.30	87.3
211	22.28	33	22	25.83	21.36	1.88	1.22	0.18	0.31	87.3
212	19.57	28	21	26.30	19.09	1.23	1.36	0.19	0.32	87.3
213	19.57	29	20	24.85	18.90	0.93	1.50	0.19	0.31	87.3
214	19.56	31	22	28.07	20.30	0.84	1.65	0.20	0.33	87.3
215	19.55	31	24	24.73	21.11	1.28	1.79	0.21	0.34	87.3
216	19.54	31	19	24.26	18.02	1.48	1.94	0.23	0.36	87.3
217	19.53	29	19	25.83	18.13	2.19	2.08	0.24	0.38	87.3
218	19.52	31	23	26.95	22.05	0.46	2.23	0.25	0.40	87.3
219	19.51	32	23	25.83	20.55	1.33	2.37	0.26	0.41	87.3
220	19.49	26	21	24.94	19.58	1.34	2.51	0.27	0.43	87.3
221	19.48	30.	21	26.08	18.35	0.69	2.65	0.28	0.45	87.3
222	20.96	32	22	26.21	19.60	1.02	2.79	0.30	0.47	87.3
223	20.94	32	24	25.96	21.35	1.81	2.93	0.31	0.48	87.3
224	20.93	32	24	26.30	21.35	1.70	3.06	0.32	0.50	87.3
225	20.91	30	22	28.69	16.12	1.15	3.19	0.33	0.52	87.3
226	20.89	24	20	23.10	18.02	0.48	3.31	0.34	0.53	87.3
227	20.87	29	21	28.00	18.54	0.95	3.44	0.35	0.55	87.3
228	20.85	31	23	26.95	19.38	1.09	3.55	0.37	0.57	87.3
229	20.83	30	20	26.60	18.90	1.47	3.66	0.38	0.59	87.3
230	13.52	29	20	26.08	17.82	0.91	3.77	0.39	0.60	87.3
231	20.78	27	21	25.15	16.17	1.00	3.87	0.40	0.62	87.3

Table D6. (Cont'.).

Day	HG	Tmax	Tmin	TDmax	TDmin	U	LAI	RD	Rmax	Pair
#	MJ m^{-2}			^oC		$m\ s^{-1}$		m	m	kPa
232	20.75	32	21	28.79	17.83	0.67	3.97	0.41	0.64	87.3
233	20.73	34	23	29.36	18.31	0.63	4.06	0.42	0.66	87.3
234	20.70	33	24	27.37	21.03	1.40	4.15	0.44	0.67	87.3
235	20.67	32	23	28.69	13.38	0.81	4.22	0.45	0.69	87.3
236	20.65	33	24	26.03	17.99	1.45	4.30	0.46	0.71	87.3
237	20.62	32	23	27.14	18.39	1.42	4.36	0.47	0.73	87.3
238	20.58	30	22	26.00	21.00	1.37	4.42	0.48	0.74	87.3
239	20.55	27	23	24.95	21.11	0.70	4.47	0.49	0.76	87.3
240	19.21	32	22	30.00	21.00	1.19	4.52	0.51	0.78	87.3
241	20.49	27	23	25.00	21.00	0.66	4.55	0.52	0.79	87.3
242	17.79	32	22	30.00	19.00	0.69	4.59	0.53	0.81	87.3
243	19.98	30	22	26.00	21.00	1.00	4.61	0.54	0.83	87.3
244	20.87	29	22	30.00	20.00	1.47	4.62	0.55	0.85	87.3
245	20.83	33	27	27.00	24.00	1.35	4.63	0.56	0.86	87.3
246	20.83	32	22	30.33	22.00	0.92	4.63	0.58	0.88	87.3
247	20.76	32	21	27.42	19.02	0.94	4.63	0.58	0.88	87.3
248	20.72	30	22	23.59	19.25	0.25	4.61	0.58	0.89	87.3
249	20.68	29	22	27.42	17.16	1.39	4.59	0.58	0.89	87.3
250	20.63	33	22	30.39	18.91	0.84	4.56	0.58	0.89	87.3
251	20.59	31	21	24.60	20.25	0.04	4.53	0.58	0.89	87.3
252	20.55	32	23	23.82	16.44	1.21	4.48	0.58	0.89	87.3
253	20.44	33	21	24.95	19.22	0.84	4.43	0.58	0.90	87.3
254	15.22	34	22	24.05	12.07	1.00	4.38	0.58	0.90	87.3
255	15.19	34	22	24.26	15.21	1.14	4.31	0.58	0.90	87.3
256	15.15	33	22	24.05	17.44	1.17	4.24	0.59	0.90	87.3
257	15.12	35	20	23.02	10.07	0.65	4.16	0.59	0.91	87.3
258	15.08	35	19	22.70	9.26	0.90	4.08	0.59	0.91	87.3
259	15.04	36	20	22.63	5.57	0.66	3.99	0.59	0.91	87.3
260	15.01	33	20	22.63	12.43	0.60	3.89	0.59	0.91	87.3
261	14.97	28	21	22.50	4.44	0.63	3.79	0.59	0.92	87.3
262	14.93	31	23	26.30	2.25	0.47	3.68	0.59	0.92	87.3
263	14.89	33	22	25.80	1.14	0.54	3.57	0.59	0.92	87.3
264	19.25	28	21	24.90	1.45	0.63	3.45	0.59	0.92	87.3
265	19.20	29	20	26.80	11.20	0.73	3.32	0.59	0.93	87.3
266	19.14	31	22	30.00	13.00	0.86	3.19	0.60	0.93	87.3
267	19.09	31	24	26.40	1.42	0.56	3.06	0.60	0.93	87.3
268	19.04	36	22	25.90	6.55	0.60	2.92	0.60	0.93	87.3
269	18.98	35	21	30.20	13.50	0.68	2.78	0.60	0.93	87.3
270	18.92	36	19	35.90	9.84	0.68	2.64	0.60	0.94	87.3
271	18.86	36	18	29.10	3.6	0.87	2.49	0.60	0.94	87.3
272	18.80	33	23	27.00	4.76	1.04	2.34	0.60	0.94	87.3
273	18.56	32	20	27.90	12.90	1.35	2.19	0.60	0.94	87.3
274	18.23	33	20	32.50	8.18	0.87	2.03	0.60	0.95	87.3
275	18.17	33	22	31.30	13.30	0.63	1.88	0.60	0.95	87.3
276	18.00	36	20	37.92	8.18	1.08	1.72	0.61	0.95	87.3
277	17.98	37	20	26.46	1.68	0.65	1.56	0.61	0.95	87.3
278	17.75	36	17	19.78	3.31	0.90	1.41	0.61	0.95	87.3

