Simulation of water-limited millet production and use of METEOSAT-derived precipitation data for Niger

a report prepared at the request of the European Communities

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15a Yan Ying. 1986. A simulation model for dry matter production of maize based on gas exchange measurements of the whole canopy.

16 C. Rappoldt. 1988. Decoding Quantimet 920 binary image files.

17 D.W.G. van Kraalingen. 1989. A three-dimensional light model for crop canopies.

18 C.Rappoldt and D.W.G. van Kraalingen. 1989. FORTRAN utility library TTUTIL.

19 G. de Moed.1990. Biologische bestrijding van floridamot, spodoptera exigua, met spodoptera exigua nuclear polyhedrosis virus.

20 A. Jansen. 1991. Effecten van temperatuur op drogestofverdeling en ontwikkeling van suikerbiet en drie eenjarige onkruiden.

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SUMMARY

The project *Agrometeorological advises and agro-ecological classification for Sahel countries* aims at the development of an applicable methodology for the simulation of millet growth and development and an agro-ecological characterization of Niger for millet production. The agro-ecological characterization comprised a long-term analysis of the potentials for millet production at 10 locations throughout the millet cultivation areas in Niger, as determined by the physical environment and its temporal and spatial variability.

Simulation of water-limited millet production was attained by applying the crop growth simulation model WOFOST, using meteorological, soil and crop data. For the *meteorological data* use was made of *(1)* measured daily precipitation data; *(2)* monthly averages of measured daily average temperature; and *(3)* monthly averages of daily global radiation, free water surface evaporation, soil evaporation and crop transpiration. Daily global radiation was derived from daily sunshine duration - applying the Ångström formula - on its turn derived from correlations with measured daily precipitation. Daily evaporation and transpiration - calculated applying the Penman formula - were derived from correlations with measured daily average temperature. For the *soil data* use was made of a standard transmission zone permeability and a soil moisture retention relationship of a medium sandy soil. For the *crop data* use was made of standard millet characteristics, whereas a precipitation incidence-dependent sowing strategy was applied. Under the specific conditions of Niger the simulation model showed a variable but considerable sensitivity to changes in precipitation and global radiation.

The simulations for long-term water-limited millet storage organ production resulted for Tillabéry in 1,394 kg $dm.ha^{-1}$ (31 years); for Niamey 1,580 (42); for Gaya 1,574 (17); for Tahoua 1,579 (32); for Birni N'Konni 1,605 (36); for Maradi 1,499 (29); for Zinder 1,439 (40); for Magaria 1,642 (7); for Maïne Soroa 1,346 (33); and for N'Guigmi 537 (24). A considerable difference between simulated water-limited millet yields and the lower actual millet yields was observed. The simulated standard deviations and coefficient of variations showed much variation among locations. Only weak correlations between independent variables precipitation and sowing date and dependent variables simulated storage organ and above ground dry matter yields were found.

METEOSAT images could well be used to derive more precise data on precipitation and global radiation. The procedure to calibrate the data - the conversion of pixel count values into temperature values - and the procedure to convert the information on the METEOSAT images into precipitation - the cold cloud duration method - are considered. The resulting precipitation pattern for Niger for the month of June, 1991, still needs verification.

1. INTRODUCTION

In the region of the Sahelian belt millet is grown as a staple crop. Actual millet productivity is low, mainly as a result of low soil fertility and low and erratic precipitation (Hoogmoed & Klaij, 1988; Sivakumar, 1988; Stoop, 1987) and limited and untimely cultural practices (Hoogmoed & Klaij, 1988). The rapidly declining per capita food production in this region urges to give full attention to increasing crop productivity. Improvement of millet productivity in the Sahelian region now is subject to research at ICRISAT Sahelian Center based near Niamey, Niger.

The improvement of millet crop husbandry requires knowledge of the relationships between millet performance and its physical environment. The modelling of these crop-environment relationships could be a first step towards the modelling and analysis of the effect of agronomic millet management practices on millet yield.

The project *Agrometeorological advises and agro-ecological classification for Sahel countries* is a cooperative undertaking of Ce.S.I.A. of the Accademia dei Georgofili in Florence, Italy; I.A.T.A. of the C.N.R. in Florence, Italy; the Institut für Meteorologie of the Freie Universität in Berlin, Germany; the Department of Meteorology of the University of Reading in Reading, United Kingdom; the Department of Meteorology of the Wageningen Agricultural University in Wageningen, the Netherlands; the Department of Theoretical Production Ecology of the Wageningen Agricultural University in Wageningen, the Netherlands; and the Meteorological Service of Niger in Niamey, Niger. The project was sponsored by the European Communities in the framework of the EC-STD2 programme, under contract number TS2-A-254-C. The project aims at the development of an applicable methodology for the simulation of millet growth and development and an agro-ecological characterization of Niger for millet production. The agro-ecological characterization comprises an analysis of the potentials for millet production throughout Niger as determined by the physical environment and its temporal and spatial variability.

At the Wageningen Agricultural University two aspects of the project were studied. First the Department of Theoretical Production Ecology[1] (B.O.M. Dirks) accounted for the *refinement and adaptation of a millet growth simulation model* and the application to an *agro-ecological classification of Niger for millet production.* It is shown that precipitation is an important parameter in this model. The *derivation of precipitation data from METEOSAT images* was studied at the Department of Meteorology[2] (H.A.R. de Bruin and M.J.M. Saraber). The results of these two studies are presented in this report.

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2. AN AGRO-ECOLOGICAL CLASSIFICATION OF NIGER FOR MILLET PRODUCTION

2.1 INTRODUCTION

Crop growth simulation models can be used for two distinct objectives: *(1)* analysis of crop growth from its underlying processes as influenced by its environment, using detailed explanatory simulation models, and *(2)* analysis of crop growth potentials as determined by the spatial and temporal environmental variability, using simplified, less sensitive simulation models. This study aims at an agro-ecological characterization of Niger for millet production, analyzing the potentials for millet production under rainfed conditions throughout Niger. It will be discussed to which extent the applied millet growth simulation model could be used within an agrometeorological expert system.

2.2 MILLET PRODUCTIVITY IN NIGER - AN OUTLINE

2.2.1 Niger - the physical environment

General information about the physical environment, history, people and economy of the republic of Niger is given by Bernus & Hamidou (1980). Located in the Sahelian and Sudano-Sahelian zone the republic of Niger is subject to highly variable environmental conditions. Rainfall is distributed unevenly throughout the year and is concentrated in one rainy season. As a result of the shifting of the Intertropical Convergence Zone northward from May and again southward from September the rainy season starts earlier and ends later in the south of the country. As a result the rainy season varies from 5 months in the south to 2 months in the north of Niger (Raulin, 1976). Figure 1 shows the strong north-south gradient of the average rainfall distribution in Niger. Especially the start of the rainy season shows an extreme variation throughout the years. Sivakumar (1988) found a strong association between the start of the rainy season and the total length of the rainy season, and hence total seasonal rainfall, which is shown in Figure 2. Annex A gives long-term monthly rainfall averages for 16 locations throughout Niger (Figure 3). Yearly averages for these locations vary between 17 mm at Bilma and 825 mm at Gaya, with standard deviations of 15 and 147 mm respectively.

The course of the temperature throughout the year is relatively moderate, due to the occurrence of the rainy season during summer. Figure 4 shows the course of the precipitation and the average day temperature at Niamey-Airport, in 1986 and 1987. The temperature profile is characterized by a dip during the wettest part of the year.

The degree of soil formation is mainly determined by the climate. Soil evolution in the north of the country, above the 200 mm isohyet, is considerably limited by the harsh climatic conditions: rainfall is extremely low, the variation in temperature is high, whereas vegetation is absent. Eolian sands and rocks are dominating. The soils south of the 200 mm isohyet are characterized by a larger degree of

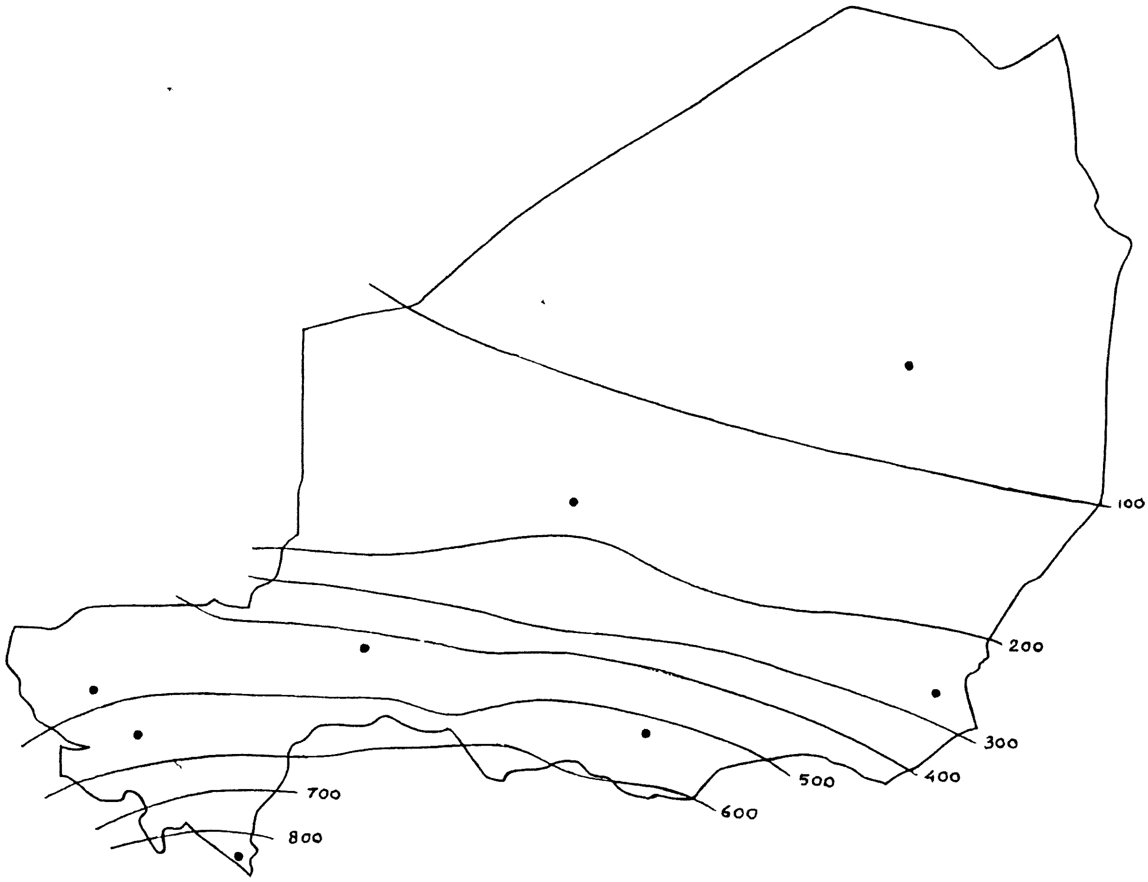


Figure 1. Long-term isohyets (mm precipitation) in Niger. Source: Morel (1980).

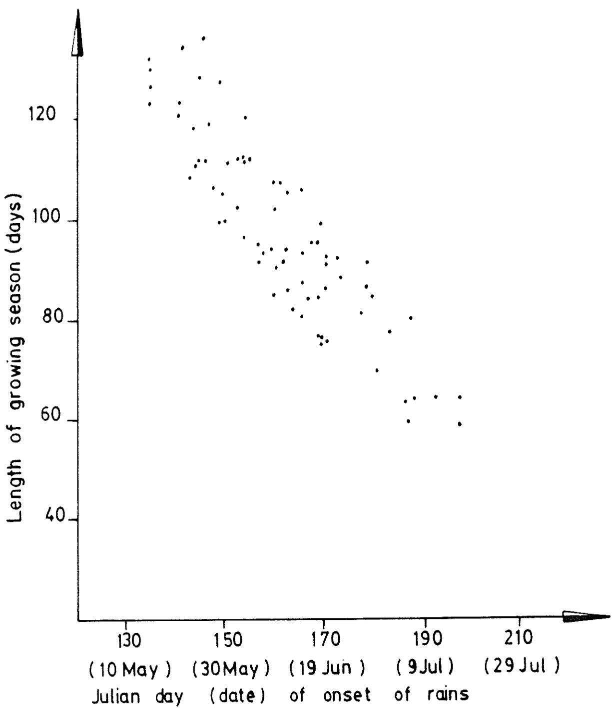


Figure 2. Length of growing season at Niamey as related to the date of onset of rains. Source: Sivakumar (1988).

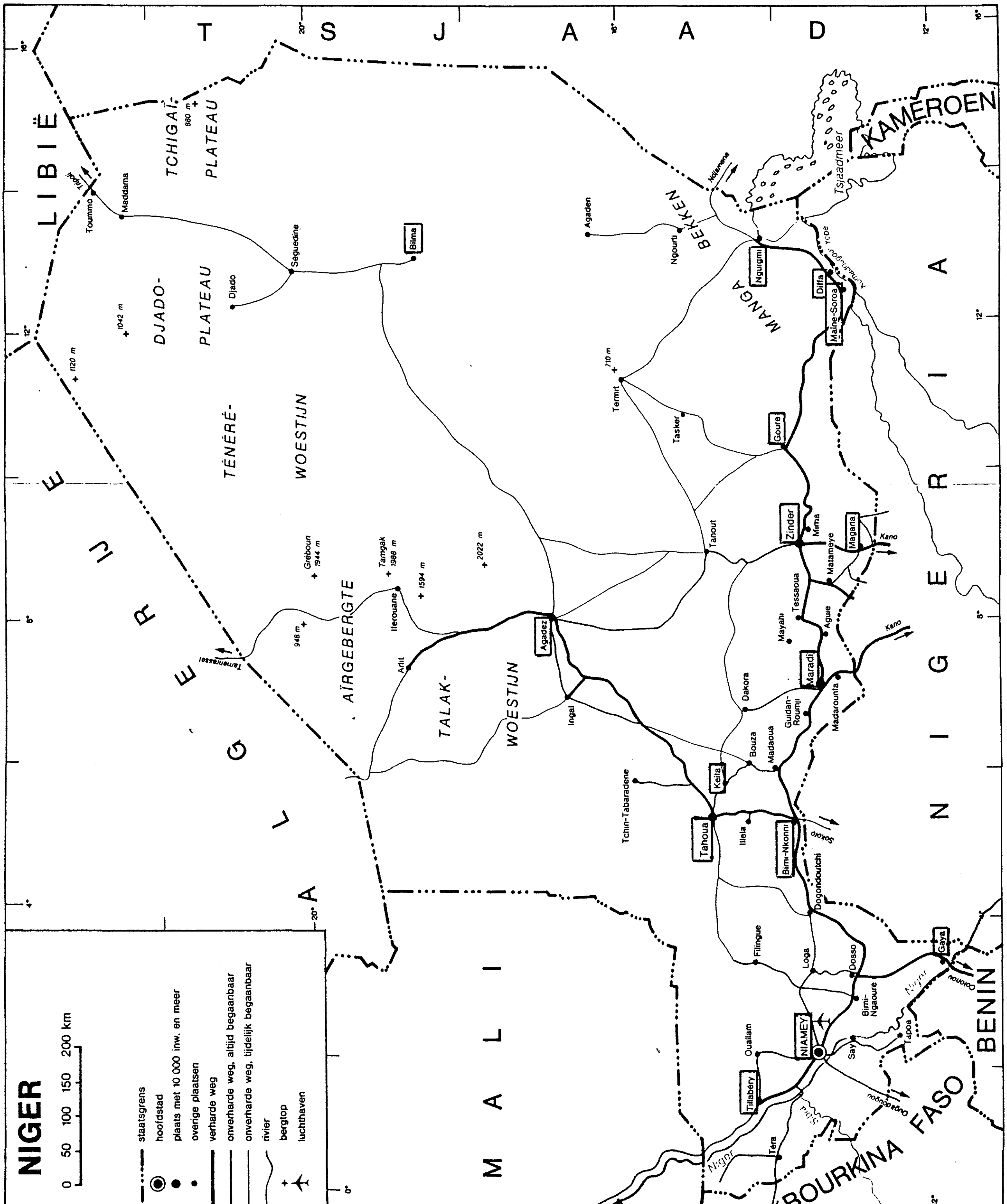
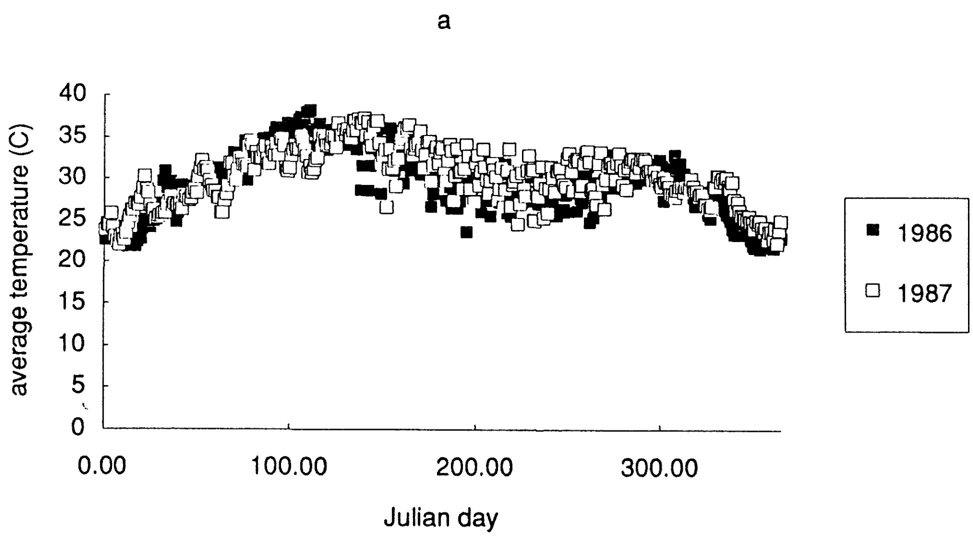


Figure 3. Topographical map of Niger. Locations for which meteorological data were available and which are referred to in the text are indicated by boxes. Source: Van Dijk & Bremmers (1987).



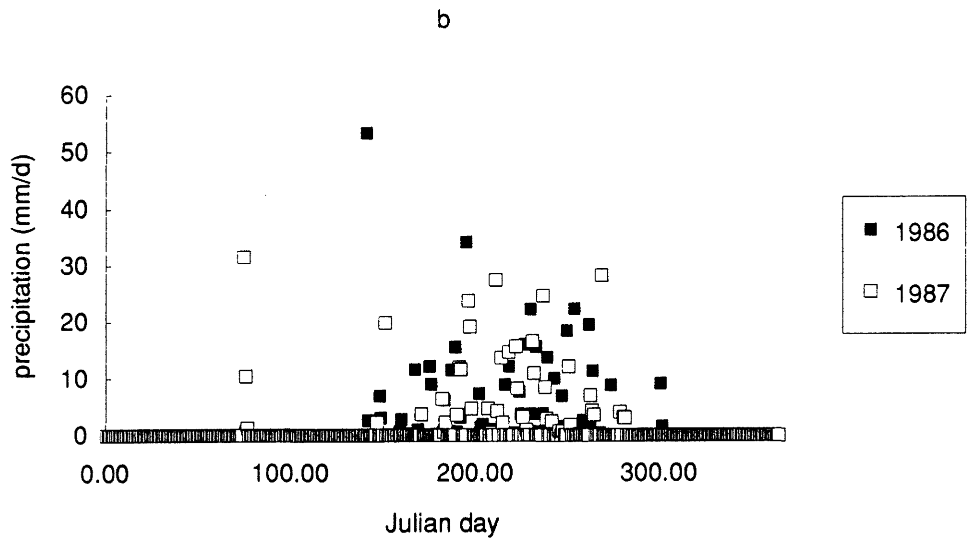


Figure 4. Daily average temperature (a) and precipitation (b) at Niamey during 1986 and 1987.

evolution. Between the 200 and 400 mm isohyet brown-red soils on eolian sand are dominating, well permeable, with a depth of 1 to 1.5 m and strongly evolved organic matter in the upper horizont. More evolved, however, are the tropical ferrous soils, occuring south of the 400 mm isohyet, with a much faster decomposing organic matter. The tropical ferrous soils are rather poor, but, due to its sandy texture, easy to till. Information about the distribution of the different soil types over Niger is given by Michel (1980).

2.2.2 Niger - millet production

Millet is the general name for several species grown in this area, such as *Pennisetum glaucum* (L.) R.Br. (Hoogmoed & Klaij, 1990; Sivakumar, 1990), *Pennisetum americanum* (Van Staveren &

Stoop, 1985) and *Pennisetum typhoides* S. & H. (Azam- Ali *et al.*, 1984; Gregory & Squire, 1979; Ong & Everard, 1979). This diversity in species likely reflects the diffuse descent of the mainly local varieties. Millet has not been subject to long-term crop improvement efforts.

In Niger 90% of the cultivated area is used for the production of millet and sorghum. In general millet is grown on light-textured soils, mostly in association with cowpea or sorghum.Statistics of the Ministry of Agriculture and Animal Husbandry of Niger show for the period from 1979 a continuous increase in cultivated millet area, with a temporary decrease in 1983 and 1984. In 1990 1,421,212 ha (27.8%) of agricultural land was used for millet production solely, 581,346 ha (11.4%) for millet production in combination with cowpea, and 1,383,931 ha (27.1%) for millet production in combination with cowpea and sorghum.

Adamou (1980) mentioned an average millet yield of approximately 400 kg grains.ha^{-1}, whereas a considerable variation is observed, both in time and space. Table 1 indicates the average millet yields for the different regions of Niger in 1990. Distinction is made between cultures of millet only, millet in combination with cowpea, millet in combination with sorghum, and millet in combination with cowpea and sorghum. Values are much lower than the mean value mentioned by Adamou (1980), and taking into account a reasonable variability values would in many cases approach to zero. A considerable variation was observed between the different regions in Niger, whereas the millet yields also strongly depended on the cropping system. For the total of Niger the combined cultivation of millet and cowpea resulted in the highest millet yield, however this effect was not obvious for all locations.

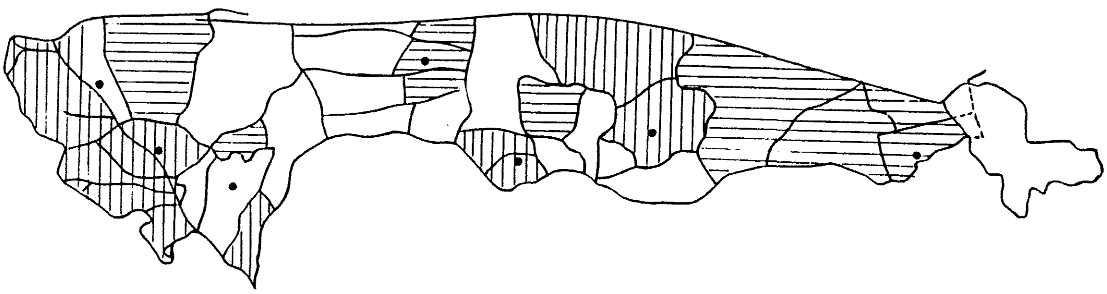


Figure 5. Spatial variability of sorghum and millet yields throughout Niger: below average (horizontal lines), average (open space) and above average (vertical lines) yields. Source: Adamou (1981).

Figure 5 gives a qualitative impression of the *spatial variability* in millet and sorghum yields. An example of the *temporal variability* in millet yields was given by Sivakumar (1990), contrasting a relatively wet year with an early start of the rainy season, 1986, and a relatively dry year with a late start of the rainy season, 1987, yielding 1,210 and 810 kg grains.ha^{-1}, respectively, at ICRISAT Sahelian Center at Sadoré, 40 km south of Niamey.

Table 1. Average millet yields for the different regions in Niger for the year 1990, distinguishing between production of millet solely, and in combination with cowpea and/or sorghum. Source data: Ministry of Agriculture and Animal Husbandry, Direction of Agriculture, Agricultural Statistics Service, Niger (1991).

region	millet ($kg.ha^{-1}$)	millet-cowpea ($kg.ha^{-1}$)	millet-cowpea-sorghum ($kg.ha^{-1}$)	millet-sorghum ($kg.ha^{-1}$)
Diffa	358	233	-	158
Dosso	290	321	357	412
Maradi	288	295	311	240
Tahoua	174	203	218	194
Tillabéry	211	267	299	191
Zinder	141	206	187	104
Total Niger	227	266	249	216

Figures 6 and 7 show the total above ground dry matter and the leaf area index (m^2 leaf surface per m^2 soil surface), respectively, of 2 millet varieties, HKP and CIVT, grown at Agrhymet Centre at Niamey during the 1990 season. The experiment was carried out by I.A.T.A.-C.N.R. CIVT values were derived from one experimental plot, whereas HKP values are the mean of 2 experimental plots. The values found are of the same order of magnitude as reported by Sivakumar (1990).

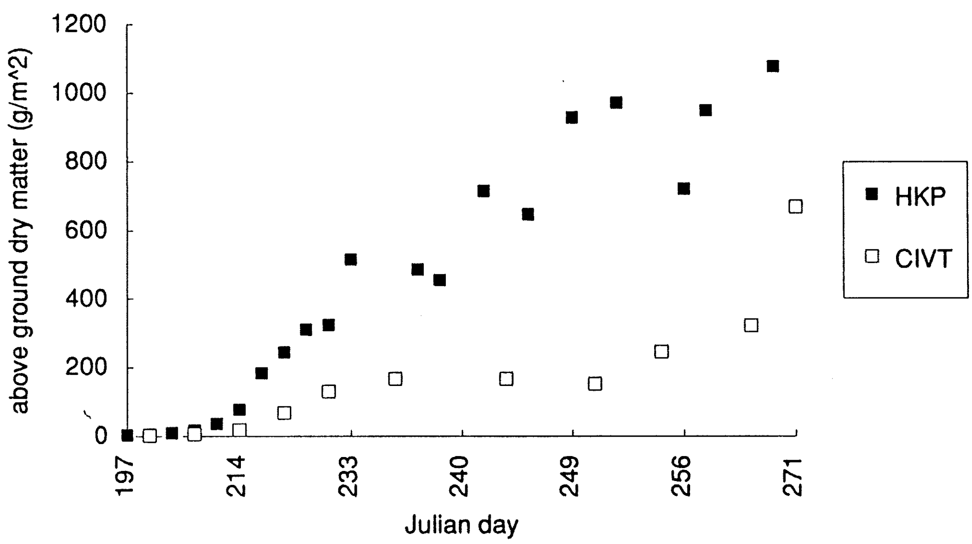


Figure 6. Total above ground dry matter yield of millet cultivars HKP and CIVT, grown at Agrhymet Centre, Niamey, during the 1990 season. HKP values are averages of two experimental plots. CIVT values are single experimental plot values.

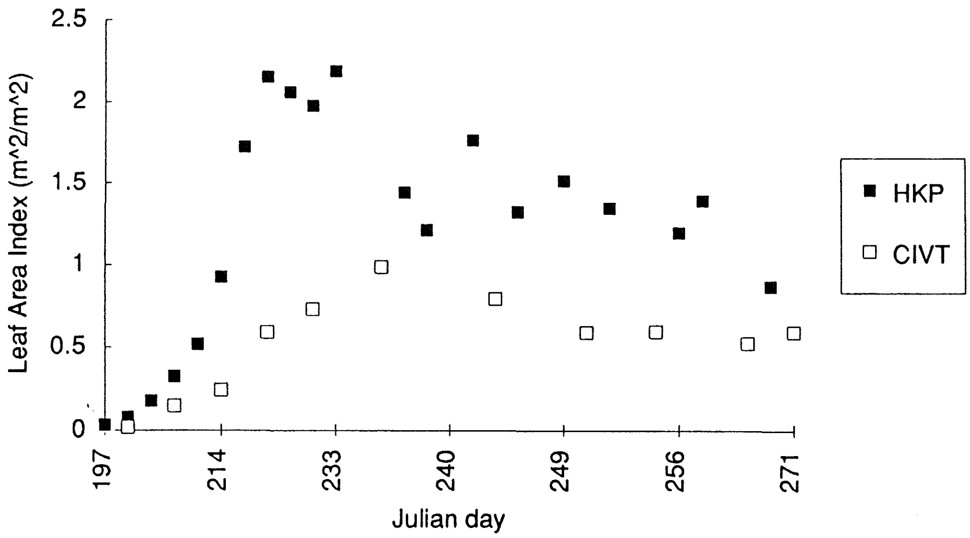


Figure 7. Leaf Area Index of millet cultivars HKP and CIVT, grown at Agrhymet Centre, Niamey, during the 1990 season. HKP values are averages of two experimental plots. CIVT values are single experimental plot values.

2.3 AGRO-ECOLOGICAL CLASSIFICATION - THE METHODOLOGY

Agro-ecological classification implies limited land evaluation to determine production potentials for a well-defined set of environmental conditions. This study aims the determination of the *production* that could be attained at *water limitation* only. At this production level production is mainly determined by temperature (mainly influencing crop development and to a lesser degree crop growth), radiation (influencing crop growth), crop characteristics (influencing crop development and crop growth) and water availability (limiting crop growth during at least a part of the growing season). It therefore assumes ample availability of nutrients and the absence of the interference of weeds, pests and diseases.

For these conditions an agro-ecological classification takes into account the temporal and spatial variations of meteorological parameters, and of meteorological and physical soil parameters, respectively, and their effects on crop growth processes. Especially under highly variable environmental conditions, like the Sahel, this approach is likely to give pronouncedly different results as compared to the use of long-term averages, due to the distribution of crop performance over a wide range of values and resulting consequences for individual years, and, more in general, due to the non-linear response of crop and crop growth simulation model to changes in meteorological and soil variable values.

2.3.1 The crop growth simulation model

Though a variety of millet growth simulation models exist the final choice was made between two models only, the one described by Van Duivenbooden & Cissé (1989), and the one described by Van Diepen *et al.* (1989), the latter known as WOFOST. Both crop growth simulation models are dynamic, explanatory models (Penning de Vries *et al.*, 1989) of a relatively transparent structure, resulting in the possibility to make the model assumptions explicit. Both crop growth simulation models knew recent application in the direct surroundings of the Centre for Agrobiological Research (CABO-DLO) and the Department of Theoretical Production Ecology of the Wageningen Agricultural University, in Wageningen, which in principle could allow a more efficient use of these models.

Whereas both models in principle are of a similar origin, they mainly differ with respect to the degree of detail to which certain processes have been incorporated into the models. In this respect WOFOST is to a much larger extent a so-called summary model (Penning de Vries *et al.*, 1989) than the model described by Van Duivenbooden & Cissé (1989). In WOFOST several processes are of a descriptive nature at a higher level of integration (Penning de Vries *et al.*, 1989) than in the model described by Van Duivenbooden & Cissé (1989). Whereas the incorporation of detailed processes is useful if these processes are subject to research, they are probably superfluous in case of a more global analysis, like an agro-ecological classification. Detailed processes in a crop growth simulation model, whether they are physiological responses to environmental conditions, or soil physical processes, or soil chemical and biological processes, *(1)* constitute an additional source of uncertainty, *(2)* make the model less robust, i.e. more sensitive to environmental variations, and *(3)* require considerably more input information which is not always available. For these reasons it was decided to apply WOFOST, version 4.1. A general description of WOFOST is provided by Van Diepen *et al.* (1989). The principles of WOFOST are described in detail by Van Keulen & Wolf (1986), whereas detailed technical information is given by Van Diepen *et al.* (1988).

2.3.2 Input data

In principle WOFOST simulates potential crop production (determined by temperature, radiation and crop characteristics), water-limited crop production (determined by temperature, radiation, crop characteristics and water availability), nutrient-limited crop production (determined by temperature, radiation, crop characteristics and nutrient availability) and water- and nutrient-limited crop production (determined by temperature, radiation, crop characteristics and water- and nutrient-availability).

For both nutrient-limited and water- and nutrient-limited crop production WOFOST requires information on the relationship between crop performance and nutrient availability, the relationship between nutrient availability and nutrient application, and mineral content of the several plant organs. As these quantitative relationships are highly dependent on cultivar, location and year, and hence cannot even be properly established by extensive experimentation, the production level of nutrient-limitation was omitted from the simulations. In case of a combined water- and nutrient-limitation WOFOST accounts for the effect on crop performance by simply applying the highest reduction factor to the gross assimilation rate. Wolf (pers.comm.) suggested to multiply the reduction factors of both water- and nutrient-limitation to obtain a new reduction factor. None of these approaches, however, does account for the complex interaction between water- and nutrient-availability.

For the environmental conditions of Niger the simulation of potential production requires environmental information on *average day temperature* and *incident radiation*, whereas the simulation of water-limited production requires additional environmental information on precipitation, potential evapotranspiration and physical soil characteristics, determining the water balance.

In WOFOST potential evapo(transpi)ration rates from a free water surface, a bare soil surface and a crop canopy are calculated following the analysis by Penman (Van Diepen *et al.*, 1988), as used by Frère & Popov (1979). For this calculation procedure use is made of the *minimum and maximum temperature*, *wind speed* and *vapor pressure*.

Under the conditions of the absence of the influence of groundwater on the waterbalance of the rooted soil layer, which was assumed for the calculations for Niger, the physical soil characteristics which determine the soil water balance in WOFOST are the *transmission zone permeability*, determining the infiltration rate of water into the soil and the rate of water loss beyond rooting depth, and the *relationship between the soil moisture tension and the volumetric soil moisture content.*

Though in principle WOFOST is able to use daily meteorological data, the necessity to do so depends on the environmental conditions. Whereas, due to the high relative variation and the pronounced effect on crop performance, daily precipitation data are always required, this does not apply to the other meteorological variables, where even monthly averages could provide satisfactory results (Rötter, pers.comm.). Nevertheless it should be realized that for all meteorological variables there is a non-linear relationship with crop response, which means that in case of a relatively high within-month variation the simulation results may differ considerably for different time resolutions.

For the agro-ecological classification of Niger use was made of daily precipitation data, whereas monthly values were used for the other meteorological variables. For a few years a more detailed analysis was made by simulation of millet growth on basis of daily meteorological data.

2.3.3 output data

WOFOST is a dynamic, explanatory simulation model, which means that the model is based on the interactions between environment and processes determining crop growth and development. As a result of which all intermediate calculated variables can be retrieved. For the purpose of the agro-ecological classification the relevant parameters are mainly constituted by crop morphological parameters (weights of the different plant organs, leaf area) and water use (transpiration, evaporation). Though for most meteorological variables monthly averages were used WOFOST calculates with time increments of one day, simply by interpolating between the average values, and simulation results can also be retrieved with a time resolution of one day.

2.3.4 the assumptions

In fact, the model assumptions are made explicit through the model structure. WOFOST is an algorithm which comprises the quantitative relationships between the main processes determining crop growth and development, and the environment. However, the complexity of the crop processes, of the feedback relationships within the crop, and of its interactions with the environment is too high to have these included in a crop growth simulation model, or even to understand. Crop growth and development is calculated for specifically defined environmental conditions, which may not be found in reality, and for clearly defined relationships between environment and crop response, which in such form may not be valid for all environmental conditions.

Neither the production situation of potential production, nor of water-limited production, assuming ample nutrient availability, is likely to occur, because *(1)* nutrient limitation is a general phenomenon, even under intensive agricultural practices as found in Western Europe, and *(2)* the absence of pests, diseases and weeds generally is unrealistic, even if hardly or not at all visible. Furthermore the simulation of nutrient-limited production assumes clear quantitative relationships between several soil chemical and soil biological processes and crop growth, whereas these relationships may not be valid for all environmental conditions or may be of a less pronounced or a more variable nature. Even measured meteorological and soil variables may not represent the actual environment, due to measurement errors, differences between the resolution of the simulations and of the measurements, and due to spatial and temporal variability.

Therefore simulation results should be considered as a survey into certain production situations, whereas these production situations represent boundary situations. In fact, the simulations for these boundary situations represent the potentials for the specific production situations. Therefore, an agro-ecological classification is, irrespective of the considered production situation, a survey into the potentials of a certain region.

2.4 THE METEOROLOGICAL DATA

To determine the potentials of the production situation of water-limited production throughout Niger WOFOST in principle requires meteorological data on precipitation, incident radiation, average day temperature and potential evapo(transpi)ration (section 2.3.2). In the following sections it will be accounted for which sources were used to obtain meteorological information, and, if necessary, which methods were applied to make this information compatible with the requirements of WOFOST.

In addition to the low resolution meteorological data mentioned in the following daily relevant meteorological data were available for Niamey-Airport and Tillabéry, for 1986 and 1987, on sunshine duration, precipitation, minimum and maximum air temperature, average wind speed and vapor pressure. These daily meteorological data were provided by De Bruin (pers.comm.) from the Meteorological Service (ASECNA - Direction de l'Exploitation Météorologique) of Niger, based at Niamey.

2.4.1 precipitation

Due to the extreme variability in precipitation in Niger - rainfall events are mostly clustered in a few days - the simulation of rainfed millet growth in Niger requires daily precipitation data. Monthly averages could on the one hand result in an overestimation of the evaporation from a - continuously wetted - bare soil surface, and on the other hand underestimate the runoff from the soil surface before infiltration and drainage beyond the rooting zone after infiltration. Furthermore there is a non-linear relationship between the soil moisture content and the soil moisture tension, and hence soil moisture availability.

Daily precipitation data were provided by De Bruin (pers.comm.) from the Meteorological Service (ASECNA - Direction de l'Exploitation Météorologique) of Niger, based at Niamey. The available data covered 16 locations throughout Niger (Figure 3), varying from 10 to 66 years of data per location. Details about these precipitation data are given in annex C.

Monthly precipitation data were provided by the National Climatic Data Center (1991) of the United States Department of Commerce, at Asheville, N.C., United States of America. The available data covered 13 locations throughout Niger (Figure 3), varying from 2 to 67 years of data per location. Details about these precipitation data are given in annex B. The monthly precipitation data were not used as direct input for WOFOST.

2.4.2 temperature

In WOFOST the average day temperature mainly influences the crop development rate. The difference between the daily maximum and minimum temperature influences the wind coefficient in the Penman evaporation calculation, which corrects the evaporative demand of the air to account for the effect of advection of dry air. The temperature difference is a direct measure for this advection (Van Diepen *et al.*, 1988; Frère & Popov, 1979).

Monthly average temperature data were provided by the National Climatic Data Center (1991) of the United States Department of Commerce, at Asheville, N.C., United States of America. The available data covered 13 locations throughout Niger (Figure 3), varying from 2 to 48 years of data per location. Details about these average temperature data are given in annex B.

2.4.3 global radiation

The absorbed global radiation determines the gross photosynthesis rate and, furthermore, is an important component of the energy balance of the leaves. An increase in the absorbed global radiation results in a heating of the leaves and a concomitant increase in transpiration. Therefore, as a meteorological parameter global radiation has a pronounced effect on crop growth, through photosynthesis and available soil moisture.

Direct measurement of global radiation by meteorological stations, however, is not common. Instead, measurements on sunshine duration are regularly made. Sunshine duration encompasses the number of hours that the sun is not covered by clouds, or the number of hours that the recorder is receiving direct radiation. Despite its empirical character the relationship between sunshine duration and global radiation has been subject to extensive research efforts since 1924, when Ångström suggested a linear relationship between both (Rietveld, 1978). Through the years this relationship has obtained the following appearance:

$$R_g = R_A \times \left(a + b \times \frac{n}{N}\right)$$

where R_g is the daily global radiation, R_A is the extra-terrestrial radiation or the Angot value (the shortwave radiation received at the top of the atmosphere), n is the sunshine duration, N is the astronomically determined daylength and a and b are the Ångström coefficients. The ratio of n over N is called the relative sunshine duration. Location- and time-specific R_A and N values can be calculated on a theoretical basis (Van Diepen *et al.*, 1988). Coefficient a is the fraction of R_A reaching the earth's surface on a completely cloud-covered day, and coefficient b is the fraction of R_A absorbed by the clouds on a completely cloud-covered day. Obviously the accuracy of the estimation of R_g depends on the accuracy with which the Ångström coefficients are estimated.

Judging the research efforts in this field, both Ångström coefficients seem to be location- and possibly also time-specific and should be determined empirically. The coefficients usually are not completely complementary (summation equals a value less than 1), because *(1)* radiation is also reflected, throughout the atmosphere, and *(2)* radiation is also absorbed by other absorbing bodies, mainly gases, which do not contribute to the observed variations in sunshine duration. The reflection could progressively decrease the part of R_A available for transmission. Reflection by dispersed clouds, however, could also enhance the downward radiation flux. Whereas the absorption by atmospheric gases implies an additional reduction factor. In literature a wide range of methods is given with different criteria to estimate the Ångström coefficients. Roughly two groups of methods could be distinguished: *(1)* relating the values of the Ångström coefficients to one specific physical phenomenon, and *(2)* relating the values of the Ångström coefficients to latitude, and hence location. The latter group of methods is likely to integrate the effects of different physical phenomena, however, may be generalized more difficultly. The first group of methods seems to have a more general value, however, the fact that all methods seem to give more or less reasonable Ångström coefficient values clearly indicates that a combination of physical phenomena is effectively involved. More geared towards the meteorological principles than to derived phenomena Rietveld (1978) mentions indications that coefficient a is to at least some degree governed by the height of the clouds: high clouds are drier than low clouds, and, therefore, absorb less radiation, resulting in a higher a value.

At least in first instance, the temporal and spatial complexity of the relationship between global radiation and sunshine duration seems to justify a robust estimation method for the Ångström coefficients. Because for Niger only sunshine duration data were available a comparison was made between 5 different methods for estimating the Ångström coefficients: *(1)* the approach described by Frère & Popov (1979), on a global scale only distinguishing between 3 different environments, and therefore 3 sets of Ångström coefficients; *(2)* the approach used by the Joint Research Centre of the European Communities (Wolf, pers.comm.), relating the values of the Ångström coefficients to the latitude; *(3)* the approach described by Glover & McCulloch (1958), relating the values of the Ångström formula to the latitude; *(4)* the approach described by Rietveld (1978), relating the values of the Ångström coefficients to the mean relative sunshine duration; and *(5)* the approach described by Gopinathan & Baholo (1987), relating the values of the Ångström coefficients to the altitude. The performance of the different approaches was compared by using simultaneously measured values on global radiation and sunshine duration. Data for the following meteorological stations and years were kindly provided by Nonhebel (pers.comm.) and De Bruin (Niamey; pers.comm.): Avignon, France (1972), Bremen, Germany (1980), Nancy, France (1980), Niamey, Niger (1985), Roskilde, Denmark (1988), Rothamsted, United Kingdom (year unknown), Silstrup, Denmark (1990), Tel Hadya, Syria (year unknown), and Wageningen, the Netherlands (1987). Information on these locations of relevance to the estimation of the Ångström coefficients is found in annex D.

Table 2 gives the Ångström coefficients a and b estimated following the 5 different methods, whereas Table 3 gives the Ångström coefficients as calculated using linear regression analysis with the relative sunshine duration as independent variable and the ratio of measured global radiation over the Angot value as dependent variable. It shows that considerable differences exist between the estimates. In most cases the method used by the Joint Research Center (1991) resulted in the highest estimates for the a coefficient, whereas the approach of Frère & Popov (1979) generally resulted in the lowest estimates. The approach of Gopinathan & Baholo (1987) resulted in the highest estimates for the b coefficient, whereas Glover & McCulloch (1958) gave the lowest estimate.

Table 3 shows considerable deviations of the calculated Ångström coefficient values from the estimated values. For Niamey the calculated slope of the curve was less steep than estimated following most methods. Furthermore considerable differences exist in the course of the relationship between n/N and R_g/R_A between the different radiation ranges. With the exception of Niamey all locations showed for the upper half of the radiation range a less steep curve and a lower correlation coefficient than for the lower half of the radiation range. The less steep curve could suggest a non-linear relationship between both variables: the fraction absorbed radiation increases less than proportionally with the fraction cloudiness. However, the increasing variability with increasing cloudiness would not allow such a conclusion. This increasing variability may find its cause in differences in distribution of the cloudiness over the day. The temporal distribution of the occurrence of clouds over the day strongly affects the relationship between n/N and R_g/R_A (Yeboah-Amankwah & Agyeman, 1990). By not taking into account a weighed cloudiness, where clouds in the early morning and in the late afternoon contribute less to the absorption of the daily R_A than clouds around noon, an increasing variation with increasing cloudiness is, even if only statistically, obvious.

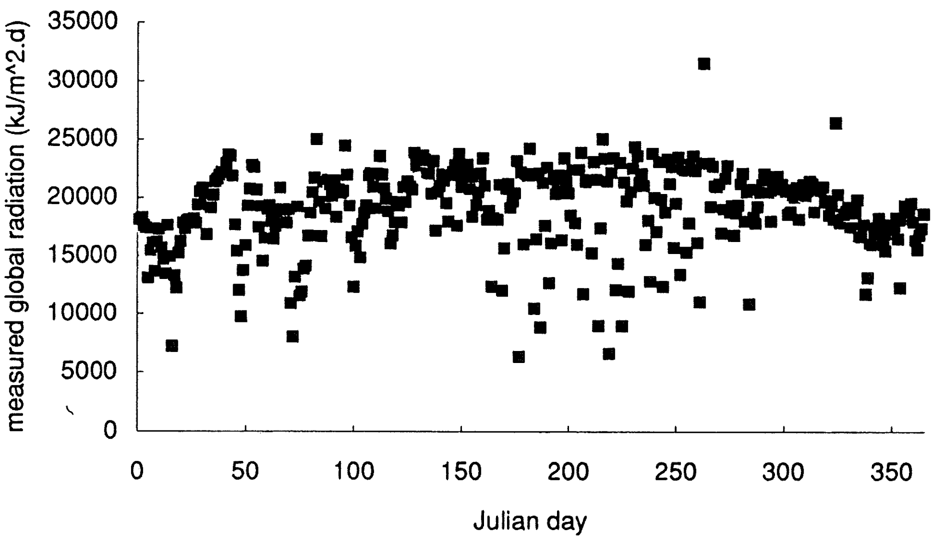


Figure 8. Daily measured global radiation at Niamey during 1985.

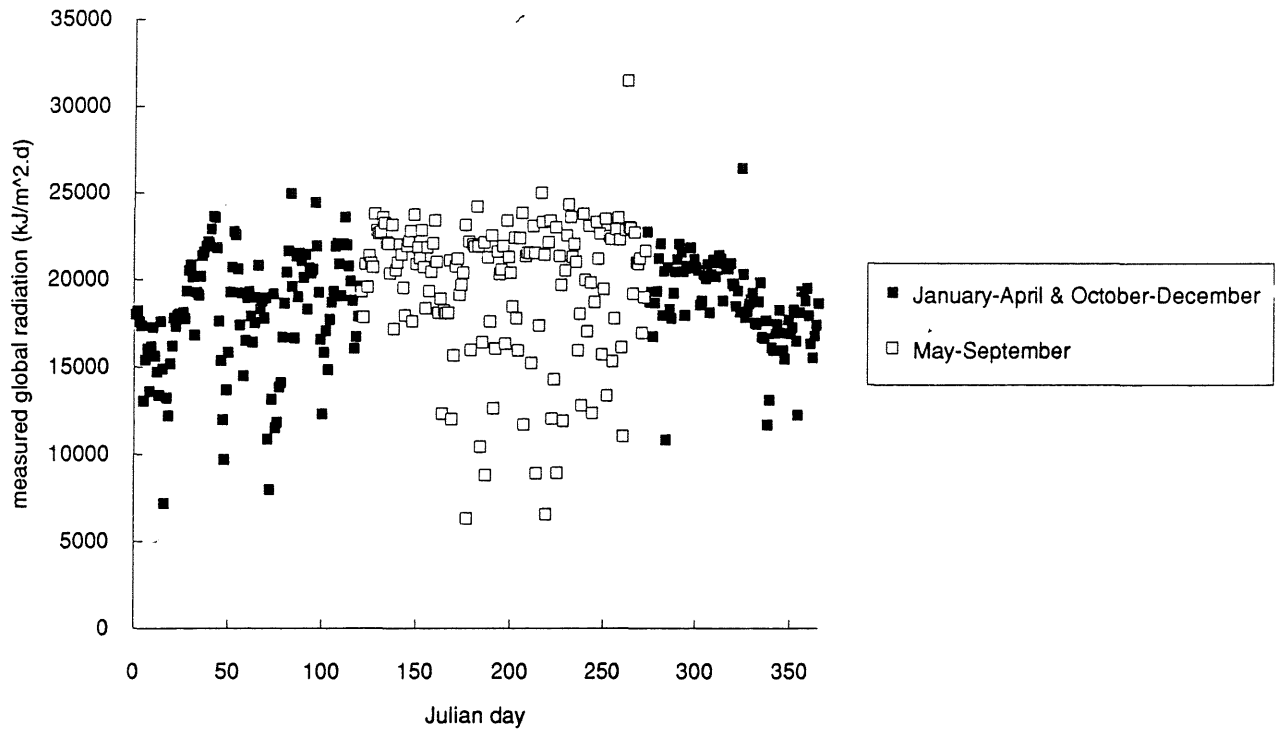


Figure 9. Daily measured global radiation at Niamey during 1985, during two distinct periods.

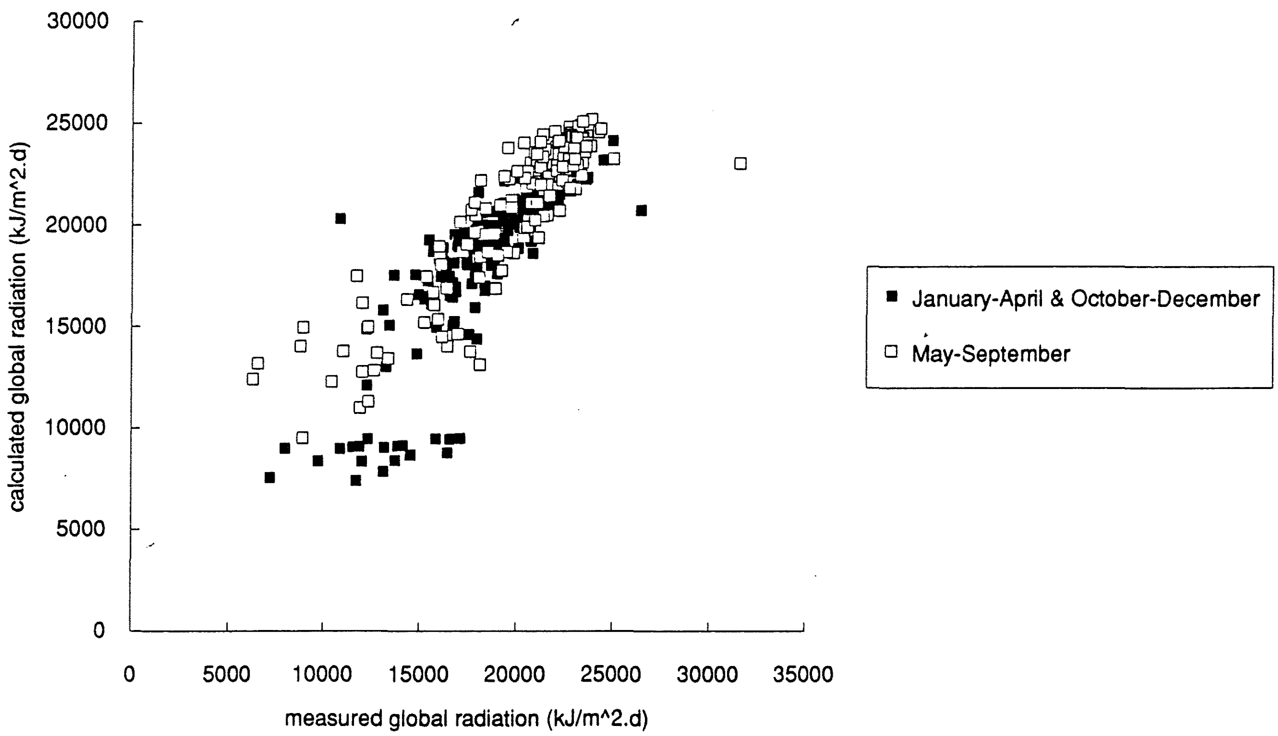


Figure 10. Relation between daily measured global radiation and daily global radiation calculated following the method described by Frère & Popov (1979), at Niamey during 1985, during two distinct periods.