Table D7. Weather and crop input data for the irrigation/nitrogen treatment.

Day	HG	Tmax	Tmin	TDmax	TDmin	U	LAI	RD	Rmax	Pair
#	MJ m^{-2}	____	____	°C	____	$m\ s^{-1}$		m	m	kPa
190	24.04	30	25	23.59	12.38	2.33	0.05	0.00	0.00	87.3
191	23.97	33	22	24.40	17.86	1.86	0.01	0.00	0.04	87.3
192	20.30	34	21	28.07	20.87	1.80	0.03	0.02	0.06	87.3
193	20.31	29	21	26.08	18.40	2.75	0.04	0.08	0.12	87.3
194	20.32	29	21	23.59	18.52	1.65	0.08	0.09	0.13	87.3
195	20.33	32	22	23.86	19.60	1.65	0.11	0.09	0.14	87.3
196	20.27	26	19	23.60	16.60	1.65	0.15	0.10	0.15	87.3
197	20.34	30	21	24.05	19.20	0.89	0.20	0.11	0.15	87.3
198	20.35	30	20	24.95	19.58	2.30	0.26	0.12	0.16	87.3
199	20.35	28	20	23.12	16.44	4.60	0.34	0.12	0.17	87.3
200	20.36	29	22	23.01	20.42	4.60	0.42	0.13	0.18	87.3
201	17.71	29	21	24.28	19.80	1.93	0.50	0.14	0.19	87.3
202	22.37	25	21	23.55	20.22	0.58	0.60	0.15	0.20	87.3
203	22.37	28	19	23.86	18.02	1.68	0.71	0.15	0.20	87.3
204	22.37	29	19	23.59	18.02	0.97	0.82	0.16	0.21	87.3
205	22.37	31	21	24.40	20.87	1.87	0.93	0.17	0.22	87.3
206	22.37	32	20	26.60	19.00	1.59	1.05	0.18	0.23	87.3
207	22.37	31	24	25.20	23.12	1.91	1.18	0.18	0.24	87.3
208	22.36	28	20	23.83	17.11	1.28	1.31	0.19	0.25	87.3
209	22.36	28	21	24.73	20.26	0.92	1.44	0.20	0.25	87.3
210	22.35	31	23	24.35	19.82	0.91	1.57	0.21	0.26	87.3
211	22.28	33	22	25.83	21.36	1.88	1.71	0.21	0.27	87.3
212	19.57	28	21	26.30	19.09	1.23	2.85	0.22	0.28	87.3
213	19.57	29	20	24.85	18.90	0.93	1.99	0.24	0.30	87.3
214	19.56	31	22	28.07	20.30	0.84	2.13	0.25	0.32	87.3
215	19.55	31	24	24.73	21.11	1.28	2.28	0.27	0.34	87.3
216	19.54	31	19	24.26	18.02	1.48	2.42	0.28	0.37	87.3
217	19.53	29	19	25.83	18.13	2.19	2.56	0.30	0.39	87.3
218	19.52	31	23	26.95	22.05	0.46	2.70	0.31	0.41	87.3
219	19.51	32	23	25.83	20.55	1.33	2.84	0.33	0.43	87.3
220	19.49	26	21	24.94	19.58	1.34	2.98	0.34	0.45	87.3
221	19.48	30.	21	26.08	18.35	0.69	3.11	0.36	0.47	87.3
222	20.96	32	22	26.21	19.60	1.02	3.24	0.37	0.49	87.3
223	20.94	32	24	25.96	21.35	1.81	3.37	0.39	0.51	87.3
224	20.93	32	24	26.30	21.35	1.70	3.50	0.40	0.54	87.3
225	20.91	30	22	28.69	16.12	1.15	3.62	0.42	0.56	87.3
226	20.89	24	20	23.10	18.02	0.48	3.74	0.43	0.58	87.3
227	20.87	29	21	28.00	18.54	0.95	3.86	0.45	0.60	87.3
228	20.85	31	23	26.95	19.38	1.09	3.97	0.46	0.62	87.3
229	20.83	30	20	26.60	18.90	1.47	4.08	0.48	0.64	87.3
230	13.52	29	20	26.08	17.82	0.91	4.18	0.49	0.66	87.3
231	20.78	27	21	25.15	16.17	1.00	4.28	0.51	0.69	87.3

Table D7. Cont'

Day	HG	Tmax	Tmin	TDmax	TDmin	U	LAI	RD	Rmax	Pair
#	MJ m^{-2}			^oC		$m\ s^{-1}$		m	m	kPa
232	20.75	32	21	28.79	17.83	0.67	4.37	0.52	0.71	87.3
233	20.73	34	23	29.36	18.31	0.63	4.45	0.54	0.73	87.3
234	20.70	33	24	27.37	21.03	1.40	4.53	0.55	0.75	87.3
235	20.67	32	23	28.69	13.38	0.81	4.61	0.57	0.77	87.3
236	20.65	33	24	26.03	17.99	1.45	4.68	0.58	0.79	87.3
237	20.62	32	23	27.14	18.39	1.42	4.74	0.60	0.81	87.3
238	20.58	30	22	26.00	21.00	1.37	4.80	0.61	0.83	87.3
239	20.55	27	23	24.95	21.11	0.70	4.85	0.63	0.86	87.3
240	19.21	32	22	30.00	21.00	1.19	4.89	0.64	0.88	87.3
241	20.49	27	23	25.00	21.00	0.66	4.93	0.64	0.88	87.3
242	17.79	32	22	30.00	19.00	0.69	4.96	0.64	0.88	87.3
243	19.98	30	22	26.00	21.00	1.00	4.98	0.64	0.88	87.3
244	20.87	29	22	30.00	20.00	1.47	5.00	0.64	0.88	87.3
245	20.83	27	23	27.00	24.00	1.35	5.01	0.64	0.88	87.3
246	20.83	32	22	30.00	22.00	0.92	5.01	0.64	0.88	87.3
247	20.76	32	21	27.42	21.02	0.94	5.01	0.65	0.88	87.3
248	20.72	30	22	23.59	19.25	0.25	5.00	0.65	0.89	87.3
249	20.68	29	22	27.42	17.16	1.39	4.99	0.65	0.89	87.3
250	20.63	33	22	30.39	18.91	0.84	4.97	0.65	0.89	87.3
251	20.59	31	21	24.60	20.25	0.04	4.94	0.65	0.89	87.3
252	20.55	32	23	23.82	16.44	1.21	4.91	0.65	0.89	87.3
253	20.44	33	21	24.95	19.22	0.84	4.86	0.65	0.89	87.3
254	15.22	34	22	24.05	12.07	1.00	4.82	0.65	0.89	87.3
255	15.19	34	22	24.26	15.21	1.14	4.77	0.65	0.89	87.3
256	15.15	33	22	24.05	17.44	1.17	4.71	0.65	0.89	87.3
257	15.12	35	20	23.02	10.07	0.65	4.65	0.65	0.90	87.3
258	15.08	35	19	22.70	9.26	0.90	4.58	0.65	0.90	87.3
259	15.04	36	20	22.63	5.57	0.66	4.50	0.66	0.90	87.3
260	15.01	33	20	22.63	12.43	0.60	4.42	0.66	0.90	87.3
261	14.97	28	21	22.50	4.44	0.63	4.34	0.66	0.90	87.3
262	14.93	31	23	26.30	2.25	0.47	4.25	0.66	0.90	87.3
263	14.89	33	22	25.80	1.14	0.54	4.16	0.66	0.90	87.3
264	19.25	28	21	24.90	1.45	0.63	4.06	0.66	0.90	87.3
265	19.20	29	20	26.80	11.20	0.73	3.97	0.66	0.90	87.3
266	19.14	31	22	30.00	13.00	0.86	3.86	0.66	0.91	87.3
267	19.09	31	24	26.40	1.42	0.56	3.76	0.66	0.91	87.3
268	19.04	36	22	25.90	6.55	0.60	3.65	0.66	0.91	87.3
269	18.98	35	21	30.20	13.50	0.68	3.54	0.66	0.91	87.3
270	18.92	36	19	35.90	9.84	0.68	3.43	0.66	0.91	87.3
271	18.86	36	18	29.10	3.6	0.87	3.31	0.67	0.91	87.3
272	18.80	33	23	27.00	4.76	1.04	3.20	0.67	0.91	87.3
273	18.56	32	20	27.90	12.90	1.35	3.08	0.67	0.91	87.3
274	18.23	33	20	32.50	8.18	0.87	2.96	0.67	0.91	87.3
275	18.17	33	22	31.30	13.30	0.63	2.85	0.67	0.92	87.3
276	18.00	36	20	37.92	8.18	1.08	2.73	0.67	0.92	87.3
277	17.98	37	20	26.46	1.68	0.65	2.62	0.67	0.92	87.3
278	17.75	36	17	19.78	3.31	0.90	2.51	0.67	0.92	87.3

Table D8. Weather and crop input data for the irrigation/nitrogen/mulched treatment.