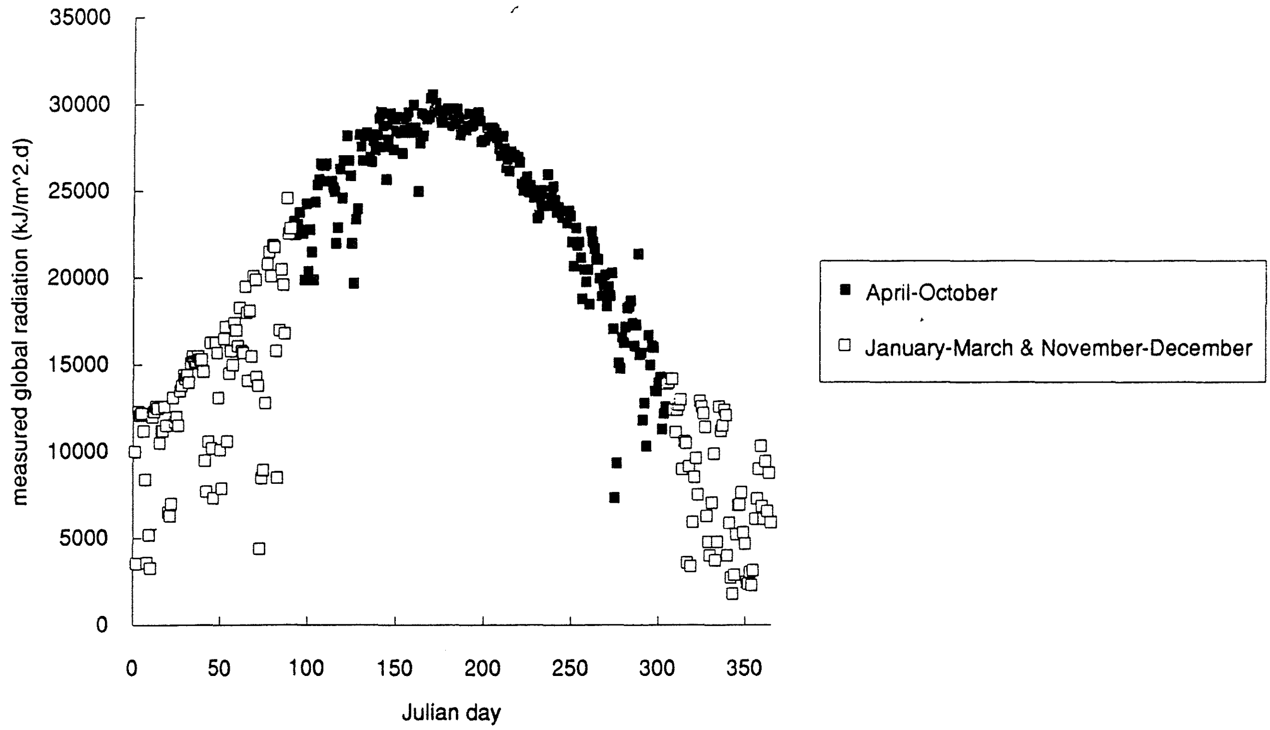


Figure 11. Daily measured global radiation at Tel Hadya, Syria, during an unknown year, during two distinct periods.

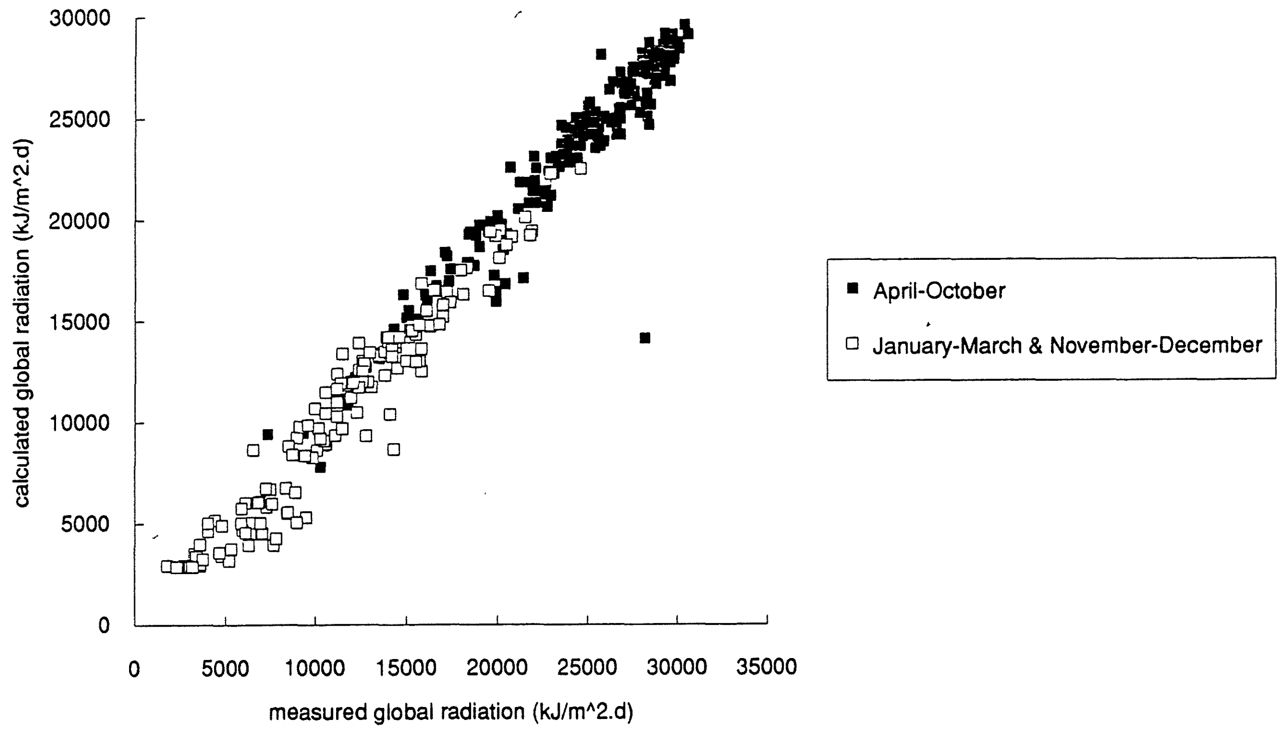


Figure 12. Relation between daily measured global radiation and daily global radiation calculated following the method described by Frère & Popov (1979), at Niamey during an unknown year, during two distinct periods.

Table 2. Values Ångström coefficients a and b for different locations and different years, estimated following different methods: Frère & Popov (1979) (1), Joint Research Center (1991) (2), Glover & McCulloch (1958) (3), Rietveld (1978) (4) and Gopinathan & Baholo (1987) (5).

location and year	Ångström coefficient	method 1	2	3	4	5
Avignon (1972)	a	0.180	0.260	0.209	0.247	0.192
	b	0.550	0.481	0.520	0.509	0.691
Bremen (1980)	a	0.180	0.213	0.175	0.189	0.184
	b	0.550	0.549	0.520	0.595	0.680
Nancy (1980)	a	0.180	0.235	0.191	0.195	0.183
	b	0.550	0.517	0.520	0.583	0.690
Niamey (1985)	a	0.250	0.418	0.282	0.265	0.185
	b	0.450	0.256	0.520	0.496	0.456
Roskilde (1988)	a	0.180	0.199	0.164	0.180	0.184
	b	0.550	0.568	0.520	0.620	0.669
Rothamsted	a	0.180	0.221	0.181	0.183	0.184
	b	0.550	0.537	0.520	0.611	0.669
Silstrup (1980)	a	0.180	0.192	0.158	0.185	0.184
	b	0.550	0.578	0.520	0.606	0.676
Tel Hadya	a	0.180	0.300	0.234	0.278	0.060
	b	0.550	0.424	0.520	0.488	0.991
Wageningen (1987)	a	0.180	0.224	0.183	0.186	0.184
	b	0.550	0.532	0.520	0.603	0.672

Tables 4, 5 and 6 show the relationship between measured global radiation and calculated global radiation using linear regression analysis, with measured global radiation as independent and calculated global radiation as dependent variable, for the whole radiation range, the lower half of the radiation range and the upper half of the radiation range, respectively. For an optimum situation the regression coefficients a and b should have values of 0 an 1, respectively. Figure 8 shows that in 1985 the radiation values at Niamey were spread relatively homogeneously over the year. The annual course of the radiation can be distinguished, whereas the variation within short time intervals, due to the rainy season especially occurring from May up to September, could be attributed to cloud occurrence. This means that the distinction between two radiation ranges does not coincide with a distinction between the dry and the rainy season.

Table 4 shows that the correlation between measured and calculated global radiation generally is reasonable, with the lowest values calculated for Niamey. The relatively low correlation coefficient for Niamey as compared to a seemingly similar location like Tel Hadya is caused by the high radiation level at Niamey, especially during the rainy season (roughly May up to September), resulting in a high variation in absolute terms (Figures 9 and 10). Whereas a comparable relative variation during the rainy season at Tel Hadya (roughly November up to March) results in a small variation in absolute terms, due to the low radiation level during winter (Figures 11 and 12). None of the methods used for estimating the Ångström coefficients proved to be consistently better than the other methods. The

Table 3. Ångström coefficients for different locations and different years, derived using linear regression analysis with the relative sunshine duration (n/N) as independent and the ratio of measured global radiation over the Angot value (R_g/R_A) as dependent variable. The whole radiation range (1), and the lower half (2) and the upper half (3) of the radiation range are distinguished.

location and year	radiation range	range n/N	n	parameter Ångström coefficient a	Ångström coefficient b	correlation coefficient r
Avignon (1972)	1	0.000-0.932	365	0.220	0.549	0.964
	2	0.000-0.650	182	0.205	0.636	0.926
	3	0.650-0.932	183	0.312	0.428	0.688
Bremen (1980)	1	0.000-0.999	366	0.200	0.650	0.938
	2	0.000-0.232	183	0.169	1.004	0.744
	3	0.238-0.999	183	0.277	0.442	0.881
Nancy (1980)	1	0.000-0.947	365	0.208	0.565	0.950
	2	0.000-0.231	182	0.176	1.004	0.812
	3	0.232-0.947	183	0.261	0.478	0.928
Niamey (1985)	1	0.000-0.954	365	0.302	0.350	0.853
	2	0.000-0.775	182	0.318	0.308	0.779
	3	0.776-0.954	183	0.099	0.593	0.570
Roskilde (1988)	1	0.000-0.945	213	0.194	0.632	0.930
	2	0.000-0.241	107	0.158	1.162	0.783
	3	0.257-0.945	106	0.262	0.517	0.873
Rothamsted	1	0.000-0.953	358	0.207	0.562	0.910
	2	0.000-0.245	179	0.179	0.968	0.722
	3	0.246-0.953	179	0.271	0.451	0.803
Silstrup (1990)	1	0.000-0.999	342	0.191	0.609	0.950
	2	0.000-0.361	171	0.161	0.869	0.833
	3	0.362-0.999	171	0.248	0.523	0.896
Tel Hadya	1	0.000-0.990	365	0.252	0.492	0.950
	2	0.000-0.880	183	0.248	0.506	0.939
	3	0.880-0.990	182	0.266	0.473	0.389
Wageningen (1987)	1	0.000-0.951	338	0.164	0.541	0.902
	2	0.000-0.187	169	0.120	1.368	0.731
	3	0.196-0.951	169	0.248	0.403	0.833

relationships varied from location to location, and would probably do so from year to year. A major distinction could be made between on the one hand the method of Gopinathan & Baholo (1987), which seemed to result in an underestimation of the global radiation at low radiation values and an overestimation at high values, and on the other hand the other methods, which went along much more. The initial overestimation of the global radiation following the other methods is gradually compensated by a regression coefficient b of less than 1.

Table 4. Relationship between measured (RAD_m) and calculated global radiation (RAD_c) ($kJ.m^{-2}.d^{-1}$) for the whole radiation range: $RAD_c = a + b \times RAD_m$, for different locations and different years. The Ångström coefficients were calculated following 5 different methods: see Table 2.

location and year	regression coefficient	radiation ($MJ.m^{-2}.d^{-1}$)	method 1	2	3	4	5
Avignon (1972)	n	1.0-31.1	365	365	365	365	365
	a		-162	1,051	297	804	-604
	b		0.938	0.929	0.927	0.955	1.141
	r		0.988	0.987	0.988	0.988	0.987
Bremen (1980)	n	0.3-28.7	366	366	366	366	366
	a		4	355	50	-50	-399
	b		0.935	0.977	0.890	1.004	1.105
	r		0.983	0.983	0.983	0.982	0.980
Nancy (1980)	n	0.8-29.0	365	365	365	365	365
	a		244	1,071	501	309	-238
	b		0.880	0.907	0.858	0.937	1.052
	r		0.979	0.980	0.980	0.979	0.975
Niamey (1985)	n	0.6-31.6	365	365	365	365	365
	a		1,914	9,704	1,996	1,775	-183
	b		0.929	0.586	1.073	1.023	0.928
	r		0.850	0.811	0.849	0.849	0.846
Roskilde (1988)	n	0.3-30.5	213	213	213	213	213
	a		411	584	312	190	80
	b		0.832	0.875	0.778	0.909	0.969
	r		0.974	0.975	0.973	0.971	0.970
Rothamsted	n	0.2-28.7	356	356	356	356	356
	a		372	800	453	247	109
	b		0.864	0.910	0.832	0.936	1.000
	r		0.970	0.973	0.971	0.933	0.966
Silstrup (1990)	n	0.2-29.9	342	342	342	342	342
	a		348	397	217	260	76
	b		0.872	0.920	0.810	0.944	1.025
	r		0.986	0.986	0.985	0.985	0.985
Tel Hadya	n	1.8-30.6	365	365	365	365	365
	a		-417	1,184	201	734	-3,213
	b		0.978	0.927	0.993	0.994	1.480
	r		0.987	0.989	0.988	0.989	0.978
Wageningen (1987)	n	0.1-27.9	338	338	338	338	338
	a		934	1,497	1,037	893	712
	b		0.875	0.918	0.846	0.944	1.018
	r		0.972	0.976	0.973	0.970	0.967

Table 5. Relationship between measured (RAD_m) and calculated global radiation (RAD_c) ($kJ.m^{-2}.d^{-1}$) for the lower half of the radiation range: $RAD_c = a + b \times RAD_m$, for different locations and different years. The Ångström coefficients were calculated following 5 different methods: see Table 2.

location and year	regression coefficient	radiation ($MJ.m^{-2}.d^{-1}$)	method 1	2	3	4	5
Avignon (1972)	n	1.0-13.0	182	182	182	182	182
	a		350	1,539	796	1,309	26.6
	b		0.869	0.859	0.859	0.883	1.058
	r		0.939	0.903	0.932	0.915	0.940
Bremen (1980)	n	0.3-7.7	183	183	183	183	183
	a		380	517	377	389	310
	b		0.883	0.977	0.848	0.940	0.981
	r		0.892	0.878	0.890	0.893	0.900
Nancy (1980)	n	0.8-8.3	182	182	182	182	182
	a		5,642	6,269	5,646	6,448	6,036
	b		0.847	0.960	0.854	0.907	0.955
	r		0.872	0.830	0.860	0.870	0.884
Niamey (1985)	n	6.3-19.3	182	182	182	182	182
	a		2,116	11,421	2,189	1,936	-372
	b		0.906	0.467	1.048	1.002	0.930
	r		0.718	0.637	0.718	0.718	0.716
Roskilde (1988)	n	0.3-10.7	107	107	107	107	107
	a		844	958	757	805	801
	b		0.747	0.803	0.692	0.789	0.826
	r		0.925	0.923	0.926	0.928	0.928
Rothamsted	n	0.2-7.8	178	178	178	178	178
	a		471	745	511	415	350
	b		0.872	0.948	0.847	0.933	0.986
	r		0.844	0.838	0.843	1.000	0.840
Silstrup (1990)	n	0.2-7.9	171	171	171	171	171
	a		553	596	469	550	511
	b		0.836	0.885	0.763	0.890	0.941
	r		0.895	0.894	0.899	0.899	0.904
Tel Hadya	n	1.8-20.0	183	183	183	183	183
	a		310	1,376	742	1,108	-1,300
	b		0.916	0.904	0.945	0.958	1.328
	r		0.966	0.970	0.970	0.971	0.945
Wageningen (1987)	n	0.1-7.5	169	169	169	169	169
	a		1,041	1,344	1,072	1,066	1,027
	b		0.894	1.006	0.882	0.949	0.991
	r		0.903	0.892	0.902	0.904	0.902

Table 6. Relationship between measured (RAD_m) and calculated global radiation (RAD_c) ($kJ.m^{-2}.d^{-1}$) for the upper half of the radiation range: $RAD_c = a + b \times RAD_m$, for different locations and different years. The Ångström coefficients were calculated following 5 different methods: see Table 2.

location and	regression	radiation	method				
year	coefficient	($MJ/m^{-2}.d^{-1}$)	1	2	3	4	5
Avignon (1972)	n	13.0-31.1	183	183	183	183	183
	a		-1,460	201	-822	-169	-2,329
	b		0.995	0.967	0.977	0.998	1.217
	r		0.959	0.967	0.963	0.966	0.956
Bremen (1980)	n	7.7-28.7	183	183	183	183	183
	a		-1,444	-730	-1,273	-1,673	-2,604
	b		1.016	1.037	0.963	1.095	1.228
	r		0.968	0.970	0.968	0.967	0.964
Nancy (1980)	n	8.5-29.0	183	183	183	183	183
	a		-1,304	236	-764	-1,293	-2,578
	b		0.964	0.950	0.926	1.024	1.179
	r		0.961	0.969	0.964	0.961	0.953
Niamey (1985)	n	19.4-31.6	183	183	183	183	183
	a		9,260	12,609	10,517	9,928	7,575
	b		0.598	0.463	0.688	0.655	0.576
	r		0.569	0.481	0.570	0.570	0.575
Roskilde (1988)	n	10.8-30.5	106	106	106	106	106
	a		-1,164	-802	-1,292	-1,995	-2,468
	b		0.908	0.942	0.856	1.015	1.092
	r		0.912	0.914	0.911	0.909	0.907
Rothamsted	n	7.8-28.7	178	178	178	178	178
	a		-710	202	-465	-1,133	-1,570
	b		0.927	0.944	0.885	1.016	1.098
	r		0.932	0.940	0.935	0.810	0.925
Silstrup (1990)	n	8.2-29.9	171	171	171	171	171
	a		-316	-260	-550	-623	-1,176
	b		0.905	0.953	0.848	0.988	1.087
	r		0.966	0.967	0.965	0.965	0.963
Tel Hadya	n	20.1-30.6	182	182	182	182	182
	a		1,213	1,868	1,515	1,760	659
	b		0.916	0.904	0.945	0.958	1.328
	r		0.890	0.916	0.901	0.909	0.852
Wageningen (1987)	n	7.6-27.9	169	169	169	169	169
	a		-91	1,049	210	-352	-937
	b		0.937	0.942	0.895	1.019	1.119
	r		0.939	0.948	0.942	0.936	0.931

Table 7. Relationship between measured (RAD_m) and calculated global radiation (RAD_c) ($kJ.m^{-2}.d^{-1}$) for the whole radiation range: $RAD_c = a + b \times RAD_m$, for Niamey, from June up to August, 1985. The Ångström coefficients were calculated following 5 different methods: see Table 2.

regression	method				
coefficient	1	2	3	4	5
n	92	92	92	92	92
a	4,720	13,177	5,192	4,797	2,199
b	0.813	0.463	0.939	0.897	0.824
r	0.896	0.895	0.896	0.896	0.896

The inconsistent results with respect to the different methods to estimate the Ångström coefficients were also obvious when distinguishing between a low and a high radiation range (Tables 5 and 6). The correlation coefficients hardly changed as compared to the whole radiation range, with the exception of Niamey with especially low values for the upper half of the radiation range. It could be concluded that for all methods for all locations the calculated global radiation values deviated considerably from the measured global radiation values.

As for the purpose of this study only calculated global radiation values for roughly the period June up to August are of relevance, just for this period a comparison was made between the different methods for estimating the Ångström coefficients (Table 7). Whereas the correlation coefficients are similar for all methods considerable differences existed between the regression coefficients, however, without an unequivocally best fit. In combination with Ångström coefficients a and b of 0.224 and 0.444, respectively (r = 0.896), derived through linear regression analysis from the June up to August values (n = 92), this observation justified the application of the simple method of Frère & Popov (1979) for the estimation of the Ångström coefficients.

Because no directly measured daily or monthly long-term sunshine duration values were available

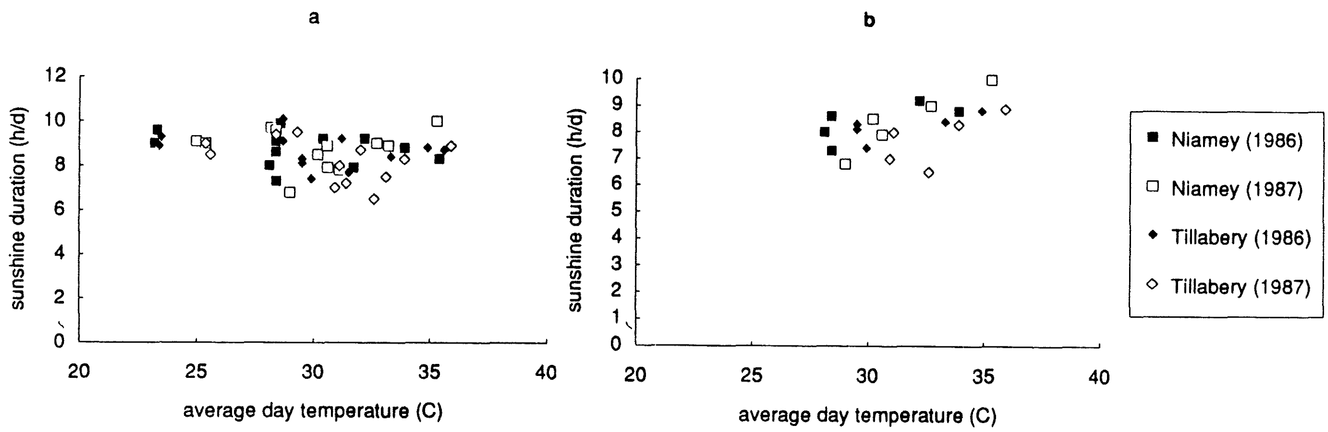


Figure 13. Relation between monthly values of independent variable average day temperature and dependent variable daily sunshine duration, for Niamey and Tillabéry, for 1986 and 1987, considering the whole year (a) and the period from May up to September (b).

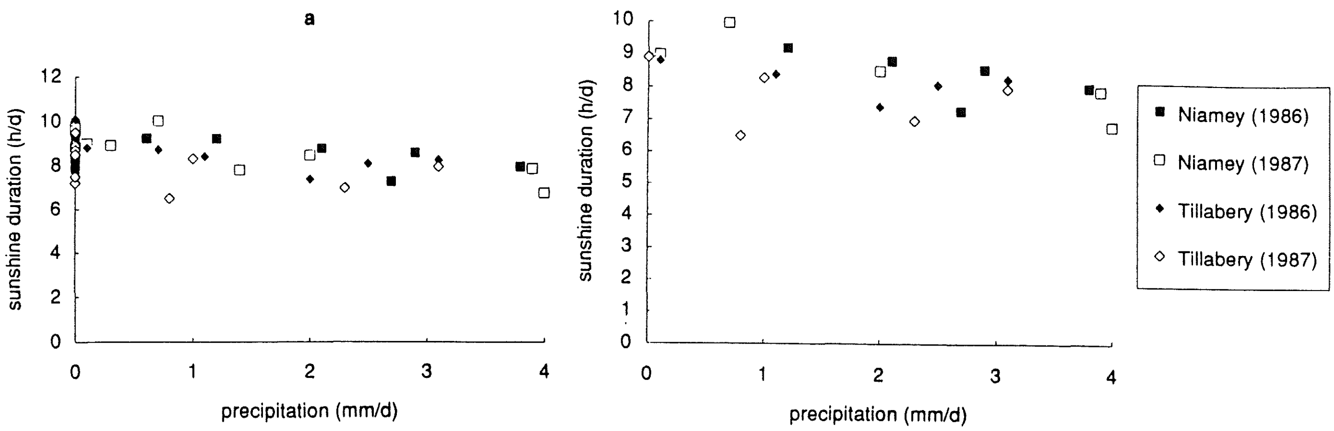


Figure 14. Relation between monthly values of independent variable daily precipitation and dependent variable daily sunshine duration, for Niamey and Tillabéry, for 1986 and 1987, considering the whole year (a) and the period from May up to September (b).

for Niger, the daily meteorological data (section 2.4) for Niamey-Airport and Tillabéry, for 1986 and 1987, were used to derive a correlation between on the one hand the monthly mean of daily precipitation or average day temperature (section 2.4.1 and 2.4.2) and on the other hand the monthly mean of daily sunshine duration. It was distinguished between correlations accounting for the whole year and correlations accounting for the months May up to September, including the rainy season. Figures 13 shows the relationship between average day temperature and sunshine duration, for the whole year and for the months May up to September. For neither situation an acceptably clear relationship existed. In a similar arrangement Figure 14 shows the relationship between precipitation and sunshine duration. For the whole year situation (n = 48) regression coefficients a 8.909 h.d^{-1} and b -0.354 h.d^{-1}/(mm.d^{-1}), and correlation coefficient -0.524 were found. For the May up to September situation (n = 20) regression coefficients a 8.806 h.d^{-1} and b -0.312 h.d^{-1}/(mm.d^{-1}), and correlation coefficient -0.465 were found. In view of the similarity between both correlations, the variation in sunshine duration at zero precipitation (due to the cyclic variation in the astronomically determined daylength) and the homogeneity as compared with other correlations (section 2.4.4), the correlation between precipitation and sunshine duration accounting for the months May up to September would best be used to derive the monthly mean of daily sunshine duration for the locations and the years for which monthly precipitation data were available (section 2.4.1).

However, this approach assumes a maximum sunshine duration of 8.8 h.d^{-1}, which is well below daily values reported for this period. Relating the daily precipitation to the daily ratio of sunshine duration over astronomical daylength did not result in acceptably clear correlations. For Niamey-Airport (1986 and 1987) and Tillabéry (1986 and 1987) for the months May up to September (n = 153) this resulted in an a value (h.d^{-1}/(h.d^{-1})), a b value ((mm.d^{-1})$^{-1}$) and a correlation coefficient of 0.6795, -0.0039 and -0.1181; 0.6856, -0.0048 and -0.1150; 0.6730, -0.0106 and -0.2243; and 0.6312, -0.0066 and -0.1253, respectively. Combining the two locations and two years (n = 612) resulted in values of 0.6664 h.d^{-1}/(h.d^{-1}), -0.0057 (mm.d^{-1})$^{-1}$ and -0.1336, respectively. These relationships all show maximum sunshine duration values which are similar to the one found for the relationship between the monthly mean of daily precipitation and sunshine duration. It seems therefore obvious that there only was a very weak relationship between cloud cover and precipitation.

2.4.4 potential evapo(transpi)ration

In WOFOST the evaporation from the soil surface is determined by the potential soil evaporation and the moisture content of the upper soil layer. The crop transpiration is determined by the potential crop transpiration and the soil moisture content up to rooting depth. Potential evaporation and transpiration are calculated following the Penman approach (Frère & Popov, 1979; Van Diepen *et al.*, 1988). The validity of these calculations is usually limited to a time resolution of no less than 10 days (Frère & Popov, 1979). Input parameters are the periodical mean of the daily maximum and minimum air temperature, daily vapor pressure, daily radiation and average daily wind speed. Because none of these Penman evaporation components were measured on a long-term basis two approaches could be followed to derive the potential evapo(transpi)ration for the locations and the years mentioned in annex B on basis of the daily meteorological data for Niamey-Airport and Tillabéry, for 1986 and 1987: *(1)* correlations could be derived between the monthly means of on the one hand daily precipitation or average day temperature and on the other hand of the daily values of the Penman evaporation components, after which the potential evapo(transpi)ration could be calculated; and *(2)* direct correlations could derived between the monthly means of on the one hand daily precipitation or average day temperature and on the other hand the daily values of the potential evapo(transpi)ration.

Figure 15 shows the relationships between average day temperature and average wind speed, and daily precipitation and average wind speed. Figure 16 shows the relationships between average day temperature and vapor pressure, and daily precipitation and vapor pressure. Both average day temperature and daily precipitation seemed to determine vapor pressure clearly, however this was not

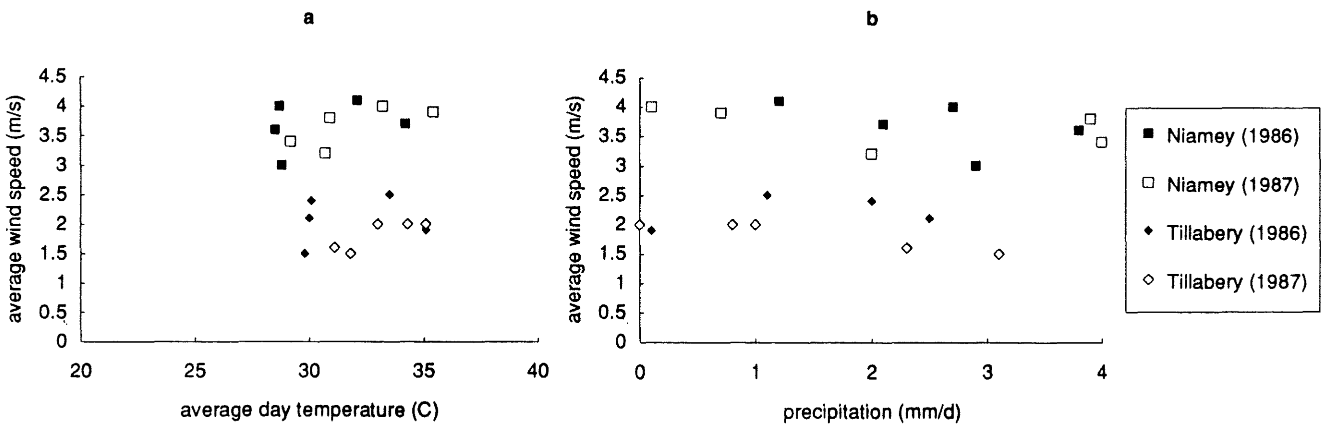


Figure 15. Relation between monthly values of independent variable average day temperature and dependent variable daily average wind speed (a), and independent variable daily precipitation and dependent variable daily average wind speed (b), for Niamey and Tillabéry, for 1986 and 1987, during the period from May up to September.

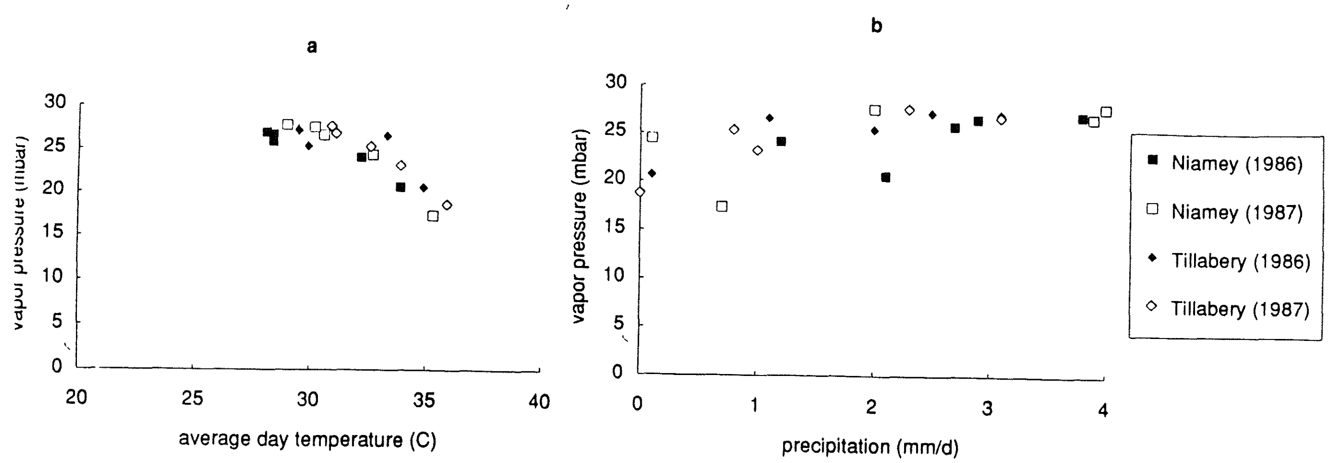


Figure 16. Relation between monthly values of independent variable average day temperature and dependent variable daily vapor pressure (a), and independent variable daily precipitation and dependent variable daily vapor pressure (b), for Niamey and Tillabéry, for 1986 and 1987, during the period from May up to September.

obvious for average wind speed. Nor was this the case for daily maximum and minimum temperature.

Basis for the calculation of the potential soil evaporation and crop transpiration was the evaporation from a free water surface, E_0, following Penman. E_0 can be calculated (Van Diepen *et al.*, 1988; Frère & Popov, 1979), but is also measured. The free water surface evaporation calculated following Penman (Van Diepen *et al.*, 1988; Frère & Popov, 1979) is often considered to underestimate the actual free water surface evaporation. Except for the implicit exclusion of advection of warm air as an additional energy source in the energy balance of a free water surface, the calculation procedure also holds several uncertainties, such as the selection of the most appropriate vapor pressure value measured over the day and the average wind speed value. Therefore the calculated free water surface evaporation values generally are considered to be indicative only, accounting for an estimate of the evaporation during a period of not less than 10 days (Frère & Popov, 1979).

The available daily meteorological for Niamey-Airport and Tillabéry hold two observations on free water surface evaporation: one on class A pan evaporation (*évaporation bac*), and one on evaporation from a continuously wetted tissue (*évaporation piche*). Measured pan evaporation was generally higher than measured tissue evaporation, in the order of magnitude of a few mm. Several factors may have contributed to these differences: *(1)* heating of the sides of the pan due to high levels of radiation may have served as an additional energy source; *(2)* due to the sides of the pan the *harmattan*, the warm winds from the north-east occuring in the Sahel during the dry season, may have served as a stronger additional energy source for the pan evaporation than for the tissue evaporation; and *(3)* the tissue may not have been wetted continuously. Figure 17 shows the course of the weekly mean of the difference between the measured and calculated E_0 at Niamey-Airport and Tillabéry, during 1986 and 1987. It is obvious that during the dry season measured evaporation was higher than calculated, whereas this tended to be the reverse or to become less pronounced during the rainy season. Hence, the course of the the calculated free water surface evaporation was less

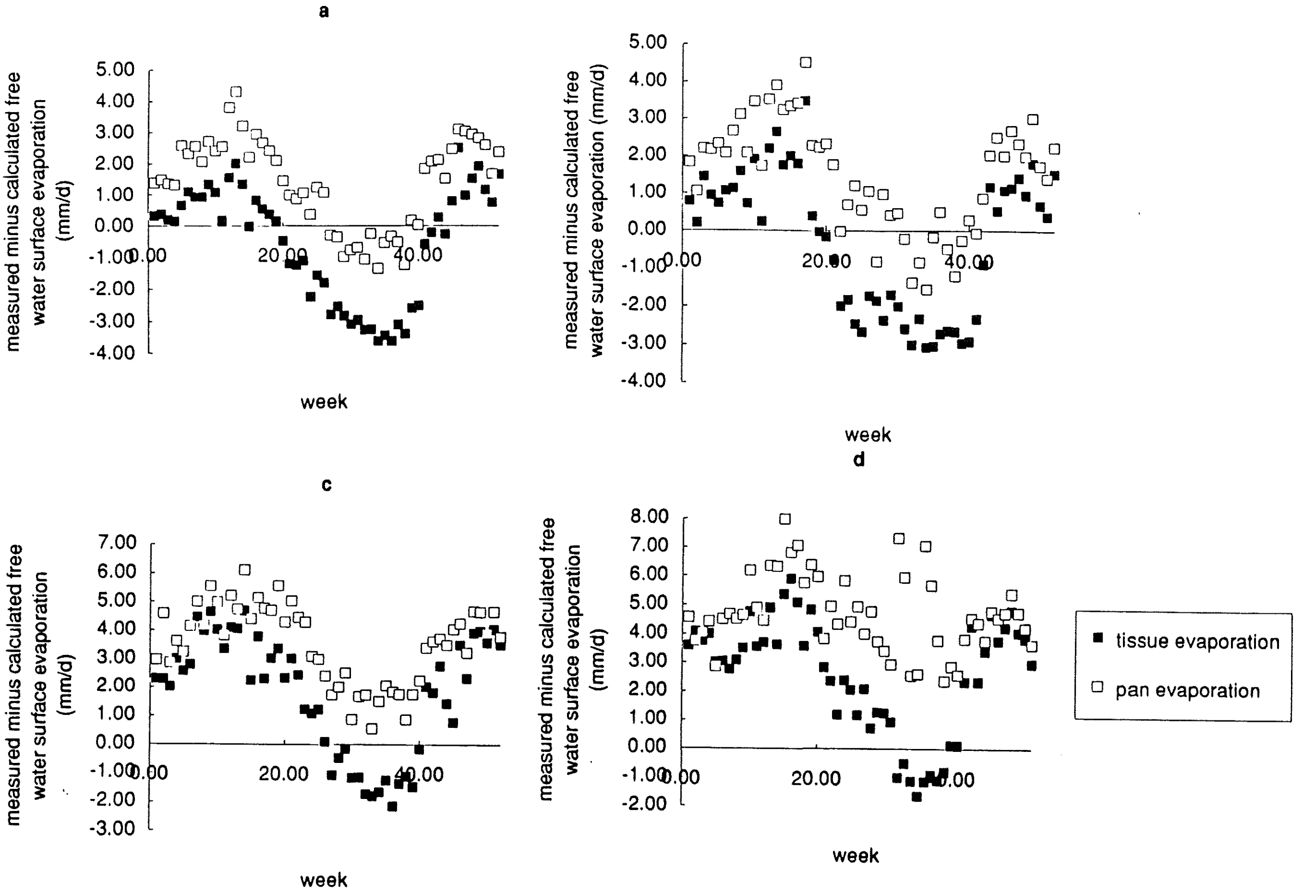


Figure 17. Weekly differences between on the one hand measured tissue or pan evaporation and on the other hand calculated free water surface evaporation, E_0, following the procedure given by Frère & Popov (1979) and Van Diepen *et al.* (1988), for Niamey, 1986 (a), Niamey, 1987 (b), Tillabéry, 1986 (c) and Tillabéry, 1987 (d).

strong than the course of the measured free water surface evaporation. Several factors may have contributed to this difference: *(1)* due to the lower levels of radiation the side heating of the pan may have been of less quantitative importance; *(2)* due to the absence of the *harmattan* during the rainy season this could not have served as an additional energy source for either transpiration; and *(3)* the precipitation may have caused errors in the evaporation measurements if the material was not shielded off sufficiently from direct weather influences. In particular a contrast could be observed between the two locations, where at Tillabéry the measured free water surface evaporation seemed to maintain a higher value relative to the calculated free water surface evaporation than at Niamey.

Figure 17 also shows that during the growing season at least pan evaporation and calculated free water surface evaporation were more or less similar. Therefore it was decided to apply the calculated free water surface evaporation (Van Diepen *et al.*, 1988; Frère & Popov, 1979) to the evapo(transpi)ration calculations in WOFOST. Because no daily or monthly long-term free water surface evaporation values were available for Niger, the daily meteorological data (section 2.4) for

Niamey-Airport and Tillabéry, for 1986 and 1987, were used to derive a correlation between on the one hand the monthly mean of daily precipitation or average day temperature (section 2.4.1 and 2.4.2) and on the other hand the monthly mean of daily calculated and measured free water surface evaporation. It was distinguished between correlations accounting for the whole year and correlations accounting for the months May up to September. If applied to the period of May up to September clear relationships existed between average day temperature or daily precipitation on the one hand and calculated and measured free water surface evaporation on the other hand, stronger, however, for the average day temperature than for the daily precipitation.Table 8 lists the regression parameters for the correlations between average day temperature as independent variable and soil evaporation and crop transpiration (Van Diepen *et al.*, 1988) as dependent variables. For the calculation of soil evaporation and crop transpiration use was made of the calculated free water surface evaporation (Van Diepen *et al.*, 1988) and the measured pan and tissue evaporation.

Monthly means of E_{soil} and T_{crop} for use in WOFOST were derived from the above-mentioned linear relationships between average day temperature and E_{soil} and T_{crop}, with the free water surface evaporation calculation following Penman (Van Diepen *et al.*, 1988), E_0. This means that, while using WOFOST for the agro-ecological classification, no direct use was made of the Penman evaporation algorithm (Van Diepen *et al.*, 1988).

Table 8. Regression coefficients for linear relationships with the average day temperature (^oC) as independent and the soil evaporation (E_{soil}) and crop transpiration (T_{crop}) ($mm.d^{-1}$) as dependent variables. Based on: *(1)* monthly means of daily average temperature, pan evaporation (E_{pan}), tissue evaporation (E_{tissue}) and calculated free water surface evaporation (E_0) derived from daily values for Niamey-Airport and Tillabéry, 1986 and 1987; and *(2)* the Penman evaporation algorithm for free water surface evaporation used by Van Diepen *et al.* (1988).

dependent variable	free water surface evaporation	regression coefficient			
		a	b	r	n
E_0		-3.048	0.327	0.686	20
E_{soil}	E_0	-3.230	0.311	0.677	20
	E_{pan}	-1.582	0.319	0.677	20
	E_{tissue}	-4.619	0.342	0.677	20
T_{crop}	E_0	-5.070	0.366	0.733	20
	E_{pan}	-3.472	0.376	0.733	20
	E_{tissue}	-6.641	0.402	0.733	20

2.5 THE SOIL DATA

As simulations were restricted to the production level of water-limited production, with respect to the soil assuming ample availability of nutrients, only soil physical data were required for WOFOST, among others determining the soil water balance. Considering *(1)* the sandy texture of the soils, limiting capillary rise from the groundwater; *(2)* the absence of major rivers, with the exception of the

Niger; and *(3)* the usually up-hill location of millet cultivation (Van Staveren & Stoop, 1985), it wasassumed that groundwater did not influence the soil water balance of relevance to the crop. In case of absence of groundwater influence on the cropping system WOFOST applies the following soil physical parameters for the simulation of water-limited crop production (Van Diepen *et al.*, 1988): *(1)* the transmission zone permeability ($cm.d^{-1}$) (Van Keulen & Wolf, 1986), limiting infiltration in case of surface storage of water and the downward transport of water from the rooting zone; *(2)* the transmission zone permeability of the subsoil, limiting water loss beyond rooting depth, often set equal to *(1)*; and *(3)* the volumetric soil moisture content ($cm^3.cm^{-3}$) as a function of the logarithm of the soil moisture tension (cm): the pF- or soil moisture retention curve.

Nigerien soils are generally described as sand to coarse sand (Daouda Ousmane *et al.*, 1991; Fechter *et al.*, 1991; Hoogmoed & Klaij, 1990; Payne *et al.*, 1991), however, due to modest clay and silt fractions (Daouda Ousmane *et al.*, 1991; Fechter *et al.*, 1991) in more specific soil classifications (e.g. Van Keulen & Wolf, 1986) several of these soils could be described as loamy sand to sandy loam. Though WOFOST holds a standard soil data files on medium to coarse sand, fine sand, loamy fine sand, very loamy fine sand and fine sandy loam (Van Diepen *et al.*, 1988), belonging to the so-called Staring series, these soil data are based on measurements made on Dutch soils, and can, therefore, not be extrapolated to the Nigerien situation without careful examination. It is generally acknowledged that seemingly similar soils at different locations can have pronouncedly different quantitative characteristics, due to a different soil texture and structure. E.g. modest quantities of silt or clay may have a strong effect on the course of the soil moisture retention curve.

2.5.1 transmission zone permeability

The transmission zone permeability determines the downward water flow in case of a wet, however not saturated, soil. The transmission zone permeability, A ($cm.d^{-1}$), is calculated as the hydraulic conductivity at a matric suction, ψ, of 10 cm (-0.667 kPa) (Van Keulen & Wolf, 1986):

$$A = k_0 \times e^{-\alpha \times \psi}$$

where k_0 is the saturated hydraulic conductivity ($cm.d^{-1}$), α a texture-specific empirical constant (cm^{-1}) and ψ the matric suction (cm). Van Keulen & Wolf (1986) mention texture-specific α values for the soils belonging to the Staring series. Because no α values were available for the Nigerien situation, in first instance in literature mentioned k_0 values were proportionally related to the k_0 and A values mentioned by Van Keulen & Wolf (1986).

Due to their sandy texture the Nigerien soils generally display a high transmission zone permeability, and therefore saturated hydraulic conductivity. Whereas Van Keulen & Wolf (1986) mention a saturated hydraulic conductivity, k_0, and an A value of 1,120 and 119 $cm.d^{-1}$, respectively, for coarse sand, 50 and 30 $cm.d^{-1}$, respectively, for fine sand, 27 and 18 $cm.d^{-1}$, respectively, for loamy sand, and 12 and 9 $cm.d^{-1}$, respectively, for fine sandy loam, in the Staring series, literature mentions much higher values for specifically Nigerien sites. However, because of the fraction of clay and loam, the top soil often forms a hardly permeable crust after heavy rainfall, drastically reducing the (saturated) hydraulic conductivity and increasing surface runoff. Hoogmoed (1986) showed that cycles of subsequent wetting and drying considerably reduced the saturated hydraulic conductivity.

Hoogmoed & Klaij (1990) give saturated hydraulic conductivity values of 100 to 250 $cm.d^{-1}$ for a sandy soil (approximately 3% clay, 4% silt and 93% sand) at ICRISAT Sahelian Center at Sadoré. For a sandy loam soil at Tara in southwestern Niger Fechter *et al.* (1991) mention values of 286 $cm.d^{-1}$ for the top layer (approximately 7% clay, 11% silt and 82% sand) up to 450 $cm.d^{-1}$ at 40 cm depth (approximately 10% clay, 11% silt and 79% sand). For a sandy soil (approximately 5% clay, 7% silt and 87% sand) at N'Dounga, Niger, Payne *et al.* (1991) found a saturated hydraulic conductivity of 173 $cm.d^{-1}$. In general it could be expected that both k_0 and A strongly depend on weather conditions and soil characteristics in time and space, earlier precipitation, field management practices and crop status.

Unless specified differently, arbitrary k_0 values of 150 and 300 $cm.d^{-1}$ were assumed for top soil and sub soil, respectively. Using a k_0/A ratio of 1.5 - a rough estimation from fine sand, loamy sand and fine sandy loam soils (Van Keulen & Wolf, 1986) - A values of 100 and 200 $cm.d^{-1}$ were applied for top soil and sub soil, respectively.

To avoid uncertainties in the calculations on the infiltration of water into the soil WOFOST offers the opportunity to subtract a certain fraction runoff from precipitation to calculate precipitation available for the soil water balance. However, the fraction runoff is likely to vary with the same factors as influencing k_0 and A, and will by no means be constant in time and space. From literature Lal (1991) mentions a total runoff fraction of 1.5 and 20% for a millet cultivated and a bare soil respectively, at a field with an unknown slope at Sadoré, Niger.

2.5.2 soil moisture retention

The relationship between the volumetric soil moisture content ($cm^3.cm^{-3}$) as a function of the logarithm of the soil moisture tension (cm) determines the water holding capacity of the soil. In WOFOST no distinction is made between different soil layers. Up to rooting depth the soil is assumed to be homogeneous. In WOFOST three points in this relationship determine the soil moisture availability for the crop: *(1)* the volumetric soil moisture content at ψ -6.667 kPa (100 cm, pF 2.0), the so-called *field capacity*, the amount of water if a saturated soil was allowed to drain for 2 days; *(2)* the *critical volumetric soil moisture content*, where at lower ψ values crops will experience growth limiting water availability; and *(3)* the volumetric soil moisture content at ψ -1,067 kPa (16,000 cm, pF 4.2), the so-called *permanent wilting point*, where at lower ψ values crops will not be able to extract moisture from the soil.

Van Diepen *et al.* (1988) give such relationships for medium to coarse sand, fine sand, loamy fine sand, very loamy fine sand and fine sandy loam, for soils from the Staring series. For specifically Nigerien conditions soil moisture retention curves for the range pF 2.0-4.2 were determined by Hoogmoed & Klaij (1990) for a sandy soil (approximately 3% clay, 4% silt and 93% sand) at Sadoré, Niger; by Payne *et al.* (1991) for a sandy soil (approximately 5% clay, 7% silt and 87% sand) at N'Dounga, Niger; and by Daouda Ousmane *et al.* (1991) for sandy soils of a variable composition at Niamey, Niger.

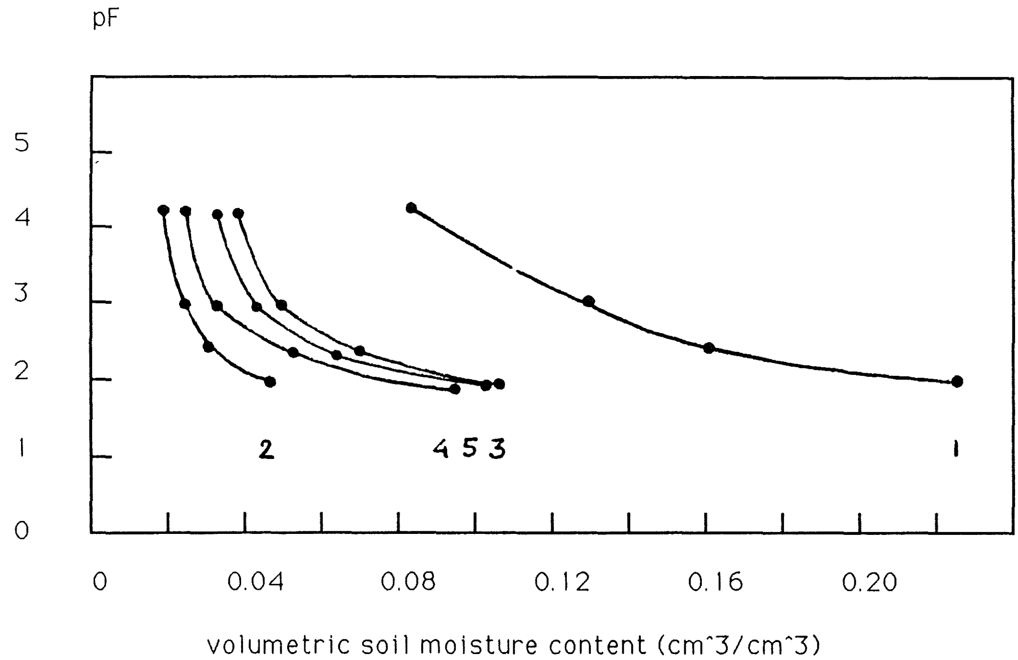


Figure 18. Soil moisture retention curves for the whole soil profile for different locations in an experimental field located on terrasses along the Niger river, as described by Daouda Ousmane *et al.* (1991). To compile these curves from the contributions of the different soil layers a weighed average was taken with respect to soil layer thickness.

Figure 18 shows the average soil moisture retention curves for the whole soil profile up to 200 to 230 cm given by Daouda Ousmane *et al.* (1991) for 5 locations within a Niger river terrace area of 3 ha. The data given by Daouda Ousmane *et al.* (1991) indicate a considerable variation in the relationship between volumetric soil moisture content and soil moisture tension, both vertically and horizontally. Figure 19 shows that the soil moisture retention curves for two similarly classified sandy soils by Van Diepen *et al.* (1988) and Payne *et al.* (1991) can differ considerably. Hoogmoed & Klaij (1990) determined the soil moisture retention curves for a high and low yielding spot in a sandy soil, both very similar to the curve found by Payne *et al.* (1991), as shown in Figure 19. Figure 20 shows the soil moisture retention curves of medium to coarse sand, fine sand and loamy fine sand, from the Staring series (Van Diepen *et al.*, 1988). Volumetric soil moisture content at field capacity and permanent wilting point only were given by Dembélé & Somé (1991) at different locations throughout Burkina Faso, and by Lal (1991) at different locations throughout northern Nigeria.

It is obvious that the variation in the course of the soil moisture retention curves can be considerable, and therefore the curves should best be determined for the specific sites. However, regarding the absence of such *in situ* experimental data and the relatively close similarity between the soil moisture retention curves found by Daouda Ousmane *et al.* (1991), Hoogmoed & Klaij (1990), both in the vicinity of Niamey, and Payne *et al.* (1991), more east of Niamey, it was decided to apply only one soil moisture retention curve, unless specified differently. Because of the wide range of available ψ values, use was made of the soil moisture retention curve for medium to coarse sand as determined by Van Diepen *et al.* (1988).

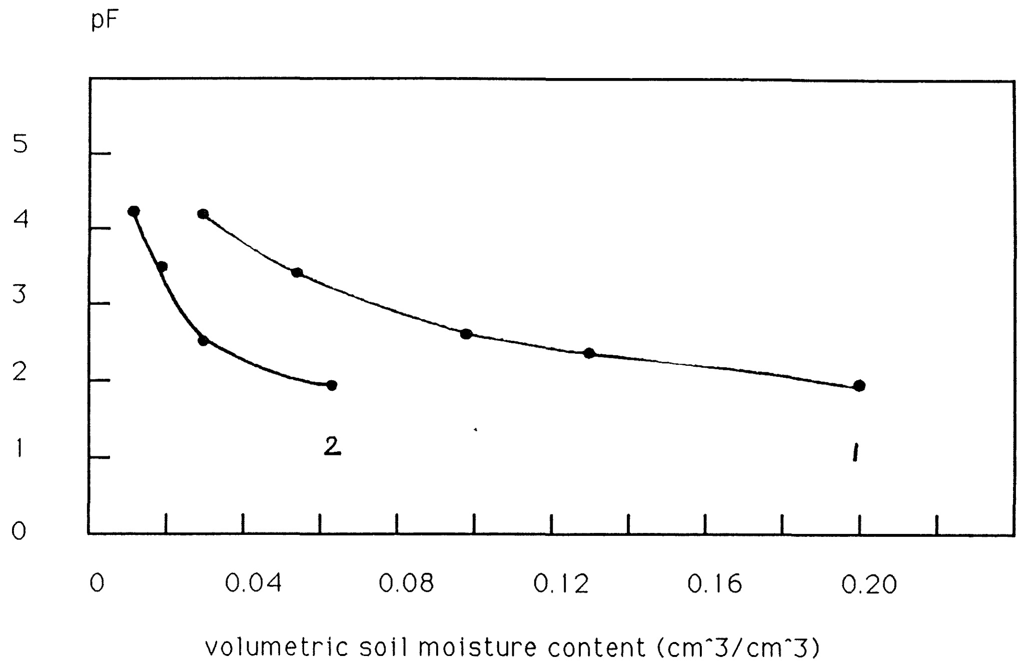


Figure 19. Soil moisture retention curves for a sandy soil from the Staring series (Van Diepen *et al.*, 1988) (1) and a loamy sand to sandy soil in Niger (Payne *et al.*, 1991) (2).