Day	HG	Tmax	Tmin	TDmax	TDmin	U	LAI	RD	Rmax	Pair
#	MJ m^{-2}	____	____	°C	____	$m\ s^{-1}$		m	m	kPa
190	24.04	30	25	23.59	12.38	2.33	0.05	0.00	0.00	87.3
191	23.97	33	22	24.40	17.86	1.86	0.12	0.00	0.02	87.3
192	20.30	34	21	28.07	20.87	1.80	0.17	0.05	0.08	87.3
193	20.31	29	21	26.08	18.40	2.75	0.19	0.10	0.14	87.3
194	20.32	29	21	23.59	18.52	1.65	0.20	0.11	0.15	87.3
195	20.33	32	22	23.86	19.60	1.65	0.22	0.12	0.16	87.3
196	20.27	26	19	23.60	16.60	1.65	0.24	0.13	0.17	87.3
197	20.34	30	21	24.05	19.20	0.89	0.26	0.14	0.18	87.3
198	20.35	30	20	24.95	19.58	2.30	0.27	0.15	0.20	87.3
199	20.35	28	20	23.12	16.44	4.60	0.29	0.16	0.21	87.3
200	20.36	29	22	23.01	20.42	4.60	0.31	0.17	0.22	87.3
201	17.71	29	21	24.28	19.80	1.93	0.33	0.18	0.23	87.3
202	22.37	25	21	23.55	20.22	0.58	0.34	0.19	0.24	87.3
203	22.37	28	19	23.86	18.02	1.68	0.36	0.19	0.25	87.3
204	22.37	29	19	23.59	19.02	0.97	0.38	0.20	0.26	87.3
205	22.37	31	21	24.40	20.87	1.87	0.40	0.21	0.27	87.3
206	22.37	32	20	26.60	19.00	1.59	0.57	0.22	0.28	87.3
207	22.37	31	24	25.20	23.12	1.91	0.72	0.23	0.29	87.3
208	22.36	28	20	23.83	17.11	1.28	0.85	0.24	0.31	87.3
209	22.36	28	21	24.73	20.26	0.92	0.98	0.25	0.32	87.3
210	22.35	31	23	24.35	19.82	0.91	1.11	0.26	0.33	87.3
211	22.28	33	22	25.83	21.36	1.88	1.25	0.27	0.34	87.3
212	19.57	28	21	26.30	19.09	1.23	1.39	0.28	0.35	87.3
213	19.57	29	20	24.85	18.90	0.93	1.53	0.29	0.36	87.3
214	19.56	31	22	28.07	20.30	0.84	1.67	0.30	0.38	87.3
215	19.55	31	24	24.73	21.11	1.28	1.81	0.31	0.39	87.3
216	19.54	31	19	24.26	18.02	1.48	1.95	0.32	0.40	87.3
217	19.53	29	19	25.83	18.13	2.19	2.09	0.33	0.41	87.3
218	19.52	31	23	26.95	22.05	0.46	2.22	0.34	0.43	87.3
219	19.51	32	23	25.83	20.55	1.33	2.36	0.35	0.44	87.3
220	19.49	26	21	24.94	19.58	1.34	2.49	0.35	0.45	87.3
221	19.48	30.	21	26.08	18.35	0.69	2.63	0.36	0.46	87.3
222	20.96	32	22	26.21	19.60	1.02	2.75	0.37	0.48	87.3
223	20.94	32	24	25.96	21.35	1.81	2.88	0.38	0.49	87.3
224	20.93	32	24	26.30	21.35	1.70	3.00	0.39	0.50	87.3
225	20.91	30	22	28.69	16.12	1.15	3.11	0.40	0.51	87.3
226	20.89	24	20	23.10	18.02	0.48	3.22	0.41	0.53	87.3
227	20.87	29	21	28.00	18.54	0.95	3.33	0.42	0.54	87.3
228	20.85	31	23	26.95	19.38	1.09	3.43	0.43	0.55	87.3
229	20.83	30	20	26.60	18.90	1.47	3.53	0.44	0.56	87.3
230	13.52	29	20	26.08	17.82	0.91	3.62	0.45	0.57	87.3
231	20.78	27	21	25.15	16.17	1.00	3.70	0.46	0.59	87.3

Table D8. (Cont'.).

Day	HG	Tmax	Tmin	TDmax	TDmin	U	LAI	RD	Rmax	Pair
#	MJ m^{-2}	____	____	°C	____	$m\ s^{-1}$		m	m	kPa
232	20.75	32	21	28.79	17.83	0.67	3.78	0.47	0.60	87.3
233	20.73	34	23	29.36	18.31	0.63	3.85	0.48	0.61	87.3
234	20.70	33	24	27.37	21.03	1.40	3.92	0.48	0.62	87.3
235	20.67	32	23	28.69	13.38	0.81	3.98	0.49	0.64	87.3
236	20.65	33	24	26.03	17.99	1.45	4.03	0.50	0.65	87.3
237	20.62	32	23	27.14	18.39	1.42	4.08	0.50	0.66	87.3
238	20.58	30	22	26.00	21.00	1.37	4.11	0.50	0.67	87.3
239	20.55	27	23	24.95	21.11	0.70	4.15	0.50	0.69	87.3
240	19.21	32	22	30.00	21.00	1.19	4.17	0.50	0.70	87.3
241	20.49	27	23	25.00	21.00	0.66	4.19	0.50	0.71	87.3
242	17.79	32	22	30.00	19.00	0.69	4.20	0.50	0.72	87.3
243	19.98	30	22	26.00	21.00	1.00	4.20	0.50	0.74	87.3
244	20.87	29	22	30.00	20.00	1.47	4.20	0.50	0.75	87.3
245	20.83	27	23	27.00	24.00	1.35	4.19	0.51	0.76	87.3
246	20.83	32	22	30.00	22.00	0.92	4.17	0.51	0.77	87.3
247	20.76	32	21	27.42	21.02	0.94	4.15	0.51	0.79	87.3
248	20.72	30	22	23.59	19.25	0.25	4.12	0.51	0.80	87.3
249	20.68	29	22	27.42	17.16	1.39	4.09	0.51	0.81	87.3
250	20.63	33	22	30.39	18.91	0.84	4.04	0.51	0.82	87.3
251	20.59	31	21	24.60	20.25	0.04	4.00	0.51	0.84	87.3
252	20.55	32	23	23.82	16.44	1.21	3.94	0.51	0.84	87.3
253	20.44	33	21	24.95	19.22	0.84	3.88	0.52	0.84	87.3
254	15.22	34	22	24.05	12.07	1.00	3.82	0.52	0.84	87.3
255	15.19	34	22	24.26	15.21	1.14	3.75	0.52	0.84	87.3
256	15.15	33	22	24.05	17.44	1.17	3.67	0.52	0.84	87.3
257	15.12	35	20	23.02	10.07	0.65	3.59	0.52	0.84	87.3
258	15.08	35	19	22.70	9.26	0.90	3.51	0.52	0.84	87.3
259	15.04	36	20	22.63	5.57	0.66	3.42	0.52	0.84	87.3
260	15.01	33	20	22.63	12.43	0.60	3.33	0.52	0.85	87.3
261	14.97	28	21	22.50	4.44	0.63	3.24	0.52	0.85	87.3
262	14.93	31	23	26.30	2.25	0.47	3.14	0.53	0.85	87.3
263	14.89	33	22	25.80	1.14	0.54	3.05	0.53	0.85	87.3
264	19.25	28	21	24.90	1.45	0.63	2.95	0.53	0.85	87.3
265	19.20	29	20	26.80	11.20	0.73	2.85	0.53	0.85	87.3
266	19.14	31	22	30.00	13.00	0.86	2.74	0.53	0.85	87.3
267	19.09	31	24	26.40	1.42	0.56	2.64	0.53	0.85	87.3
268	19.04	36	22	25.90	6.55	0.60	2.54	0.53	0.86	87.3
269	18.98	35	21	30.20	13.50	0.68	2.44	0.53	0.86	87.3
270	18.92	36	19	35.90	9.84	0.68	2.34	0.54	0.86	87.3
271	18.86	36	18	29.10	3.6	0.87	2.25	0.54	0.86	87.3
272	18.80	33	23	27.00	4.76	1.04	2.15	0.54	0.86	87.3
273	18.56	32	20	27.90	12.90	1.35	2.06	0.54	0.86	87.3
274	18.23	33	20	32.50	8.18	0.87	1.98	0.54	0.86	87.3
275	18.17	33	22	31.30	13.30	0.63	1.89	0.54	0.86	87.3
276	18.00	36	20	37.92	8.18	1.08	1.82	0.54	0.87	87.3
277	17.98	37	20	26.46	1.68	0.65	1.75	0.54	0.87	87.3
278	17.75	36	17	19.78	3.31	0.90	1.68	0.54	0.87	87.3

Table D9. Constants used in ENWATBAL.BAS that may change from one run to another.

0.001	"Zo, surface roughness length [m]."
0	"WPCrMx, maximum crop water potential [m]."
1E+9	"SRCr, specific hydraulic resistance of the crop [s]."
0.2	"DetCap, ponded water detention capacity [m]."
16.3	"Lat, latitude [Deg.]."
87.3	"AvBarP, average barometric pressure [kPa] at Maradi."
10.0	"TStepL, lower limit of time step in s."
30.0	"TStepH, upper limit of time step in s."
1.0	"Gradient to use for water flux at lower soil boundary (m m^{-1})."

Table D10. Leaf water potential [m] versus epidermal conductance [m s^{-1}]

```
Data for array ClvsWP, leaf water potential versus epidermal conductance:
CLVSWP
8
   -500., .0002
  -200., .0002
   -165., .0005
   -140., .003
    -80., .0165
    -50., .0195
    -35., .02
      0., .02
```

Table D11. Incident solar radiation [W m^{-2}] versus epidermal conductance [m s^{-1}]

```
Data for array ClvsGr, solar radiation versus epidermal conductance
CLVSGR
4
      0.0, .0002
     20.0, .0002
    200.0, .02
   1200.0, .02
```

Table D12. Volume fraction of water versus soil water potential [m]

```
'Data for array TvsP1, volumetric water content versus soil water potential [m]:
'Horizon 1, Alluvial, Maradi, Niger.
'Added 1st point of 0.001 and -100000 to see if divergence of soil surface
'temp. was affected. It was. Divergence stopped.
'Added another first point on 12 Oct. 90 to avoid divergence:
'        theta    ppot
TVSP1
31
        0.0,    -1E+36
        0.0001, -1000000
         0.001, -100000
         0.005, -70000
          0.01, -2500
          0.03,  -1500
          0.05,  -1800
          0.07,  -1000
          0.09,   -800
          0.11,   -675
          0.13,   -650
          0.15,   -610
          0.17,    -515
          0.19,    -400
          0.21,    -30
          0.23,    -5
          0.25,    -4
          0.27,    -3
          0.29,     -2.5
          0.31,   -2
          0.33,   -1
          0.35,   -0.1
          0.37,   -0.1
          0.39,   -0.1
          0.41,   -0.1
          0.43,   -0.1
          0.45,   -0.1
          0.47,   -0.1
          0.49,   -0.1
          0.50,    0.0
          1.00,    0.0
```

Table D13. Data for array TvsP2, volumetric water content versus soil water potential [m]

```
'Horizon 2, Alluvial, Maradi, Niger.
'        theta    ppot
TVSP2
29
        0.005,  -30000
         0.01,  -10000
         0.03,   -1200
         0.05,   -1000
         0.07,   -985
         0.09,   -750
         0.11,    -450
         0.13,    -250
         0.15,    -125
         0.17,    -60
         0.19,    -32
         0.21,    -28
         0.23,    -21
         0.25,    -19
         0.27,    -18
         0.29,     -17
         0.31,     -15
         0.33,     -10
         0.35,     -8
         0.37,     -6
         0.39,     -4
         0.41,     -3
         0.43,      -2
         0.45,    -1
         0.47,    -0.5
         0.49,    -0.5
         0.51,    -0.5
         0.52,     0.0
         1.00,     0.0
```

Table D14. Volume fraction of water versus soil hydraulic conductivity [m s^{-1}]

```
'Data for array TvsC1, volumetric water content versus hydraulic conductivity [m]:
'Horizon 1, Maradi, Niger
'Added 1st point to see if evaporation rate was affected. It was not.
'        theta  K(theta)
TVSC1
27
        0.005, 1.9E-20
        0.02, 1.9E-20
        0.04, 3.29E-17
        0.06, 8.15E-16
        0.08, 1.32E-13
        0.1, 1.41E-12
        0.12, 6.69E-12
        0.14, 2.14E-11
        0.16, 5.43E-11
        0.18, 1.18E-10
        0.2, 2.28E-10
        0.22, 4.08E-10
        0.24, 6.82E-10
        0.26, 1.08E-09
        0.28, 1.65E-09
        0.3, 2.43E-09
        0.32, 3.48E-09
        0.34, 4.84E-09
        0.36, 6.59E-09
        0.38, 8.08E-09
        0.4, 1.16E-08
        0.42, 1.50E-08
        0.44, 1.91E-08
        0.46, 2.41E-08
        0.48, 4.53E-08
        0.5, 6.03E-08
        1.0, 6.03E-08
```