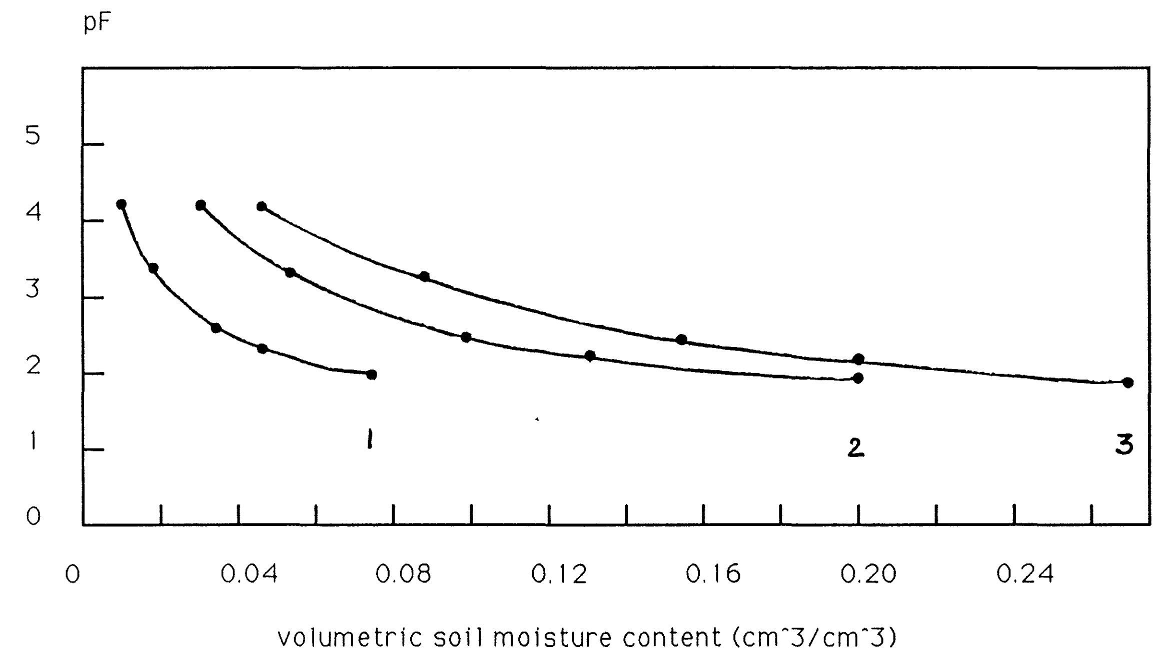


Figure 20. Soil moisture retention curves for medium to coarse sand (1), fine sand (2) and loamy fine sand (3), from the Staring series (Van Diepen *et al.*, 1988).

WOFOST does not take into account the effect of *hysteresis*, i.e. the differences in course of the relationship between volumetric soil moisture content and the logarithm of the soil moisture tension upon wetting and drying.

2.6 THE CROP DATA

WOFOST version 4.1 holds standard crop data on millet (*Pennisetum typhoides* S. & H.) based on Van Heemst (1988). As Van Heemst (1988) collected these data from a variety of literature sources, and hence comprise data from different millet varieties and different environmental conditions, these millet data should in principle be used carefully. The crop data requirements are listed by Van Diepen *et al.* (1988). For the agro-ecological classification use was made of the standard values supplied by Van Diepen *et al.* (1988). No data were used for nutrient concentrations in the plant organs, because no nutrient-limited production was simulated.

On average the millet cultivar simulated has a crop cycle of 75 days, with slight variations caused by differences in average day temperature during the growing period. This length can be considered as extremely short, as compared to the improved short duration millet cultivars that mature in 90 days (Bacci, pers.comm.; Sivakumar, 1990) and the traditional cultivars that mature in 110-120 days (Sivakumar, 1990). It was assumed that the millet crop was not day length sensitive, though the traditional, local cultivars are. Bacci (pers.comm.) reports 50% anthesis in local cultivars during the first week of September, when day length is falling below 12-13 h. Day length insensitivity allows a more flexible cropping strategy. Early maturation of the millet crop would allow the establishment of a relay crop like cowpea (Sivakumar, 1990) and hence make better use of the potentials offered by rainy seasons exceeding the average length.

WOFOST simulates crop growth and development after emergence, to avoid the uncertainties which influence the period between sowing and emergence. However, for practical purposes a fixed period of 5 days between sowing and emergence was implemented for this study. This value was determined experimentally for 2 pearl millet varieties at ICRISAT Sahelian Center at Sadoré, Niger, during the 1988 season.

In case of a crop with a Leaf Area Index of 0.002 or less and a development stage of larger than 0.5, WOFOST aborts the calculation procedures. However, no effect of drought stress on seedling survival is taken into account. ICRISAT research has shown that drought stress, and to a lesser degree heat stress, have a pronounced effect on seedling establishment. To account for the relationship between moisture availability and seedling survival a simple empirical formula was implemented (Bacci, pers.comm.), relating the amount of precipitation during successive days at sowing to the maximum period of seedling survival:

$$s_s = 0.5 \times P + 2$$

where S_s is the maximum period of seedling survival from sowing (d), and P the amount of precipitation (mm) during successive days at sowing. If during S_s no precipitation occurs, then the calculation procedures are aborted.

2.7 CROP MANAGEMENT PRACTICES

In its standard conformation WOFOST version 4.1 does not hold algorithms on crop management practices. In the framework of an agro-ecological classification the inclusion of management practices after sowing is not applied.

For the sowing strategy Bacci (pers.comm.) distinguishes between three different periods and matching sowing criteria throughout the growing season. According to this strategy millet seeds are best sown when during the *early period* during 2 successive days total precipitation exceeds 20 mm, secondly when during the *intermediate period* during 2 successive days total precipitation exceeds 15 mm, and thirdly when during the *late period* during 2 successive days total precipitation exceeds 10 mm. It is obvious that with progressing sowing date the length of the growing season becomes increasingly shorter, but also that the chance of a dry spell during early crop development becomes increasingly smaller. The exact duration of the three different periods depends on the location. With increasing average annual precipitation these periods shift to earlier in the season, whereas the length of the periods increases. For the agro-ecological classification in this study use was made of average periods determined for the Ouallam region (Bacci, pers.comm.), the validity of which were extrapolated to the other locations: the *early period* lasts from Julian day 149 up to 162, the *intermediate period* from day 163 up to 182, and the *late period* from day 183 up to 197.

2.8 MODEL PERFORMANCE

For all simulations in section 2.8 a maximum surface storage capacity of 3 cm was assumed, unless specified differently. Additionally it was assumed that ground water did not influence the soil water balance. To account for a realistic simulation for the soil water balance were well started before the simulations of millet growth. In the following the combination of Julian day of start of the simulation of the soil water balance and of sowing will be indicated as a combination of two days. E.g. 100/110 indicates that the simulation of the soil water balance started at Julian day 100, whereas the millet crop was sown on Julian day 110.

2.8.1 results millet growth simulations using daily meteorological data

Millet growth simulations for Niamey and Tillabéry for 1986 and 1987 were carried out using WOFOST version 4.1 with the input data as specified in the preceding sections. Use was made of the available daily meteorological data for these locations and years.

Figures 21 up to 24 show the course of the dry matter yield of the storage organs and the above ground dry matter for different sowing dates for potential (production level 1) and water-limited (production level 2) millet production (section 2.3.2). In general simulation of the soil water balance at Niamey (1986), Niamey (1987), Tillabéry (1986) and Tillabéry (1987) started at Julian days 140; 189; 166; and 191, respectively. Exceptions were 74/77 and 150/152; 114/117, 131/133, 137/142 and 158/160; and 176/178; for Niamey (1987), Tillabéry (1986) and Tillabéry (1987), respectively.

The course of the potential production shows a dip during the rainy season, because clouds interfered with the growth-determining radiation whereas moisture availability is assumed to be ample. The course of the water-limited production shows a peak during the rainy season, because moisture acts as a growth limiting factor which is alleviated by the occuring precipitation. The slopes of the

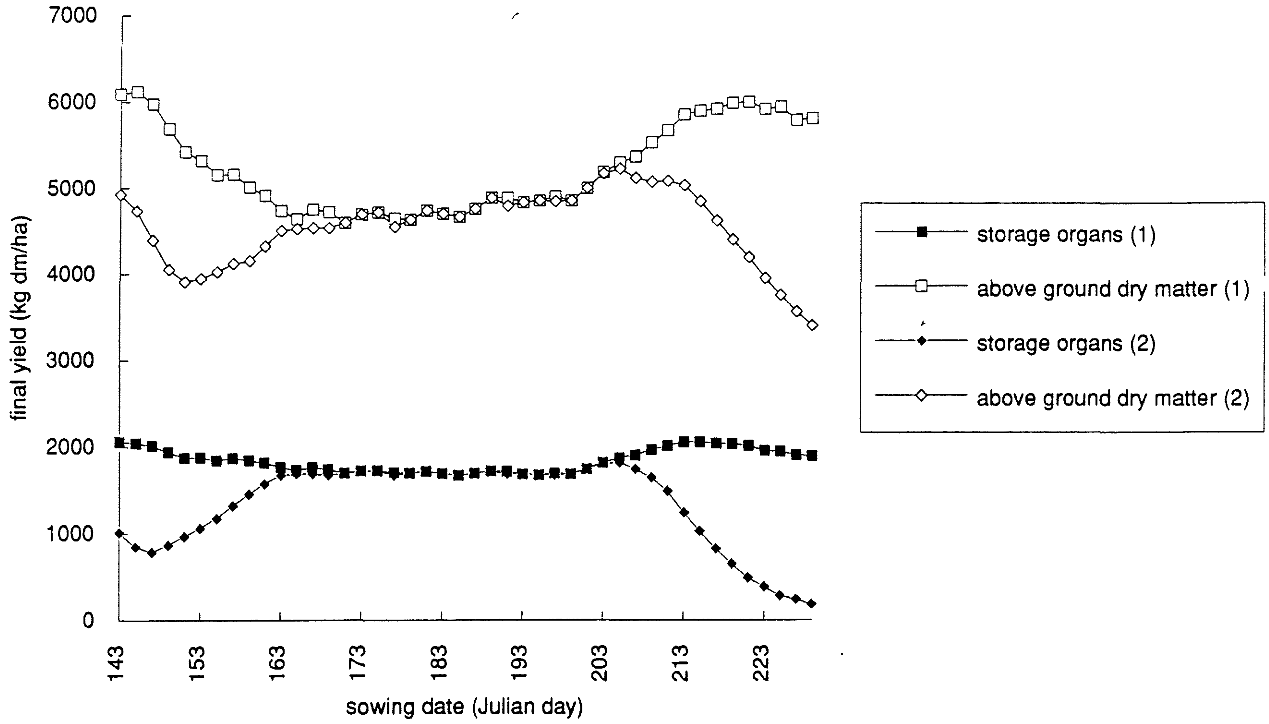


Figure 21. Simulated final dry matter yields of total above ground dry matter and storage organs for production level 1 (potential millet production) and production level 2 (water-limited millet production) for different sowing dates, at Niamey, 1986, using daily meteorological data.

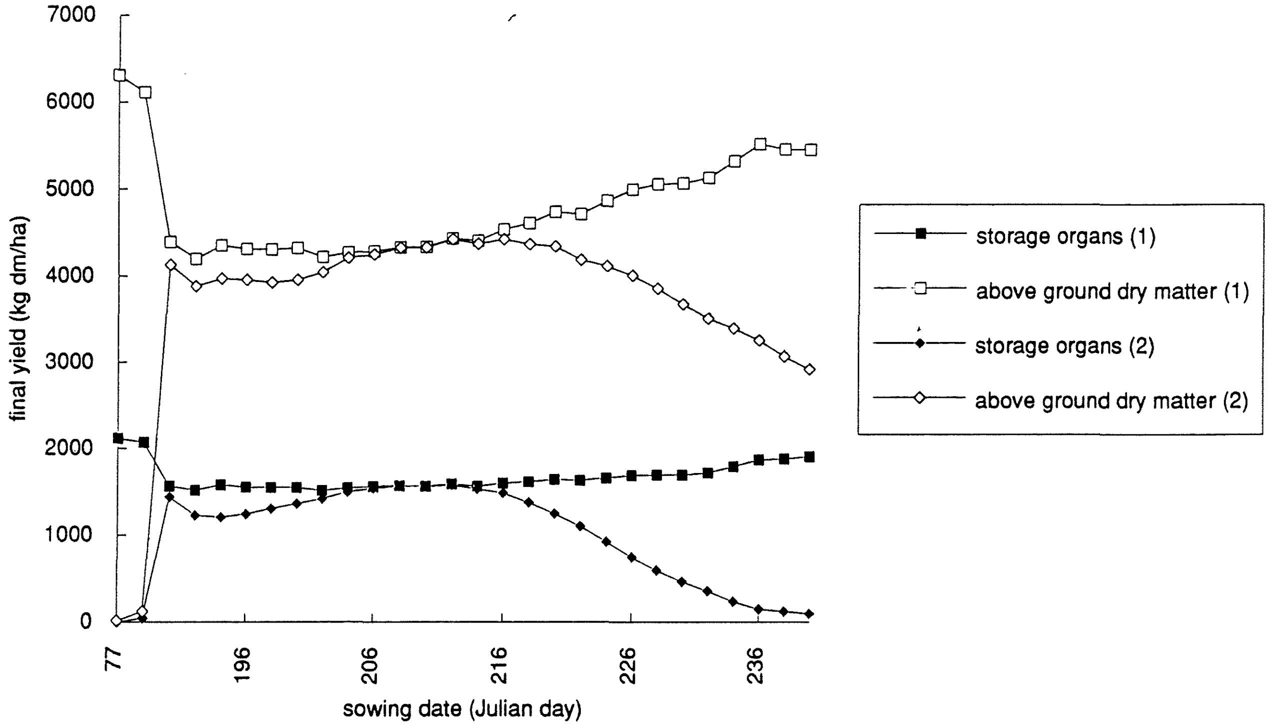


Figure 22. Simulated final dry matter yields of total above ground dry matter and storage organs for production level 1 (potential millet production) and production level 2 (water-limited millet production) for different sowing dates, at Niamey, 1987, using daily meteorological data.

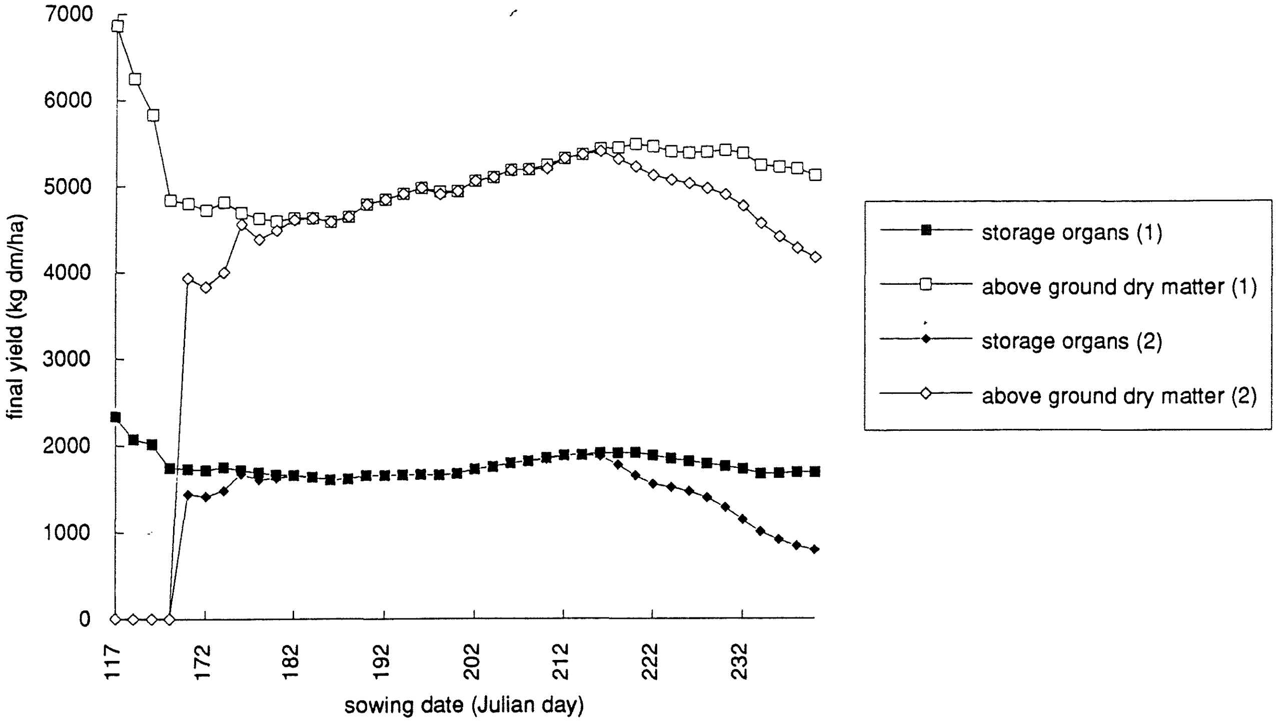


Figure 23. Simulated final dry matter yields of total above ground dry matter and storage organs for production level 1 (potential millet production) and production level 2 (water-limited millet production) for different sowing dates, at Tillabéry, 1986, using daily meteorological data.

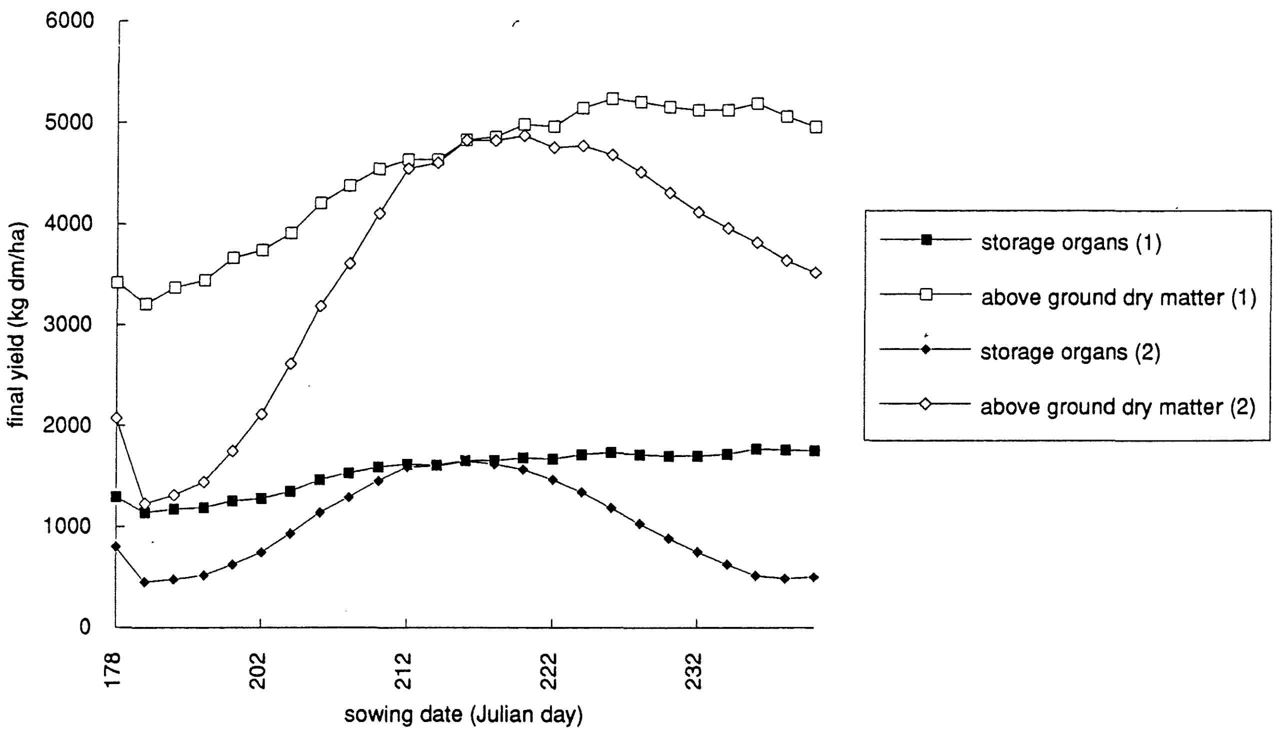


Figure 24. Simulated final dry matter yields of total above ground dry matter and storage organs for production level 1 (potential millet production) and production level 2 (water-limited millet production) for different sowing dates, at Tillabéry, 1987, using daily meteorological data.

peaks for water-limited production indicate a quantitatively stronger influence of water availability than of radiation. For certain sowing dates water-limited production approached or equaled potential production as a result of sufficient availability of moisture, more often so for the relatively wet year of 1986.

The potential yield level is similar for both locations and both years: approximately 4,500 kg above ground dry matter per ha and 1,800 kg storage organ dry matter per ha during the part of the growing season with most sufficient precipitation. In general 1986 seemed to have somewhat higher yield potentials than 1987, probably because of the higher average day temperatures and incident radiation during the 1987 growing season resulting from the lower precipitation.

If the in section 2.7 indicated sowing strategy was implemented for the water-limited simulations, then storage organ dry matter yields for Niamey (1986), Niamey (1987), Tillabéry (1986) and Tillabéry (1987) were obtained of 1,032; 0; 1,442; and 0 kg dm.ha^{-1}, at sowing dates 140/143; 150/152; 166/170; and 176/178, respectively. Resowing at Niamey (1987) and Tillabéry (1987), at days 189/192 and 191/193, resulted in storage organ dry matter yields of 432 and 1,208 kg dm.ha^{-1}, respectively.

A comparison between on the one hand the growth occuring following the in section 2.7 indicated sowing strategy, and on the other hand the growth resulting in the highest yield, as seen from Figures 25 up to 27, learned that yields can be considerably higher than the ones obtained following mentioned sowing strategy, simply by delaying the sowing date. However, the cultivation of a relay crop requires the early maturation of the millet crop, whereas the increased millet yields would not offset not cultivating such a relay crop. Figures 26 and 27 show the growth curves for a millet crop

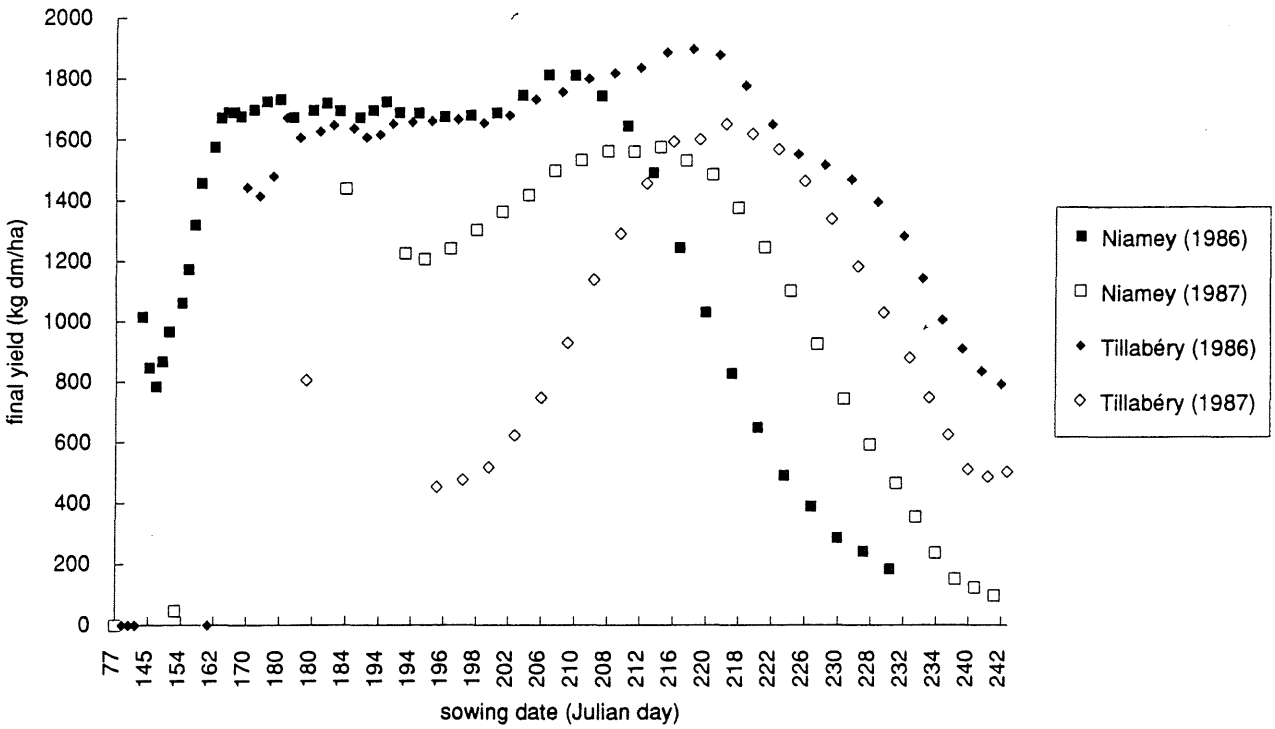


Figure 25. Simulated final dry matter yields of storage organs for water-limited millet production for different sowing dates at Niamey and Tillabéry, during 1986 and 1987, using daily meteorological data.

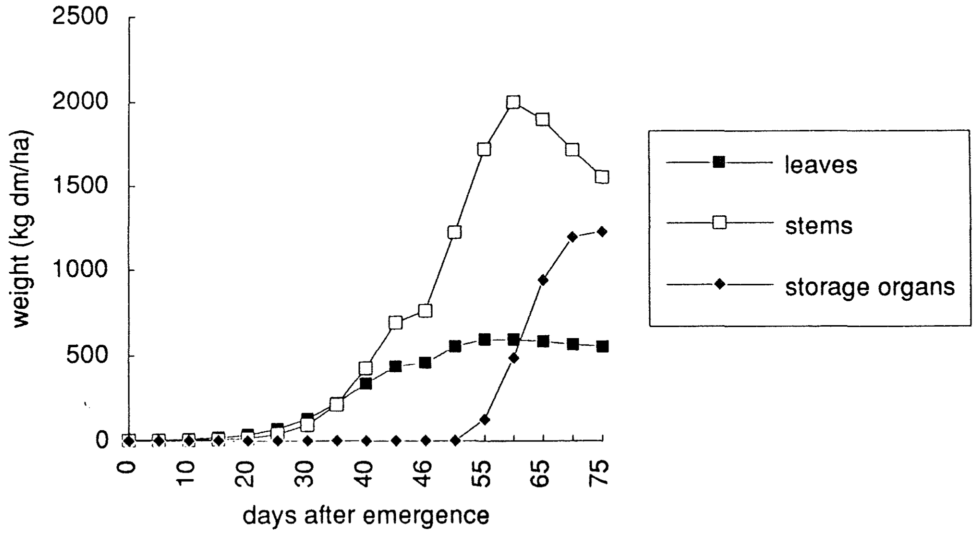


Figure 26. Simulated dry matter yield of leaves, stems and storage organs for water-limited millet production at Niamey during 1987, after sowing date 189/192, using daily meteorological data.