Table D15. Data for array TvsC2, volumetric water content versus hydraulic conductivity [m]

```
'Horizon 2, Alluvial, Maradi, Niger.
'       theta  K(theta)
TVSC2
28
        0.005, 6.13E-33
         0.02, 1.50E-31
         0.04, 1.20E-29
         0.06, 8.19E-27
         0.08, 6.28e-25
          0.1, 4.82e-23
         0.12, 3.70e-21
         0.14, 2.84e-19
         0.16, 2.18e-17
         0.18, 1.67e-15
          0.2, 1.28e-13
         0.22, 1.82e-12
         0.24, 2.54e-12
         0.26, 4.87e-12
         0.28, 9.28e-12
          0.3, 1.80e-11
         0.32, 3.41e-11
         0.34, 6.42e-11
         0.36, 1.18e-10
         0.38, 2.16e-10
          0.4, 4.00e-10
         0.42, 7.67e-10
         0.44, 1.56e-9
         0.46, 3.33e-9
         0.48, 7.45e-9
          0.5, 7.50e-8
         0.52, 7.60e-8
         1.00, 7.60e-8
```

Table D16. Soil water content [m^{-3} m^{-3}] versus soil albedo

```
'Data for array SoilAL. Good only for 1 mm or less thick top soil layer.
'Reference: Idso, S.B., R.D. Jackson, R.J. Reginato, B.A. Kimball, and F.S.
'Nakayama. 1975. The dependence of bare soil albedo on soil water content.
'J. Applied Meteorology, 14(1)109-113.
SOILAL
3
  0.00,  0.175
  0.25,  0.175
  1.00,  0.175
```

Table D17. Soil temperature [Deg.C] versus heat conductivity by vapor [W m^{-1} C^{-1}]

Data for array TevsKO0, soil temp. versus heat conductivity by vapor:
TEVSKO
9

-1.000,	0.02000
0.000,	0.02470
10.000,	0.04190
20.000,	0.07990
30.000,	0.12600
40.000,	0.24700
50.000,	0.38100
60.000,	0.65000
70.000,	1.17000

Table D18. Initial soil moisture and temperature profile for dryland plots

Thickness	Water content	Temperature	Horizon #
m	m^3 m^{-3}	°C	
0.005	0.156	37.1	1
0.010	0.156	37.1	1
0.015	0.156	37.1	1
0.020	0.156	37.1	1
0.020	0.156	37.1	1
0.020	0.156	37.1	1
0.025	0.126	37.1	1
0.030	0.126	36.9	1
0.030	0.126	36.9	1
0.035	0.033	36.9	1
0.040	0.033	36.9	1
0.040	0.033	36.7	1
0.050	0.033	36.7	1
0.060	0.033	36.7	1
0.070	0.012	36.7	1
0.080	0.042	36.7	2
0.090	0.031	36.7	2
0.150	0.023	34.2	2
0.200	0.024	32.5	2
0.250	0.035	32.2	2
0.350	0.028	32.2	2
0.360	0.014	32.4	2

Table D19. Initial soil moisture and temperature profile for irrigated plots

Thickness	Water content	Temperature	Horizon #
m	$m^3\ m^{-3}$	°C	
0.005	0.196	35.2	1
0.010	0.197	35.0	1
0.015	0.210	35.0	1
0.020	0.186	35.0	1
0.020	0.195	35.0	1
0.020	0.196	36.0	1
0.025	0.182	37.1	1
0.030	0.126	37.1	1
0.030	0.126	36.9	1
0.035	0.033	36.9	1
0.040	0.033	36.9	1
0.040	0.033	36.9	1
0.050	0.033	36.7	1
0.060	0.012	36.7	1
0.070	0.042	36.7	1
0.080	0.031	36.7	2
0.090	0.023	34.2	2
0.150	0.024	32.5	2
0.200	0.035	32.2	2
0.350	0.028	32.2	2
0.360	0.014	32.4	2

Table D20. Day, Begin-End, Amount of precipitation for dryland plots

190	0		
191	1		
	5.00	22.15	15.00
192	0		
193	0		
194	0		
195	0		
196	1		
	6.41	7.00	25.00
197	0		
198	1		
	2.00	4.25	22.00
199	0		
200	1		
	2.00	9.75	14.00
201	0		
202	0		
203	1		
	22.00	23.25	8.00
204	0		
205	1		
	22.00	23.25	14.00
206	0		
207	0		
208	0		
209	0		
210	0		
211	0		
212	0		
213	0		
214	0		
215	1		
	1.3	4.5	1.00
216	1		
	21.00	23.80	49.00
217	0		
218	0		
219	0		
220	1		
	7.50	13.80	23.00
221	0		
222	0		
223	0		
224	0		
225	0		
226	2		
	8.00	12.00	10.06
	21.00	23.50	6.84
227	0		
228	0		
229	0		
230	1		
	4.00	5.00	4.40

Table D20. Cont'

231	0		
232	0		
233	0		
234	0		
235	0		
236	0		
237	0		
238	0		
239	0		
240	0		
241	1		
	3.00	8.00	45.00
242	0		
243	1		
	3.00	7.00	5.00
244	0		
245	0		
246	0		
247	1		
	19.00	23.00	1.01
248	0		
249	0		
250	1		
	2.00	5.00	30.95
251	0		
252	0		
253	1		
	6.00	8.00	6.00
254	0		
255	0		
256	0		
257	0		
258	0		
259	0		
260	0		
261	0		
262	0		
263	0		
264	0		
265	0		
266	0		
267	0		
268	0		
269	0		
270	0		
271	0		
272	0		
273	1		
	5.00	9.00	3.00
274	0		

Table D21. Day, Begin-End, Amount of precipitation for irrigated plots

190	0		
191	1		
	5.00	22.15	15.00
192	0		
193	0		
194	0		
195	0		
196	1		
	6.41	7.00	25.00
197	0		
198	1		
	2.00	4.25	22.00
199	0		
200	1		
	2.00	9.75	14.00
201	0		
202	0		
203	1		
	22.00	23.25	8.00
204	0		
205	1		
	22.00	23.25	14.00
206	0		
207	0		
208	0		
209	0		
210	0		
211	0		
212	0		
213	0		
214	0		
215	1		
	1.3	4.5	1.00
216	1		
	21.00	23.80	49.00
217	0		
218	0		
219	0		
220	1		
	7.50	13.80	23.00
221	0		
222	0		
223	0		
224	0		
225	1		
	6.50	20.45	25.00
226	2		
	8.00	12.00	10.06
	21.00	23.50	6.84
227	0		
228	0		
229	0		

Table D21. Cont'

230	1		
	4.00	5.00	4.40
231	0		
232	0		
233	0		
234	0		
235	0		
236	0		
237	0		
238	1		
	7.30	21.75	25.00
239	0		
240	0		
241	1		
	3.00	8.00	45.00
242	0		
243	1		
	3.00	7.00	5.00
244	0		
245	0		
246	0		
247	1		
	19.00	23.00	1.01
248	0		
249	0		
250	1		
	2.00	5.00	30.95
251	0		
252	0		
253	1		
	6.00	8.00	6.00
254	0		
255	0		
256	0		
257	0		
258	1		
	8.30	17.50	25.00
259	0		
260	0		
261	0		
264	0		
266	0		
267	0		
268	0		
269	1		
	7.30	8.25	25.00
270	0		
271	0		
272	0		
273	1		
	5.00	9.00	3.00
274	0		

APPENDIX E. MISCELLANEOUS DATA

Table E1. Parameters of water retention cubic equations for the different soil horizons.

Layer (m)	Intercept	Coefficient†			R^2
	a	b	c	d	
0 - 0.46	15.731	-1.740	0.078	-0.0012	0.916
0.46 - 0.65	18.663	-2.096	0.091	-0.0013	0.938
0.65 - 0.82	16.641	-2.685	0.186	-0.0045	0.987
0.82 - 1.07	13.060	-3.009	0.298	-0.0096	0.954
1.07 - 1.58	12.936	-2.805	0.264	-0.0084	0.981

†: Coefficients of Eq: $\ln(\Psi) = a + b\,\theta_i + c\,\theta_i^2 + d\,\theta_i^3$
where a, b, c, and d are constants and θ_i is volumetric soil water content of soil layer i.

Table E2. Parameters of hydraulic conductivity equations for the different soil layers.

Layer	$d\theta/dt=a*T^{b}$†		$K(\theta)=K_o*EXP(A*(\theta_o-\theta_i))$‡				
	a	b	R^2	Ko	A	θo	R^2
m				(mm h^{-1})			
0 - 0.46	0.0019	-1.062	0.95	14.66	-67	0.35	0.96
0.46 - 0.65	-0.010	-0.006	0.96	16.42	-123	0.16	0.95
0.65 - 0.82	-0.006	-1.060	0.98	3.99	-207	0.10	0.98
0.82 - 1.07	-0.005	-1.032	0.91	0.42	-217	0.13	0.89
1.07 - 1.58	-0.003	-1.023	.95	50.03	-152	0.12	0.92

† Derived from the equation of ln(water content) versus ln(time)
‡ Derived from Eq: $\ln(Z*(d\theta/dt) = f\,(\theta_o - \theta_i)$
where Z is soil depth (m).

Table E3. Selected regression equation for soil properties

Parameter	Regression equation	R^2
Unsaturated hydraulic conductivity (Ki) of the top horizon (0 - 0.25 m) as a function of volumetric soil moisture content (θ_i)	$K_i = 2.7183^{-13.413} * \theta_i^{4.6318}$	0.98
Percent sand content (S) as a function of soil depth (Z†)	$S = 41.8+22.6* Z$	0.86
Percent silt content (Si) as a function of soil depth (Z)	$Si = 43.21-17.75*Z$	0.84
Percent clay content (C) as a function of soil depth (Z)	$C = 15.03 - 4.86*D$	0.97
Percent organic matter content (OM) as a function of soil depth (Z)	$OM = 3.49-9.59*Z+11*Z^2- 5.53*Z^3+0.92*Z^4$	0.97
Percent macro-aggregation (AG) as a function of soil depth (Z)	$AG = 109.3-117*Z+47.15*Z^2-6.48*Z^3$	0.94
Macro-aggregation as a function of silt content.	$AG = 22.31- 5.56*Si+0.569*S_i^2-1.058*S_i^3$	0.97
Macro-aggregation as a function of organic matter content	$OM = 0.2989 + 0.01995*AG$	0.84
Macro-aggregation as a function of organic matter content	$OM = -0.349+0.12*AG-0.0034*AG^2+29*10^{-6}*AG^3$	0.99
Neutron probe calibration equation volumetric water content (WC) as a function of the count ratio (CR)	$WC = - 0.36 + 35.56 * CR$	0.94

† in meters

Table E4. Climatic parameters between calendar day 182 and 320 at the experiment site.