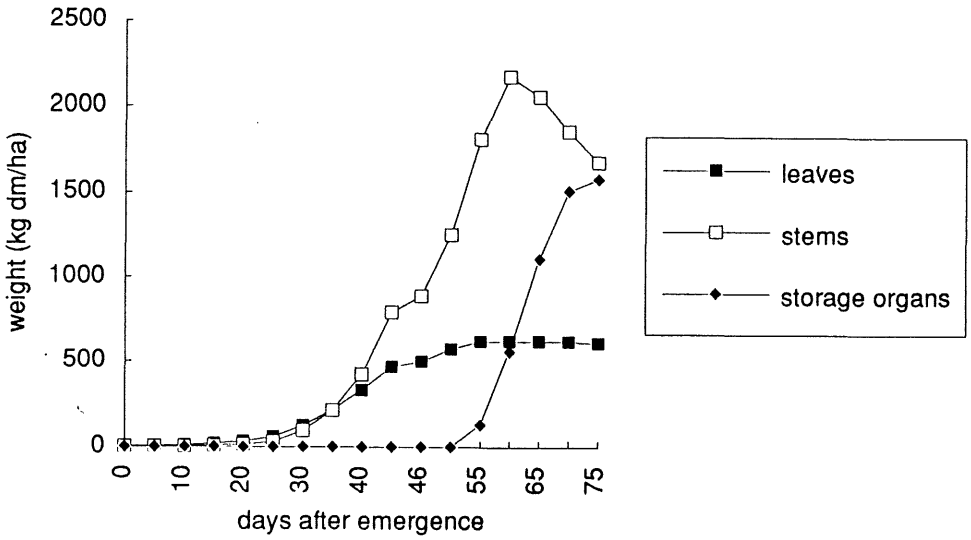


Figure 27. Simulated dry matter yield of leaves, stems and storage organs for water-limited millet production at Niamey during 1987, after sowing date 189/212, using daily meteorological data.

at Niamey in 1987, for sowing dates 189/192 and 189/212, respectively. It is noted that the latter sowing date results in higher dry matter yields of all crop components. Figure 28 indicates that the crop sown at day 189/212 even received less precipitation than the crop sown at day 189/192. However, the distribution of the precipitation for the crop sown at day 189/212 appeared to be much more favorable, resulting in a higher leaf area index throughout the growing period (Figure 29). The low leaf area index values indicate the importance of the specific leaf area (m^2 leaf.kg^{-1} leaf dm) parameter, which determines how much leaf area is eventually formed after assimilate allocation to the leaves.

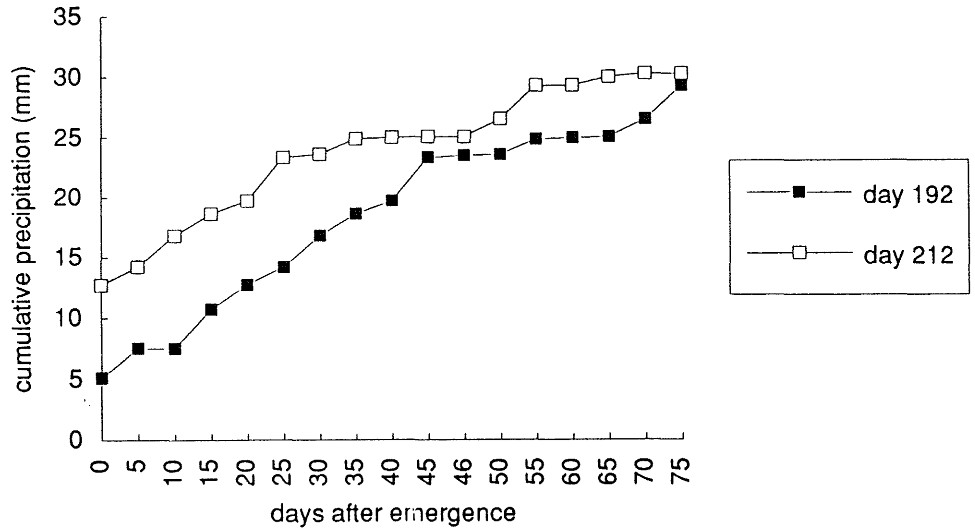


Figure 28. Cumulative precipitation at Niamey during 1987, during the growing period following sowing dates 189/192 and 189/212, starting after onset of the simulation of the water balance.

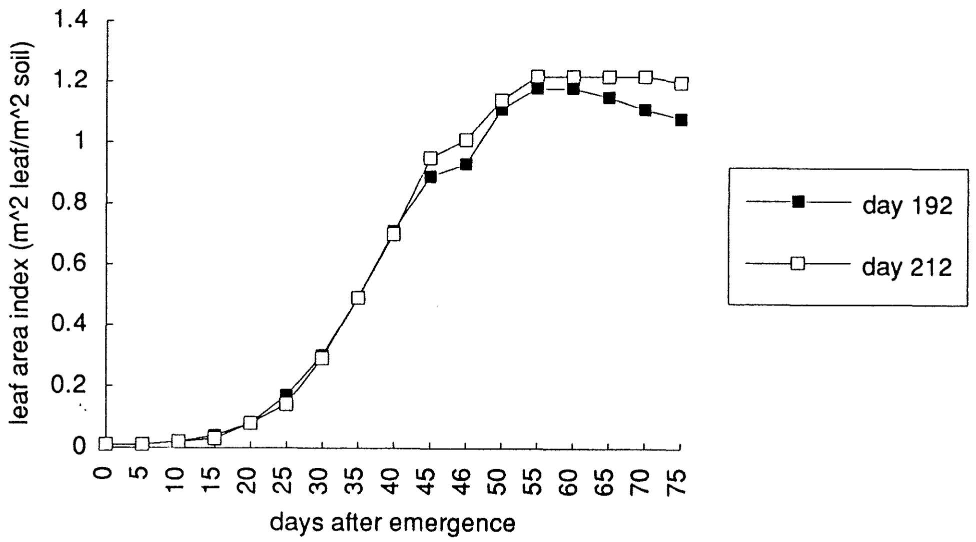


Figure 29. Simulated leaf area index for water-limited millet production at Niamey during 1987, after sowing dates 189/192 and 189/212, using daily meteorological data.

2.8.2 sensitivity analysis millet growth simulations using daily meteorological data

A sensitivity analysis was carried out for the performance of the millet growth model for the conditions of Niamey in the years 1986 and 1987, for the sowing dates resulting from the in section 2.7 indicated sowing strategy, and for the sowing dates resulting in the highest yield. The *(1)* duration of the vegetative growth; the *(2)* duration of the generative growth; the *(3)* soil moisture content between pF 2.4 and 4.2; the *(4)* transmission zone permeability of the top soil and sub soil; the *(5)* maximum surface storage; the *(6)* maximum rooting depth; the *(7)* precipitation; the *(8)* global radiation; the *(9)* average day temperature; the *(10)* vapor pressure; the *(11)* average wind

Table 9. Relative sensitivity of millet growth model WOFOST version 4.1 to changes in parameter values as indicated in the text of section 2.8.2, for Niamey in 1986 and 1987, and two sowing dates.

parameter	Δ	total above ground dry matter				storage organs			
		Niamey 1986		Niamey 1987		Niamey 1986		Niamey 1987	
		140/143	140/203	189/192	189/212	140/143	140/203	189/192	189/212
(1)	-10%	83%	68%	60%	69%	129%	70%	61%	74%
	0%	100%	100%	100%	100%	100%	100%	100%	100%
	10%	109%	128%	165%	126%	53%	102%	157%	93%
(2)	-10%	97%	93%	93%	94%	103%	89%	91%	91%
	0%	100%	100%	100%	100%	100%	100%	100%	100%
	10%	103%	106%	107%	106%	99%	109%	109%	107%
(3)	-10%	99%	100%	108%	100%	93%	100%	108%	100%
	0%	100%	100%	100%	100%	100%	100%	100%	100%
	10%	102%	107%	93%	100%	107%	100%	94%	100%
(4)	-10%	100%	100%	100%	100%	100%	100%	100%	100%
	0%	100%	100%	100%	100%	100%	100%	100%	100%
	10%	100%	100%	100%	100%	100%	100%	100%	100%
(5)	-10%	100%	100%	100%	100%	100%	100%	100%	100%
	0%	100%	100%	100%	100%	100%	100%	100%	100%
	10%	100%	100%	100%	100%	100%	100%	100%	100%
(6)	-10%	98%	101%	118%	100%	89%	101%	117%	100%
	0%	100%	100%	100%	100%	100%	100%	100%	100%
	10%	102%	99%	87%	100%	111%	99%	87%	100%
(7)	-10%	97%	100%	81%	100%	96%	100%	82%	100%
	0%	100%	100%	100%	100%	100%	100%	100%	100%
	10%	101%	100%	121%	100%	105%	100%	121%	100%
(8)	-10%	74%	69%	62%	68%	98%	70%	62%	69%
	0%	100%	100%	100%	100%	100%	100%	100%	100%
	10%	126%	132%	154%	133%	97%	125%	154%	127%
(9)	-10%	92%	86%	88%	89%	97%	85%	86%	88%
	0%	100%	100%	100%	100%	100%	100%	100%	100%
	10%	102%	110%	103%	103%	104%	109%	103%	102%
(10)	-10%	100%	100%	101%	100%	100%	100%	101%	100%
	0%	100%	100%	100%	100%	100%	100%	100%	100%
	10%	100%	100%	99%	100%	100%	100%	99%	100%
(11)	-10%	103%	100%	111%	100%	111%	100%	111%	100%
	0%	100%	100%	100%	100%	100%	100%	100%	100%
	10%	97%	100%	91%	100%	91%	100%	91%	100%
(12)	-10%	106%	100%	132%	100%	121%	100%	131%	100%
	0%	100%	100%	100%	100%	100%	100%	100%	100%
	10%	94%	100%	78%	100%	85%	99%	79%	98%

speed; and the *(12)* potential evaporation rate from a water and soil surface, and potential evapotranspiration rate, were increased and decreased with 10% to monitor the effect on final total above ground dry matter yield and storage organ dry matter yield. To obtain a range of simulation results to account for natural variability in the parameters, an estimation should be made of this variability. The percentage used for this sensitivity analysis is not representative for this variability.

In general the quantitative sensitivity of the model varied not only among years but also among sowing dates, whereas the model response was non-linear. Table 9 shows the relative responses of the millet growth model to the changes in parameter values.

On average a change in the duration of the vegetative growth resulted in a strong change in the dry matter yield, more unequivocal for the total above ground dry matter than for the storage organs. A less strong reaction was observed for a change in the duration of the generative growth, likely because the generative growth lasts shorter than the vegetative growth and because CO_2 assimilation may be hampered by leaf senescence and water shortage.

An equivocal and modest effect of changes in water holding capacity of the soil was observed for the early sowing only. No sensitivity of the model was observed for changes in the transmission zone permeability and maximum surface storage. Changes in maximum rooting depth had a highly variable but relatively modest effect on model performance.

For the early sowing a decrease and an increase in precipitation resulted in an unequivocal decrease and increase in yield, respectively. In case of the early sowing a considerable part of the crop cycle falls within the part of the growing season with the highest variability in precipitation. This variability is partly alleviated or amplified by the increased or decreased precipitation, respectively. The most pronounced effect was noted for changes in global radiation. In all but one situation an increase or decrease in global radiation resulted in a more than proportional increase or decrease in yield, respectively. Apparently CO_2 assimilation was not completely saturated, despite the low leaf area index (Figure 29), which was confirmed earlier by Figures 21 up to 24, showing a depression of the yield as a result of radiative transmission reducing clouds. The smallest effect is seen for the situation where yield is not so much determined by global radiation as it is limited by moisture availability: the early sowing at Niamey in 1986.

The positive, however modest response of simulated yield to an increased average day temperature indicates that yield formation was to a certain degree determined by temperature as well. Temperatures below optimum may have hampered leaf appearance or CO_2 assimilation.

For the early sowing an increase in the potential evaporation rate from a water and soil surface and an increase in the potential evapotranspiration rate resulted in a decrease in yield, likely for the same reason as for variations in precipitation.

2.8.3 results millet growth simulations using monthly meteorological data

The same simulation procedures for millet growth as under section 2.8.1 were carried out, now using daily precipitation data (section 2.4.1) and monthly data for *(1)* average day temperature (section 2.4.2), *(2)* daily sunshine duration (section 2.4.3); *(3)* daily free water surface evaporation (E_0) (section 2.4.4); *(4)* daily soil evaporation (E_{soil}) (section 2.4.4); and *(5)* daily crop transpiration (T_{crop}) (section 2.4.4).

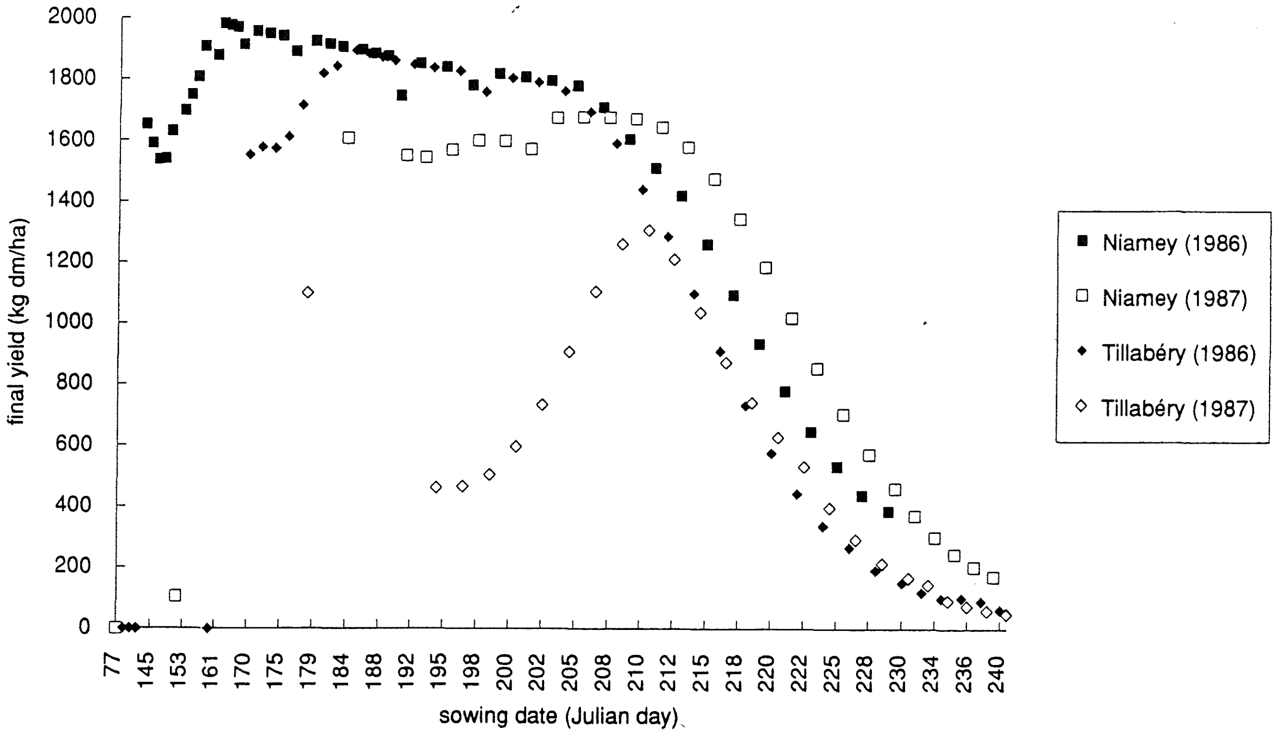


Figure 30. Simulated final dry matter yields of storage organs for water-limited millet production for different sowing dates at Niamey and Tillabéry, during 1986 and 1987, using monthly meteorological data.

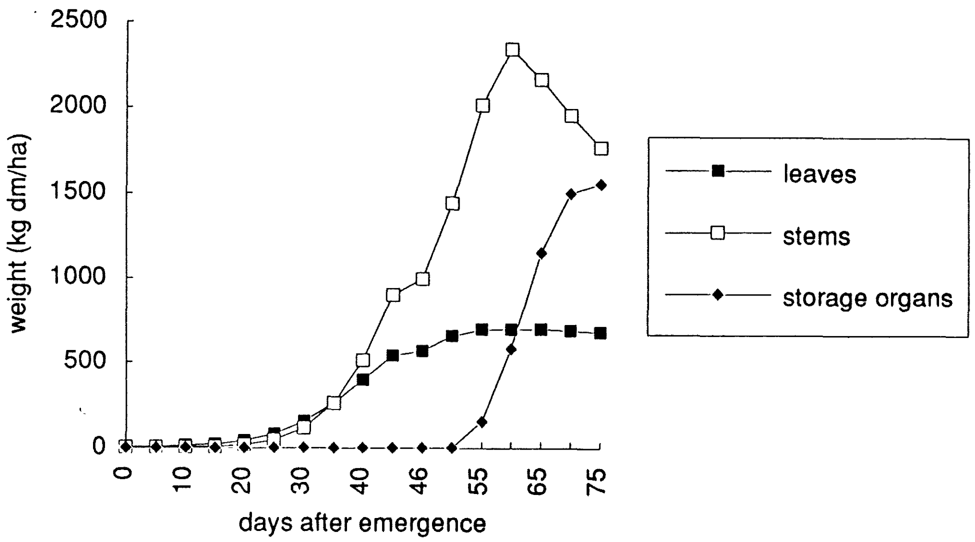


Figure 31. Simulated dry matter yield of leaves, stems and storage organs for water-limited millet production at Niamey during 1987, after sowing date 189/192, using monthly meteorological data.

Figure 30 shows the course of the yield of the storage organs for different sowing dates. For the early sowings at Niamey millet showed higher storage organ yields for the simulations on basis of monthly data than on basis of daily data. Whereas a similar trend - but much stronger - was observed for the late sowings at Tillabéry. Comparison of Figures 25 and 30 clearly learns that considerable

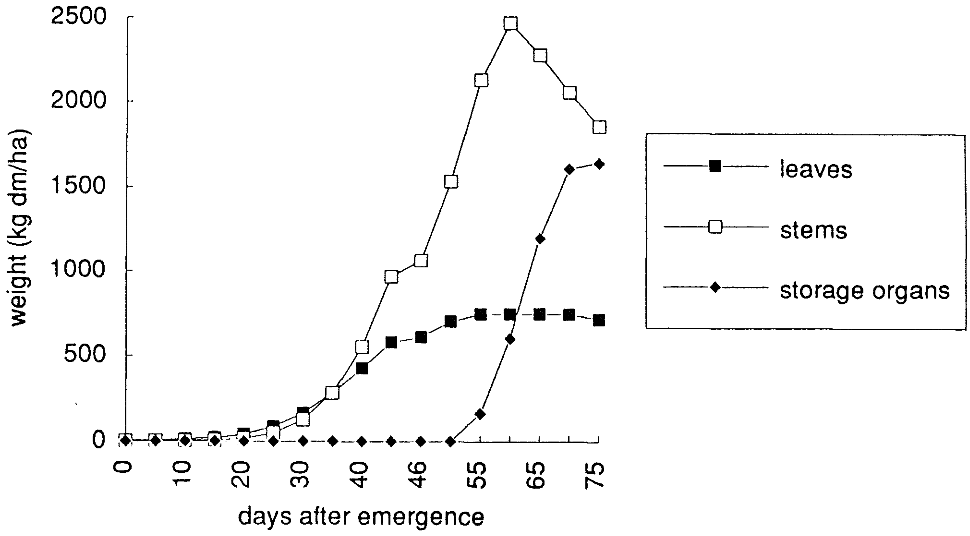


Figure 32. Simulated dry matter yield of leaves, stems and storage organs for water-limited millet production at Niamey during 1987, after sowing date 189/212, using monthly meteorological data.

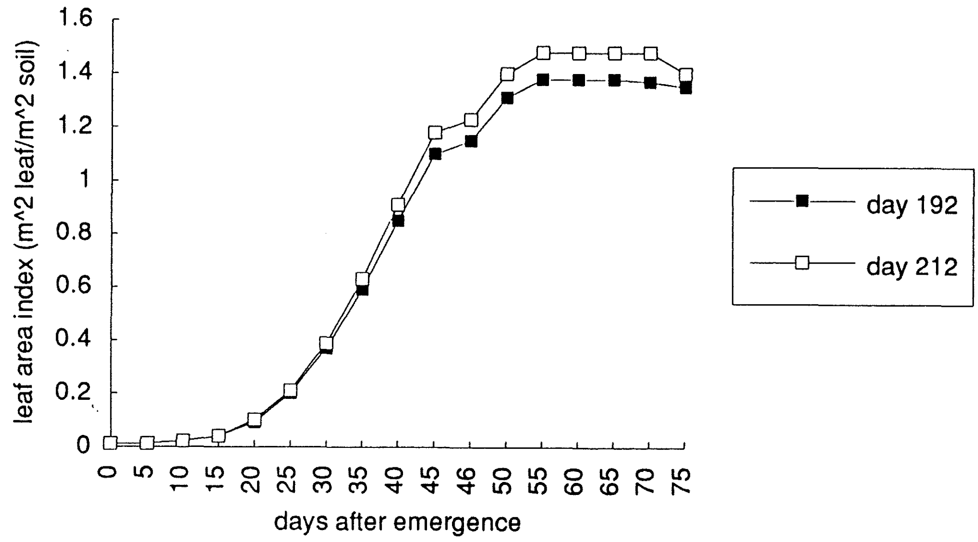


Figure 33. Simulated leaf area index for water-limited millet production at Niamey during 1987, after sowing dates 189/192 and 189/212, using monthly meteorological data.

differences existed between the millet growth simulations with different time resolution weather data. The higher yields for the monthly based weather data simulations can be seen in more detail in the growth curves of Figures 31 and 32, for the 189/192 and 189/212 sowings, respectively. Comparison with Figures 26 and 27 shows that the higher yields were calculated for all organs. The differences appeared to be larger for the 189/192 sowing. For the 189/192 sowing the daily and monthly weather data based simulations resulted in a storage organ yield of 1,227 and 1,553 kg dm.ha^{-1}, respectively, whereas for the 189/212 sowing this was 1,577 and 1,648 kg dm.ha^{-1}, respectively. Comparison of Figures 29 and 33 shows that calculated leaf area development was affected by the shift in time resolution. The monthly based weather data simulations showed a higher leaf area index, whereas this difference was more pronounced for the 189/192 than for the 189/212 sowing.

2.9 AN AGRO-ECOLOGICAL CLASSIFICATION

2.9.1 an agro-ecological classification - results

In order to account for a temporal variability an agro-ecological classification requires long-term weather records. Millet growth simulations as mentioned in section 2.8.3 were done for Tillabéry (31 years), Niamey (42 years), Gaya (17 years), Tahoua (32 years), Birni N'Konni (36 years), Maradi (29 years), Zinder (40 years), Magaria (7 years), Maïne Soroa (33 years) and N'Guigmi (24 years) (Figure 3). Annex C summarizes the years for which millet growth was simulated. A maximum surface storage capacity of 3 cm was assumed. Additionally it was assumed that ground water did not influence the soil water balance. For each location and each year sowing date was determined according to the strategy mentioned in section 2.7. The simulation of the soil water balance started 3 days before sowing. Table 10 gives the results of this analysis. Whereas Figure 42 shows the cumulative frequency distributions for the storage organ yields. The cumulative frequency distributions for total above ground yield showed a similar pattern.

From Table 10 it could be derived that for Magaria considerably higher long-term yields were calculated than for Zinder in connection with a much lower temporal variability, though their location is relatively close (Figure 3). Even though Magaria actually receives more precipitation (long-term yearly average of 576 mm) than Zinder (long-term yearly average of 534 mm) with a smaller standard deviation (184 and 197 mm, respectively), it should be noted that for Zinder 40 years were used for the calculation of the long-term figures, whereas for Magaria this were only 7 years, coinciding with a period of relatively high and stable yields. For relatively small time spans the temporal variation appears to be not normally distributed. As this could seriously affect the viability of a comparison, Magaria will not be included in the following considerations.

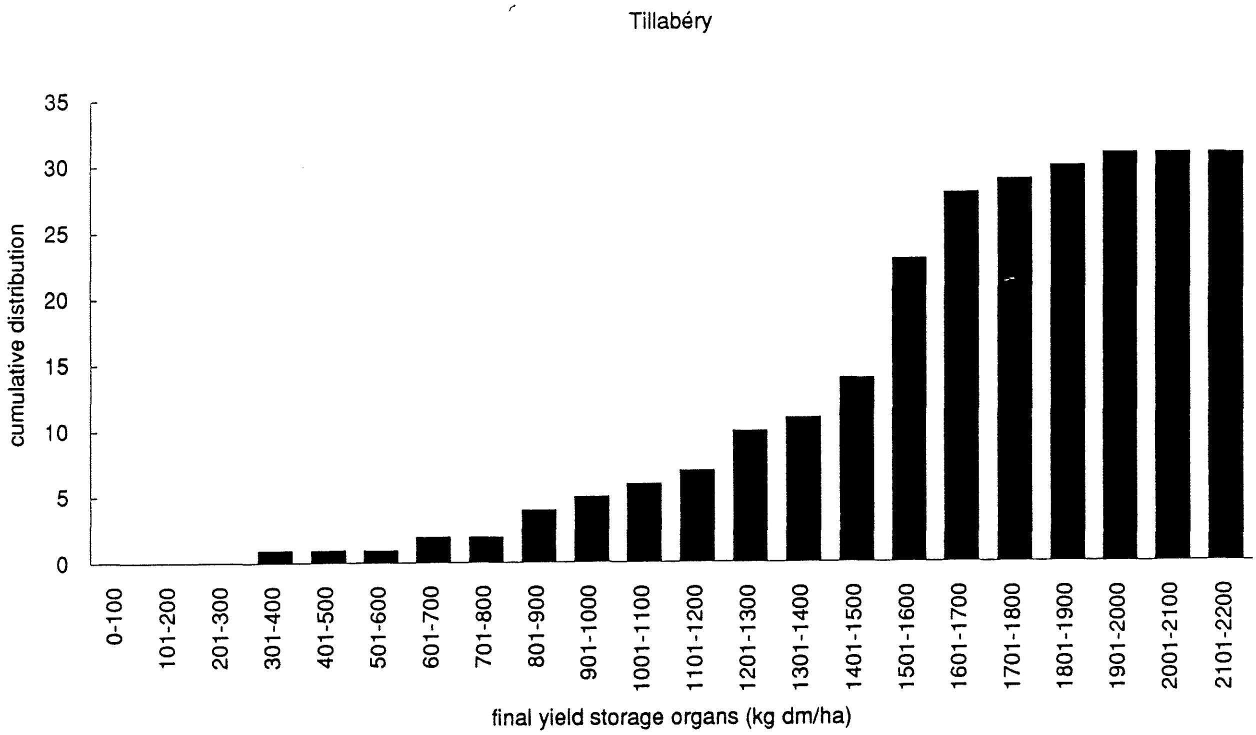
Table 10 shows that the highest long-term storage organ yield was calculated for Birni N'Konni, 1,605 kg $dm.ha^{-1}$. N'Guigmi showed the lowest long-term storage organ yield, 537 kg $dm.ha^{-1}$, coinciding with the highest standard deviation calculated, both in absolute (512 kg $dm.ha^{-1}$) and relative (95.3%) terms. With the exception of N'Guigmi all long-term storage organ yields did not differ considerably: varying between 1,346 and 1,605 kg $dm.ha^{-1}$. The standard deviation, however, showed a much larger variability: varying between 205 kg $dm.ha^{-1}$ for Niamey and 467 kg $dm.ha^{-1}$ for Maïne Soroa. Converted to the coefficients of variation, this was between 13.0% for Niamey and 34.7% for Maïne Soroa. In rough terms storage organ yields in Niamey, Gaya, Tahoua and Birni N'Konni showed relatively low coefficients of variations: 13%, 14.5%, 16%, and 16.6%, respectively.