Parameter	Value
Mean atmospheric pressure	87.3 kPa
Mean saturated vapor pressure	40 kPa
Mean actual vapor pressure	27 kPa
Mean atmospheric CO_2 concentration	330 ppm
Total heat units (15°C reference)	1023°
Mean relative humidity	69%
Total wind run	9218 km
Total solar radiation	2695 MJ m^{-2}
Total pan evaporation	616 mm
Total rainfall	354 mm
Irrigation input	142 mm

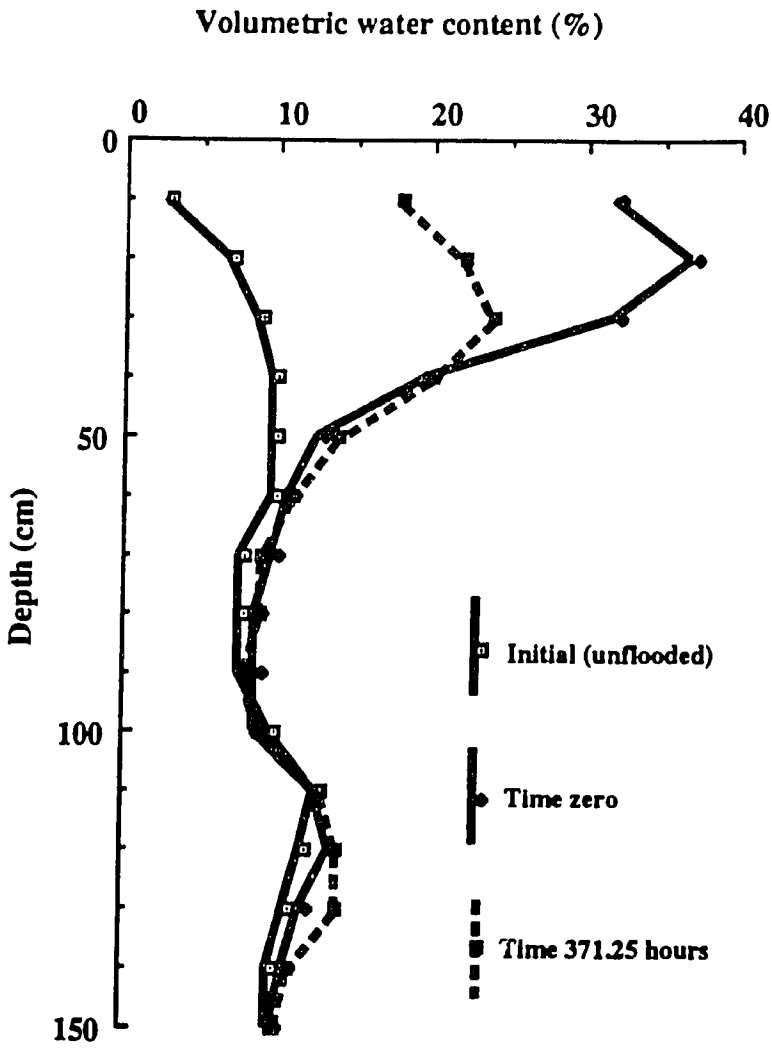

Figure E1. Initial and final soil moisture profile during free internal drainage.

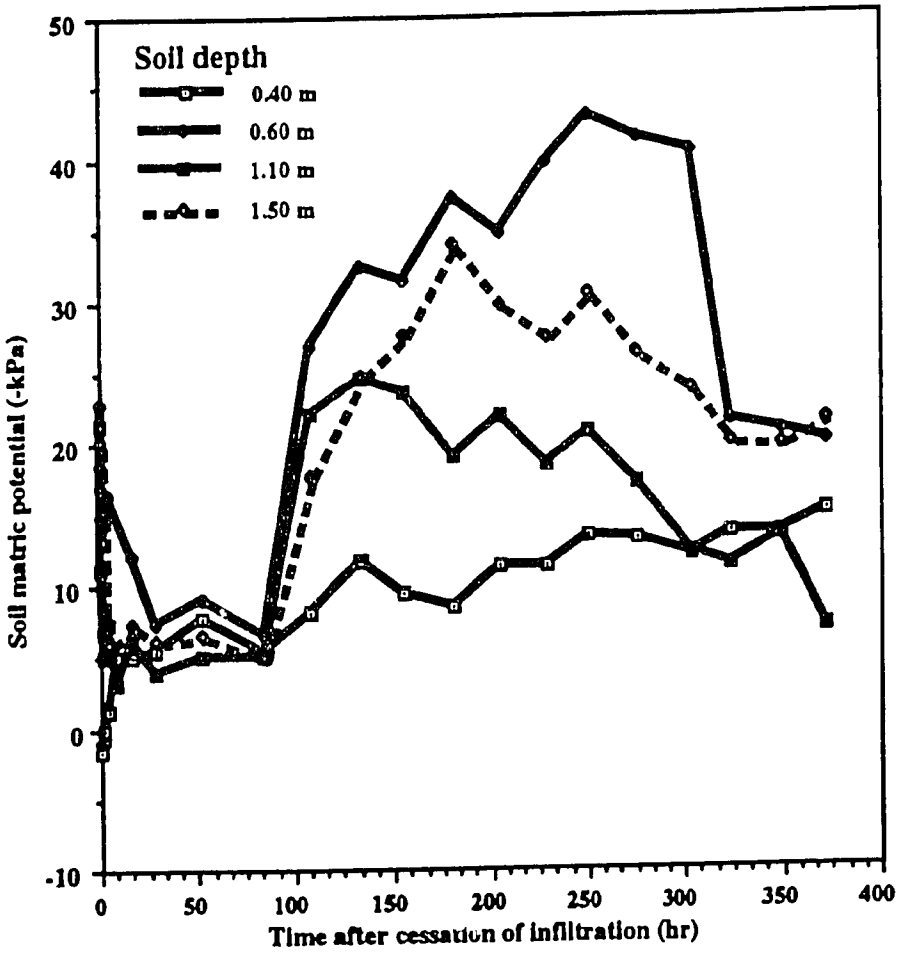

Figure E2. Dynamic of soil matrix potential at the experiment sites during free internal drainage

VITA

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