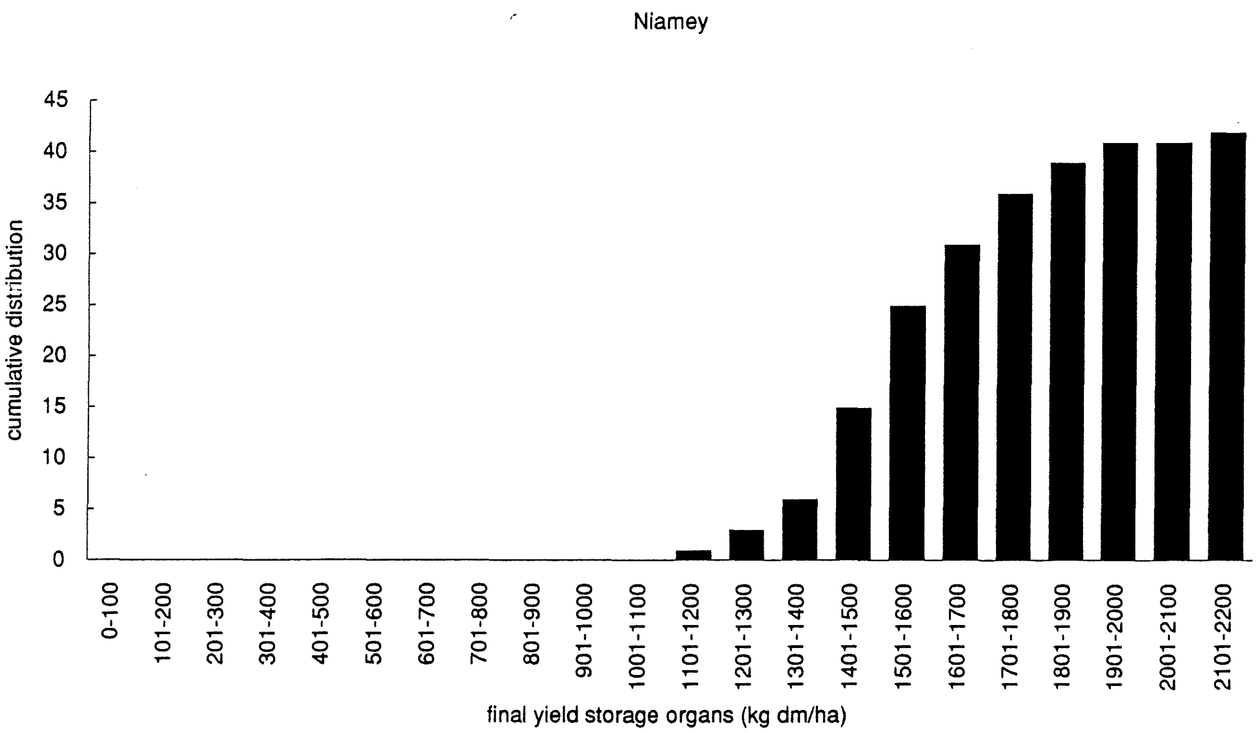
The variability between locations in long-term total above ground yield was less than for storage organ yield. The highest long-term total above ground yield was calculated for Birni N'Konni, 4,564 kg $dm.ha^{-1}$.. N'Guigmi showed the lowest long-term total above ground yield, 3,039 kg $dm.ha^{-1}$, coinciding with the highest coefficient of variation (36.7%). The highest standard deviation was found for Zinder. Excluding N'Guigmi, the long-term total above ground yields varied between 3,957 and 4,731 kg $dm.ha^{-1}$. The standard deviation varied between 637 kg $dm.ha^{-1}$ for Niamey and 1,254 kg $dm.ha^{-1}$ for Zinder. Considering the coefficients of variation, it varied between 14.2% for Niamey and 29.6% for Zinder. The coefficients of variation did not deviate substantially from the coefficients of

Table 10. Averages and standard deviations of sowing day, storage organ yield, total above ground yield, cumulative available precipitation, cumulative transpiration and available precipitation use efficiency for simulated water-limited millet production for 10 locations throughout Niger for long-term periods.

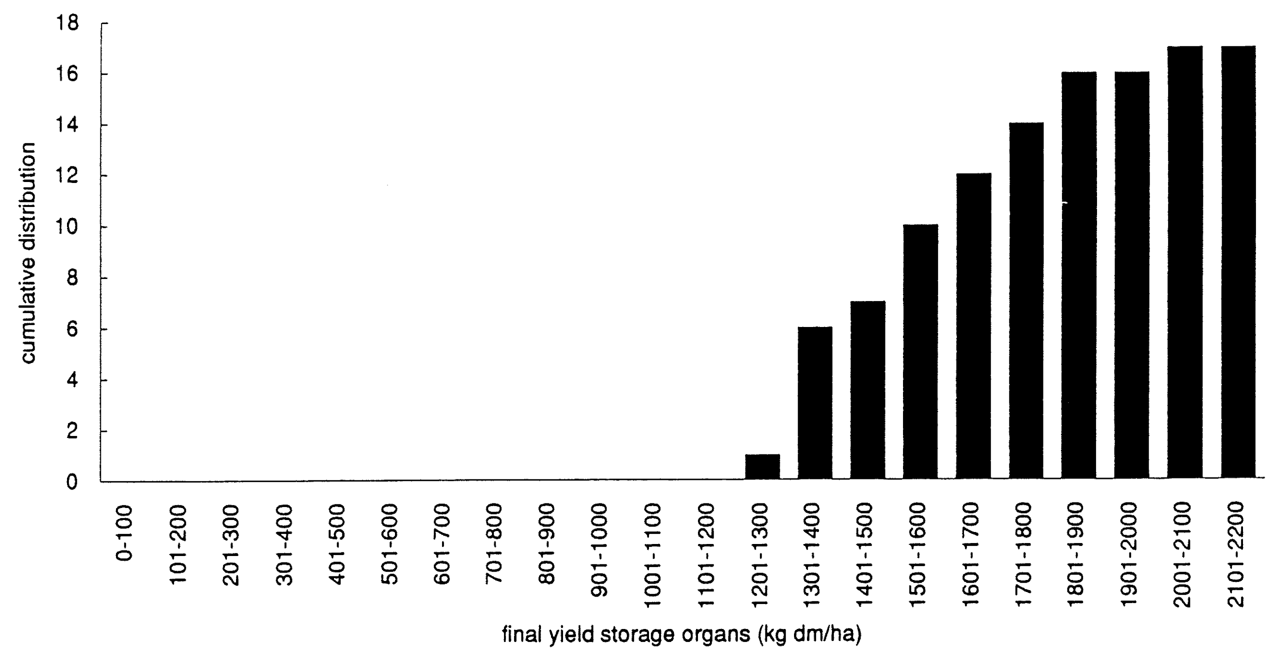
station		sowing day	storage organ yield (kg dm.ha^{-1})	total above ground yield (kg dm.ha^{-1})	cumulative precipitation (mm)	cumulative transpiration (mm)	precipitation use efficiency (kg so dm.mm^{-1})
Tillabéry	x	174	1,394	3,957	325	76	4.65
	σ	11	357	1,072	110	21	1.76
	n	31	31	31	31	31	31
Niamey	x	169	1,580	4,492	416	81	4.18
	σ	13	205	637	116	12	1.56
	n	42	42	42	42	42	42
Gaya	x	158	1,574	4,433	459	75	3.78
	σ	7	229	722	126	13	1.46
	n	17	17	17	17	17	17
Tahoua	x	176	1,579	4,598	295	85	5.73
	σ	14	252	714	86	15	1.68
	n	32	32	32	32	32	32
Birni N'Konni	x	167	1,605	4,564	390	82	4.63
	σ	14	267	820	128	16	1.85
	n	36	36	36	36	36	36
Maradi	x	175	1,499	4,310	381	73	4.29
	σ	15	368	1,095	114	19	1.72
	n	29	29	29	29	29	29
Zinder	x	177	1,439	4,238	379	75	4.09
	σ	16	382	1,254	122	20	1.42
	n	40	40	40	40	40	40
Magaria	x	171	1,642	4,731	376	83	4.81
	σ	9	154	569	147	10	1.34
	n	7	7	7	7	7	7
Maïne Soroa	x	182	1,346	4,025	302	72	4.70
	σ	13	467	1,071	111	19	2.03
	n	33	33	33	33	33	33
N'Guigmi	x	201	537	3,039	153	57	3.16
	σ	15	512	1,116	72	19	2.34
	n	24	24	24	24	24	24

variation found for the storage organ yield, with the exception of Maïne Soroa and N'Guigmi. At Maïne Soroa and N'Guigmi the coefficients of variation for the storage organ yields (34.7 and 95.3%, respectively) were considerably higher than for the total above ground yield (26.6 and 36.7%, respectively).


Tillabéry
cumulative distribution
0
5
10
15
20
25
30
35
0-100
101-200
201-300
301-400
401-500
501-600
601-700
701-800
801-900
901-1000
1001-1100
1101-1200
1201-1300
1301-1400
1401-1500
1501-1600
1601-1700
1701-1800
1801-1900
1901-2000
2001-2100
2101-2200
final yield storage organs (kg dm/ha)

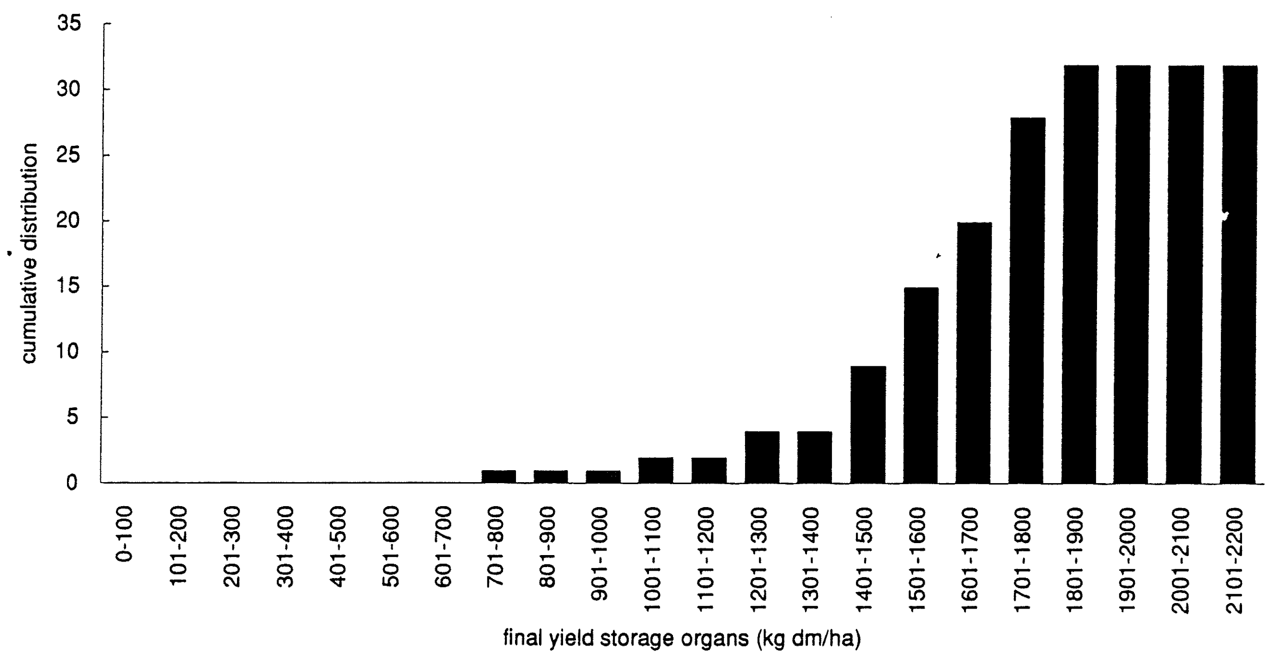

Niamey
cumulative distribution
0
5
10
15
20
25
30
35
40
45
0-100
101-200
201-300
301-400
401-500
501-600
601-700
701-800
801-900
901-1000
1001-1100
1101-1200
1201-1300
1301-1400
1401-1500
1501-1600
1601-1700
1701-1800
1801-1900
1901-2000
2001-2100
2101-2200
final yield storage organs (kg dm/ha)

Gaya



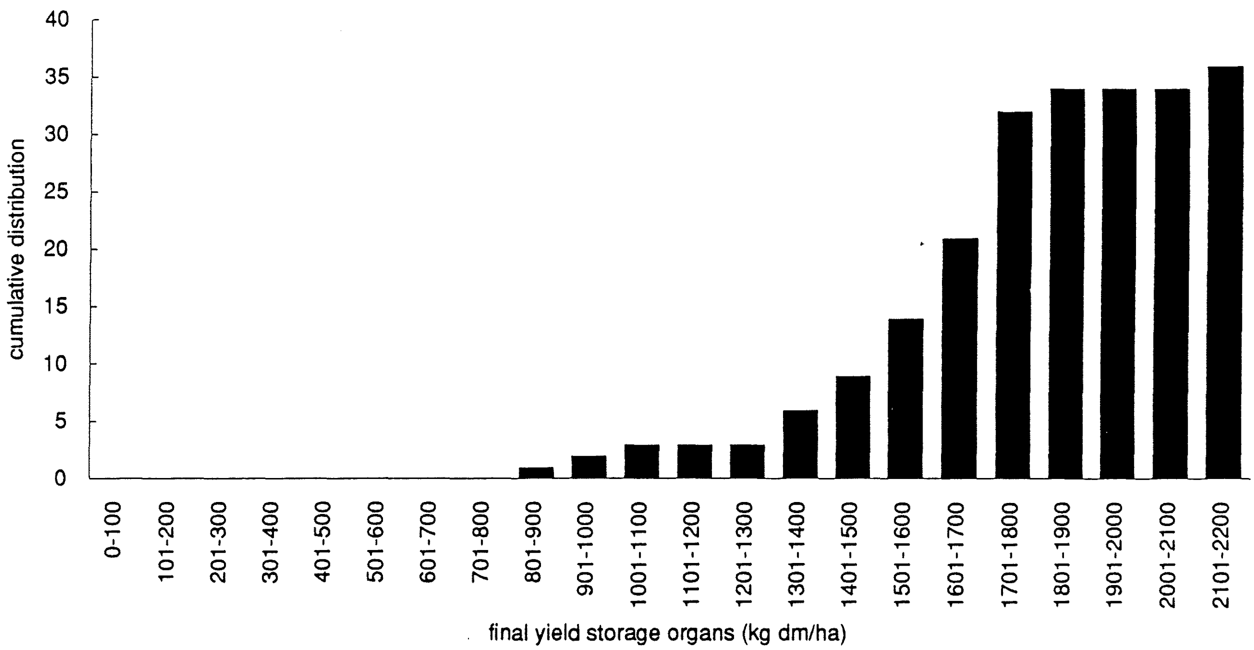
cumulative distribution
0
2
4
6
8
10
12
14
16
18
0-100
101-200
201-300
301-400
401-500
501-600
601-700
701-800
801-900
901-1000
1001-1100
1101-1200
1201-1300
1301-1400
1401-1500
1501-1600
1601-1700
1701-1800
1801-1900
1901-2000
2001-2100
2101-2200
final yield storage organs (kg dm/ha)

Tahoua

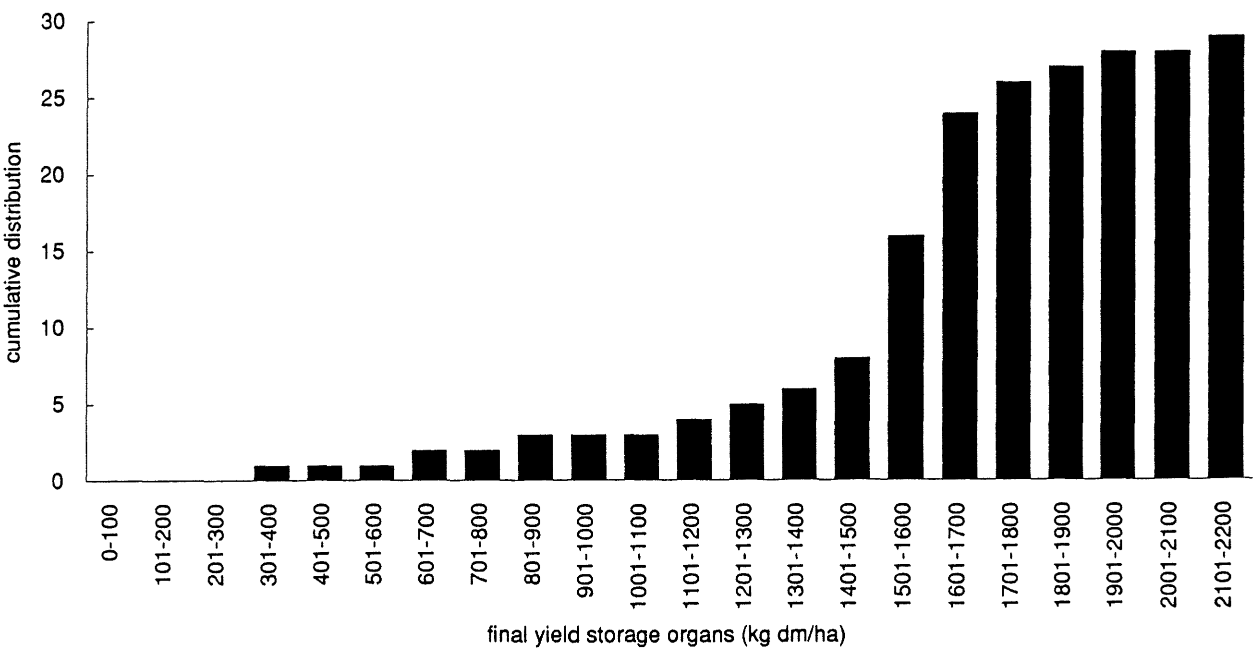


cumulative distribution
0
5
10
15
20
25
30
35
0-100
101-200
201-300
301-400
401-500
501-600
601-700
701-800
801-900
901-1000
1001-1100
1101-1200
1201-1300
1301-1400
1401-1500
1501-1600
1601-1700
1701-1800
1801-1900
1901-2000
2001-2100
2101-2200
final yield storage organs (kg dm/ha)

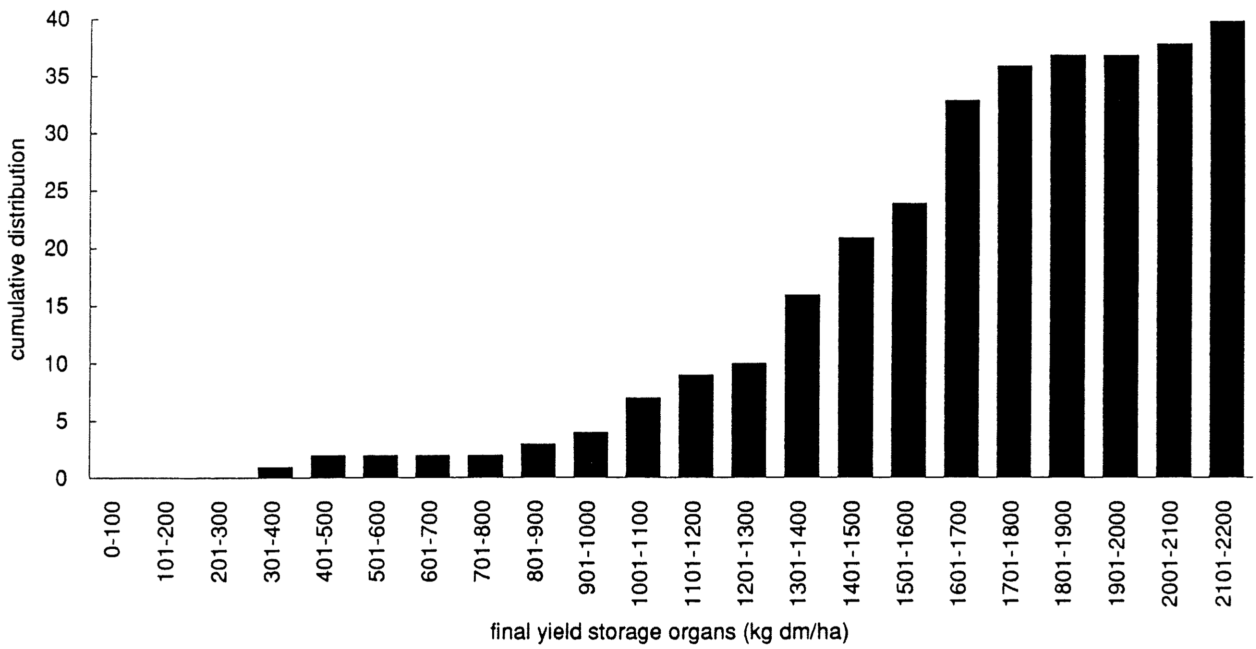
Birni N'Konni



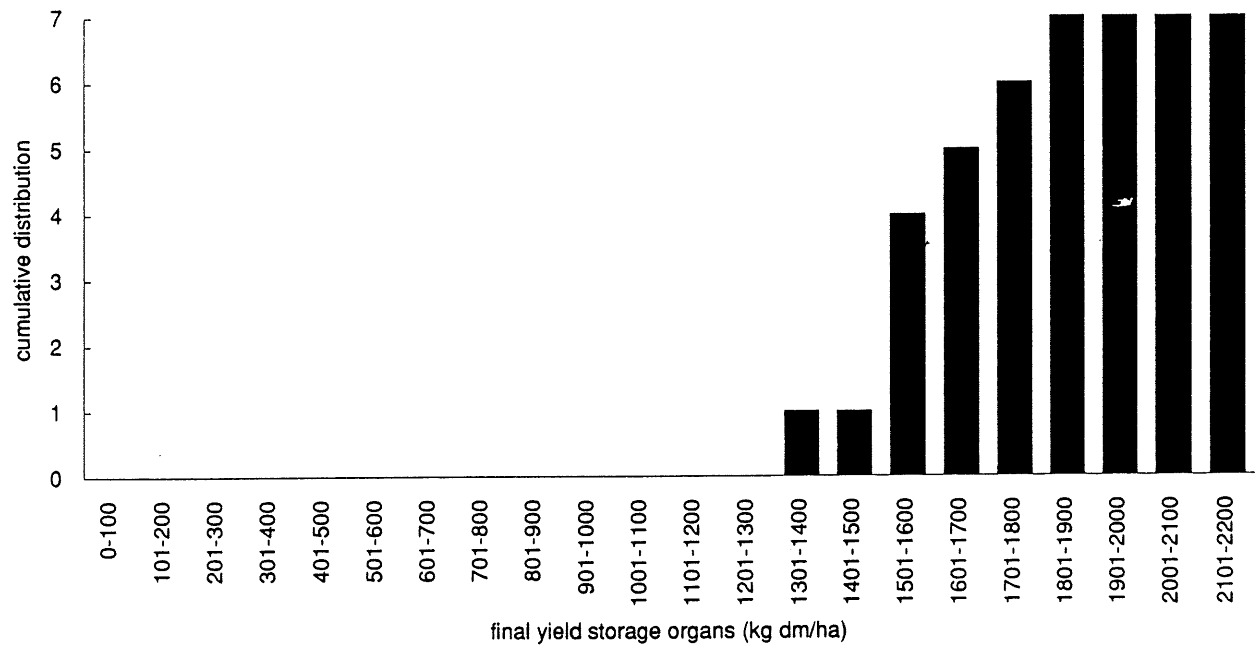
Maradi

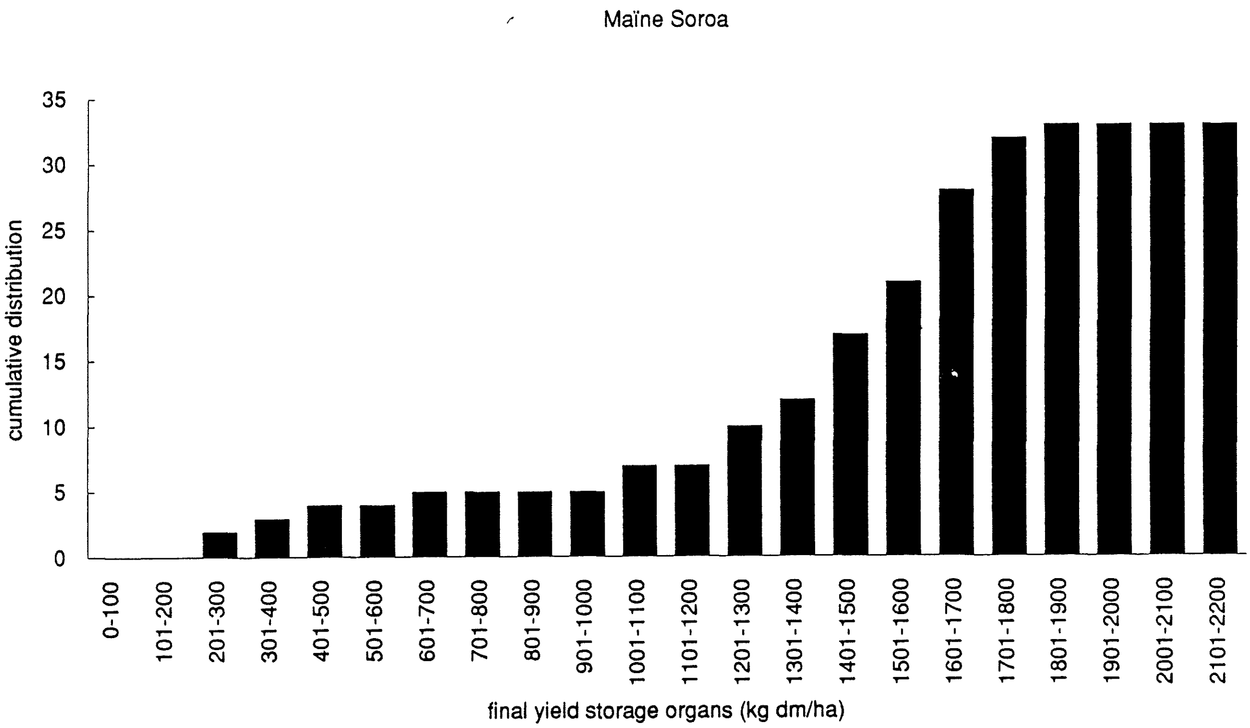


Zinder



Magaria





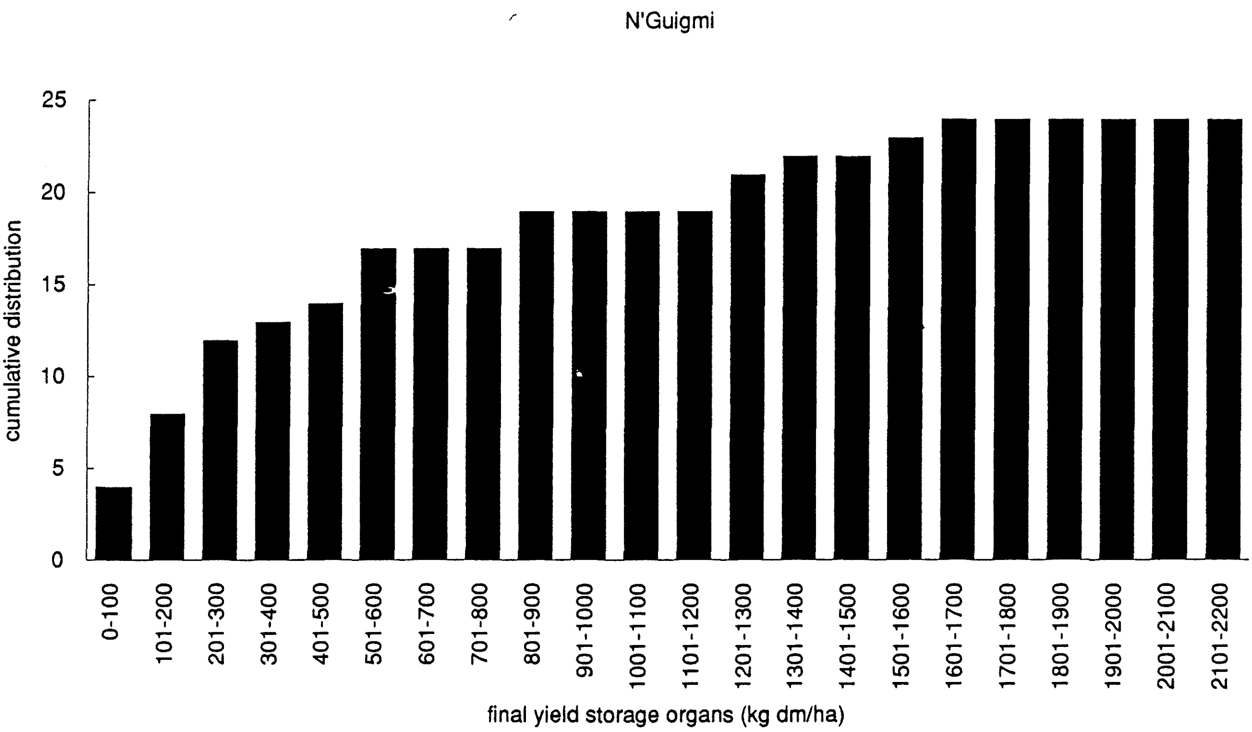


Figure 34. Frequency distributions of simulated final dry matter yields of storage organs for water-limited millet production for different locations throughout Niger for long-term periods, using monthly meteorological data.

Table 11. Correlation coefficients for long-term relationships between sowing date and available precipitation as independent variables and storage organ dry matter and total above ground dry matter as dependent variables, for simulated water-limited millet production for 10 locations throughout Niger for long-term periods.

station		independent variable			
		sowing date		precipitation	
		dependent variable			
		storage organs	above ground	storage organs	above ground
Tillabéry	r	0.164	0.197	0.239	0.217
	n	31	31	31	31
Niamey	r	0.028	0.084	-0.498	-0.569
	n	42	42	42	42
Gaya	r	-0.378	-0.371	-0.628	-0.611
	n	17	17	17	17
Tahoua	r	-0.067	0.030	0.120	-0.050
	n	32	32	32	32
Birni N'Konni	r	-0.122	-0.116	-0.448	-0.485
	n	36	36	36	36
Maradi	r	-0.041	0.058	0.151	0.047
	n	29	29	29	29
Zinder	r	0.023	0.117	0.159	0.044
	n	40	40	40	40
Magaria	r	0.642	0.513	-0.659	-0.533
	n	7	7	7	7
Maïne Soroa	r	-0.089	0.193	0.315	0.129
	n	33	33	33	33
N'Guigmi	r	-0.583	-0.249	0.637	0.495
	n	24	24	24	24

The long-term efficiency with which the precipitation was used to produce storage organ dry matter varied between 3.16 kg dm.mm^{-1} for N'Guigmi and 5.73 kg dm.mm^{-1} for Tahoua. The long-term precipitation use efficiency for Birni N'Konni amounted to 4.63 kg dm.mm^{-1}. The standard deviation for the long-term precipitation use efficiency varied between 1.42 kg dm.mm^{-1} for Zinder and 2.34 kg dm.mm^{-1} for N'Guigmi, with coefficients of variations of 34.7% and 74%, respectively.

Table 11 shows that long-term correlations between on the one hand independent variables sowing date and available precipitation and on the other hand dependent variables storage organ dry matter and total above ground dry matter were weak. The strongest correlations were found for independent variable available precipitation - in absolute terms varying between 0.047 and 0.637, omitting Magaria from these considerations. These correlations were not unequivocal: both positive and negative correlations were found. Negative correlations were found for locations with relatively high precipitation (Niamey, Gaya and Birni N'Konni), whereas positive correlations could be found for locations with relatively low precipitation (Tillabéry, Maïne Soroa and N'Guigmi) - albeit both were still weak to very weak.

2.9.2 an agro-ecological classification - discussion

When comparing different figures, it should be born in mind that differences in considered time spans could interfere. This was best illustrated for Magaria: the period considered was not representative for a longer time span - neither with respect to its average values nor its temporal variation. To avoid this sort of complications it is advisable to apply longer periods only.

The simulated long-term water-limited millet yields did not show a high spatial variation: excluding N'Guigmi, located in a very low rainfall area (see annex A), storage organ dry matter yields varied between 1,346 and 1,605 (Birni N'Konni) or 1,642 (Magaria) kg $dm.ha^{-1}$. In a similar setting total above ground dry matter yields varied between 3,957 and 4,598 (Tahoua) or 4,731 (Magaria) kg $dm.ha^{-1}$. The value of both variables seemed to be associated with their location in the different precipitation zones (Figure 1) - only to the degree that the dryer locations Tillabéry, Maïne Soroa and N'Guigmi could more or less be distinguished from the other locations.

The temporal variation, however, was markedly larger. Only the temporal variation is of main importance to the local actor, who sees himself confronted with certain boundary conditions. As only actual yields are determinant for a successful crop, and not relative yields, it is the standard deviation that determines whether a certain temporal variation is acceptable or not. However, because most simulated yield averages were rather close, also the coefficients of variation could be indicative. Then it shows that in the upper yield category encompassing most locations - Tillabéry, Niamey, Gaya, Tahoua, Birni N'Konni, Maradi and Zinder - considerable differences in temporal variation could be observed. For the storage organ yields it varied from 205 (13.0%) kg $dm.ha^{-1}$ for Niamey to 382 (26.5%) kg $dm.ha^{-1}$ for Zinder. For the total above ground yield this varied from 637 (14.2%) kg $dm.ha^{-1}$ for Niamey to 1,254 (29.6%) kg $dm.ha^{-1}$ for Zinder. This variation of variations could hardly be associated with long-term precipitation averages. Relatively high precipitation locations as Maradi and Zinder showed much higher standard deviations for the storage organ yields (368 and 382 kg $dm.ha^{-1}$, respectively) than a low precipitation location as Tahoua (252 kg $dm.ha^{-1}$). Whereas the lower yield category, consisting of Maïne Soroa and N'Guigmi only, with low precipitation figures showed much higher standard deviations: 467 kg $dm.ha^{-1}$ for Maïne Soroa and 512 kg $dm.ha^{-1}$ for N'Guigmi.

This impression is confirmed by the absence of an acceptably solid correlation between available precipitation and dry matter yield. Considering the correlations between precipitation and yield it may be noted that for locations on either side of the precipitation range a trend could be observed. For locations characterized by a high long-term precipitation average - Niamey, Gaya and Birni N'Konni - weak negative correlations could be observed, whereas for locations characterized by a low long-term precipitation average - Maïne Soroa and N'Guigmi - weak positive correlations could be observed. Displaying some reserve when seriously considering these weak correlations, it could be hypothesized that in the high precipitation areas precipitation had a somewhat negative effect on simulated yield as a result of its interference with available radiation. This might indicate that under such conditions radiation is limiting simulated growth more than precipitation. However, as already mentioned in section 2.8.1, this effect highly depends on the course of the specific leaf area. In the low precipitation areas precipitation might have had a somewhat positive effect on simulated yield because of an actual water-limitation.

The similar coefficients of variation for storage organ yield and for total above ground yield for the upper yield category, and the substantially deviating coefficients of variation for storage organ yield and for total above ground yield for the lower yield category, seem to be indicative for a sharply decreasing yield stability. Especially the simulated storage organ yield was sensitive to changing precipitation patterns, whereas the simulated total above ground yield showed a much higher stability. Still, this could not simply be attributed to differences in seasonal precipitation. Maïne Soroa and Tahoua showed similar long-term yearly precipitation averages (373 and 379 mm, respectively), with similar standard deviations (115 and 101 mm, respectively). For the simulated total above ground yield in Maïne Soroa and Tahoua coefficients of variation of 15.5 and 26.6%, respectively, were calculated, whereas for the storage organ yield this amounted to 16 and 34.7%, respectively. The difference in available precipitation and its standard deviation may to a certain degree explain the differences in yield and yield stability: Tahoua had a somewhat lower available precipitation (295 vs. 302 mm), however, also a lower standard deviation (86 vs. 111 mm), than Maïne Soroa. In this comparison Tillabéry seems to occupy an intermediate position: a relatively high standard deviation (110 mm), partly offset by an increased available precipitation (325 mm), resulting in intermediate coefficients of variation for simulated storage organ yield and total above ground yield of 25.6 and 27.1%, respectively.

Still it seems obvious that available precipitation data or even yearly precipitation data do not give sufficient insight in the crop growth potentials of a certain location. Correlations in this field were weak. The distribution of the precipitation over the growth period and its link with crop growth and development processes is of at least equal importance.

When comparing the millet growth potentials calculated in section 2.9.1 with the actual millet production figures, whether mentioned in Table 1, or by Adamou (1980), it seems obvious that millet yields in Niger are still far below their potentials. Applying the average Nigerien value of 400 kg grains.ha^{-1}, mentioned by Adamou (1980), millet yield could generally still be increased by a factor 3 to 4. When comparing the millet growth potentials with actual millet production figures, however, and the drawing of conclusions concerning a possible increase in production, it should be realized that the actual millet production figures do not necessarily give a reliable picture of the actual production. This is already demonstrated by the difference in production figures mentioned by Adamou (1980) and by the Nigerien Ministry of Agriculture and Animal Husbandry, shown in Table 1 - roughly a factor 2.

When compiling actual crop yield data for comparison with simulation results some aspects deserve special attention. *(1)* Reliable estimates of actual production should be free of objectives other than reliably estimating crop production - a complex, actually political problem involving all national and international institutions directly or indirectly involved in its food production and food distribution. *(2)* It is very likely that high losses of already harvested product occur - losses that increase with time after harvest. These losses should clearly be distinguished from field production, because they involve different problems with different approaches to solve these problems. *(3)* Losses occur during the field period and during the harvest itself, which interfere with a clear view on the field production. Though the magnitude of these losses - e.g. caused by insects, mammals and birds consuming storage organs without further seriously affecting the functions of the crop, and weather conditions and mechanical harvest activities enhancing the loss of seeds from the ears - is obviously roughly related to the magnitude of the field production, these losses occur after production, and should therefore be accounted for as such. As a matter of course these effects should be distinguished from the so-called growth-reducing factors - pests, diseases, and also insects - that interfere with crop growth processes reducing the crop's ability to produce.

Subsequently it should be determined whether the calculated crop growth potentials represent the potentials envisaged, i.e. whether all environmental conditions were accounted for sufficiently accurately and the cultivar characteristics used for the simulations were representative for the relevant cultivars. The availability of data on environmental conditions is very variable, and may be limited. As was the case in this study. However, considering the survey nature of this type of studies, the spatial and temporal resolution of these data does not necessarily have to be as high as possible. For crop characteristics which strongly influence simulated crop growth and development, a range of genotypic variation should be determined to allow better anticipation on the prevailing environmental conditions and to make a better assessment of the crop growth potentials. With this respect Stoop (1986; 1987) reported about the use of different crops and crop cultivars in cropping systems for different toposequences, i.e. spatial variation of environmental conditions. Whereas Sivakumar (1988; 1990) reported about so-called weather-responsive crop management tactics, i.e. the adaptation of crop management to the temporal variation in the distribution of precipitation and soil moisture conditions. Finally it needs to be determined what the sowing criteria and crop management practices are of the local farmers, because they were established on basis of long-term experience under the prevailing environmental and socio-economic conditions. The millet growth simulation model presented in this report could be used in further studies in this field.

When using the millet growth simulation model along with currently measured meteorological data - to follow the course of the yield of the prevailing millet crop - it should be realized that the model calculates the course of the yield of a crop that is limited by water availability only - and for environmental conditions (weather and soil) and a crop (cultivar characteristics) as specifically defined in the model. It was noted before that there was a substantial difference between actual millet production and simulated water-limited yield potential. This difference could, along with uncertainties in the actual millet yield figures mentioned before, be attributed to: *(1)* millet growth limited by the availability of nutrients; *(2)* millet growth reduced by insects, pests and diseases; *(3)* millet growth interfered with by the occurrence of weeds; *(4)* an incorrect reproduction of millet cultivar characteristics; and *(5)* an incorrect or insufficient reproduction of the millet growth processes involved in water-limited production. Occurrence of nutrient-limitation and growth reduction as a result of insects, pests, diseases and weeds could at least partially be responsible for the observed difference between actual and simulated millet yield. Therefore the simulated millet yields could at their best indicate the trend in the production, i.e. the courses of actual and simulated yields coincide. However, occurrence of nutrient-limitation, and reduced growth as a result of insects, pests, diseases and weeds not only sets an additional reduction to yield figures, it will likely interact seriously with water-limited growth as well. This interaction generally results in growth characteristics different from a situation with water-limitation only. Along with earlier remarks on cultivar characteristics, it should therefore be validated in advance whether the course of the simulated water-limited millet yield, within and between the years, follows the course of the actual millet yield. Considering mentioned environmental and crop factors involved in actual yield formation and their temporal and spatial variability, the methodology presented in the preceding can in first instance be used for a survey into regional production potentials only.

3. METEOSAT AND WEATHER DATA

3.1 INTRODUCTION

The Department of Meteorology of the Wageningen Agricultural University, on a routine basis receives digital METEOSAT images. As part of this project, a low cost personal computer based image processing system is under development for the processing of METEOSAT images. One part of this project is the calculation of estimated rainfall from the thermal infrared images, over the Niger area. The results of these calculations will be used, together with global radiation data, also derived from METEOSAT images, as input for the model for crop yield potential prediction.

After each decade, images are archived on optical disk and magnetic tape and can be processed for rainfall estimation.

3.2 DATA RECEPTION

The Department of Meteorology of the Wageningen Agricultural University has a PDUS METEOSAT Receiver at its disposal, with which (half)hourly digital METEOSAT images can be received. The receiver is coupled to an IBM compatible Personal Computer, on which a computer programme is running, that automatically starts the data reception and archiving of images for a certain, predefined region. The METEOSAT receiver and AUTOSAT software package have been developed at the University of Bradford.

The system is a low cost system and works automatically, that is almost without human interference. Only a regular control, once every few days, is done to see whether the system is running as it should. The image files are archived temporarily on optical disk and permanently on a digital tape. The optical disk, which can easily be accessed, serves as a data storage medium for the further analysis of the images.

3.3 THE SAHELIAN CLIMATE

3.3.1 general features

Figure 35 shows the area of northern Africa which is covered by the METEOSAT images. Niger is situated in the central part of the images. The Climate of the Sahel zone, and thus the climate of Niger, is strongly influenced by the movement of the Inter Tropical Convergence Zone (ITCZ) and its associated zone of rainfall.

The ITCZ is a belt of lower pressure (10-12 mbar lower than its surroundings), found in the heart of the tropics. The ITCZ migrates seasonally with the sun and is related to the maximum solar heating of the earth in the equatorial latitudes. It is convenient to consider two distinct seasons, the winter season and summer season, and two intermediate seasons.

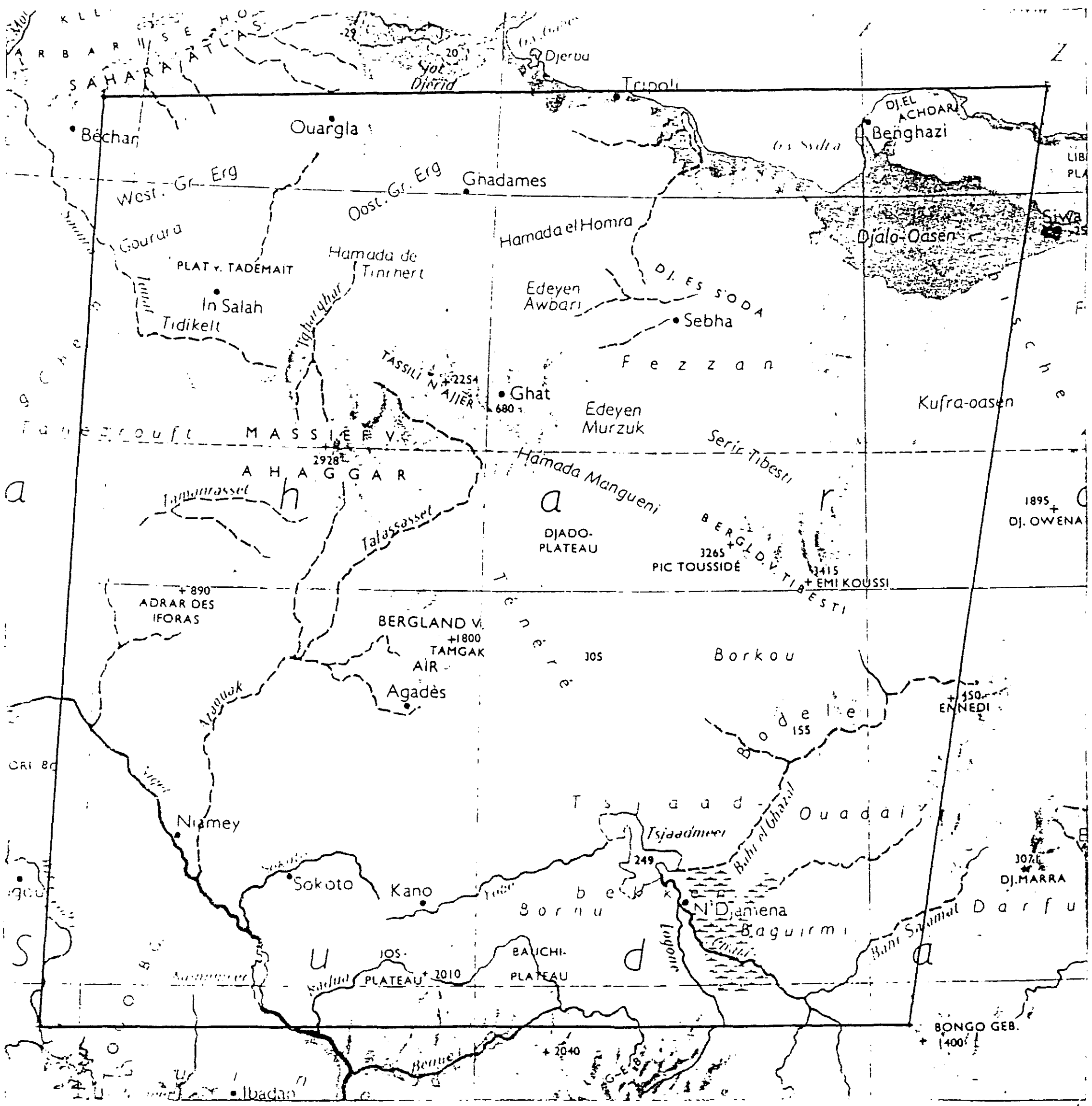


Figure 35. Area of north Africa covered by METEOSAT images.

3.3.2 winter season (December-February)

In figure 36, a typical pressure pattern and airflow for this season is shown. As can be seen from this figure, the ITCZ is close to the equator. The Sahel zone then is under the influence of northeasterly trade winds (*harmattan*). These winds generally bring very dry and stable air masses and hardly any rain is received during this period. This is the dry season.

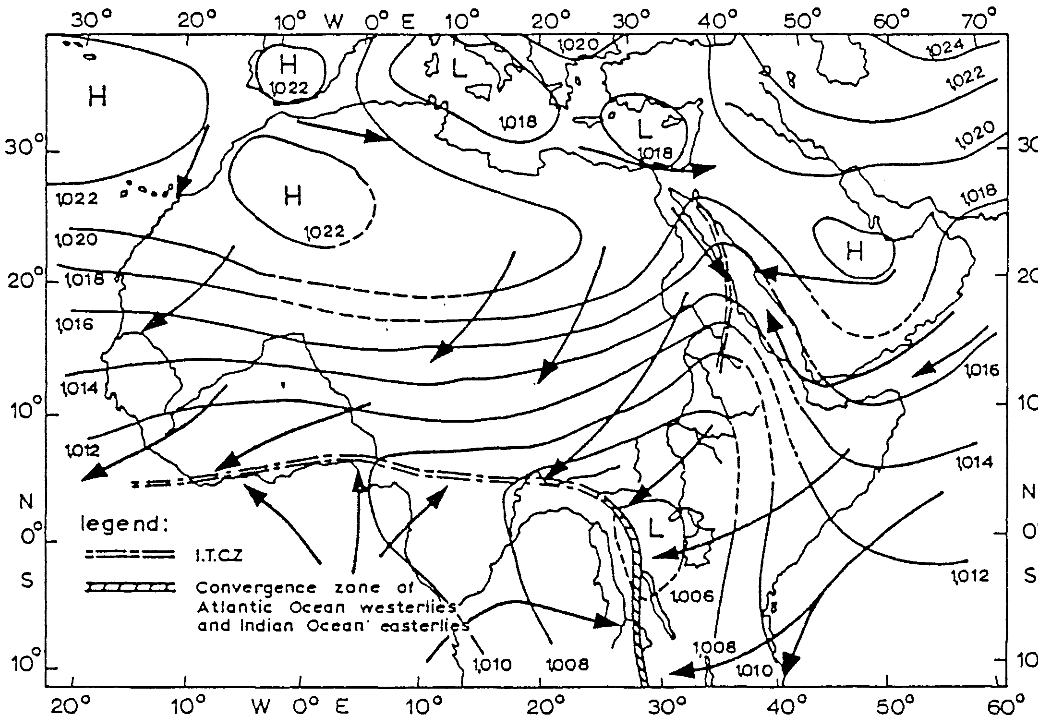


Figure 36. Pressure pattern and winds during winter season.

3.3.3 summer season (June-September)

For this season the typical pressure distribution and winds are shown in figure 37. During the summer season, high temperatures prevail over the continent and a thermal low builds up at a position about 20 degrees north. As a consequence, the ITCZ slowly moves northward. This movement is not continuous, but often interrupted or even temporarily reversed.

South of the ITCZ, the winds are most southwesterly and air trajectories are such that air masses reaching most of the Sahara, have remained over sea a reasonably long time and therefore are moist. Therefore in a zone about 500-1,000 km south of the ITCZ, there is heavy rainfall. The rainfall is concentrated along disturbance lines, like the mesoscale squall lines, but conventional thunderstorms also occur in scattered distribution patterns.

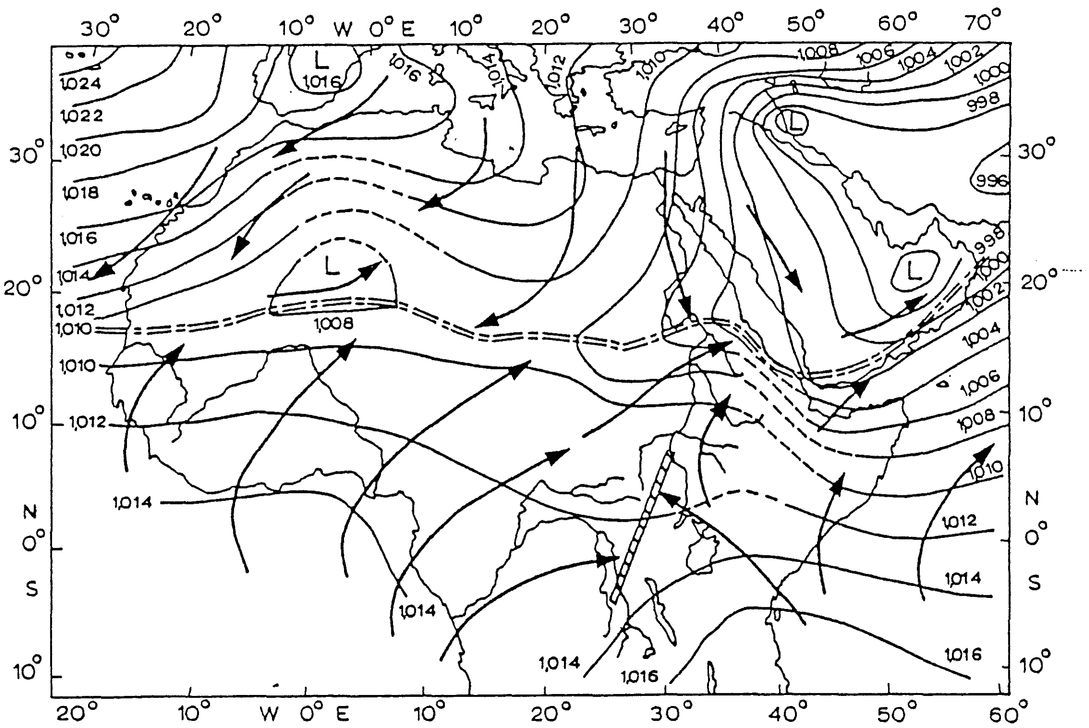


Figure 37. Pressure distribution and winds during summer season.

3.3.4 intermediate seasons

Between the winter season and summer season, there are two intermediate seasons. The first season, from March to May, is the season of the advancing ITCZ. The ITCZ moves to the north. During the other intermediate season, from October to November, the ITCZ retreats to the south.

Figure 38 shows typical pressure distributions and winds during these seasons. There are many similarities between these two seasons, but also some significant differences. In general the northward move of the ITCZ is slower than the southward move. Because of this, the southern Sahara generally records the highest temperatures immediately before the onset of the rains, for long periods of cloudless skies and the resulting intense insolation precede the ITCZ.

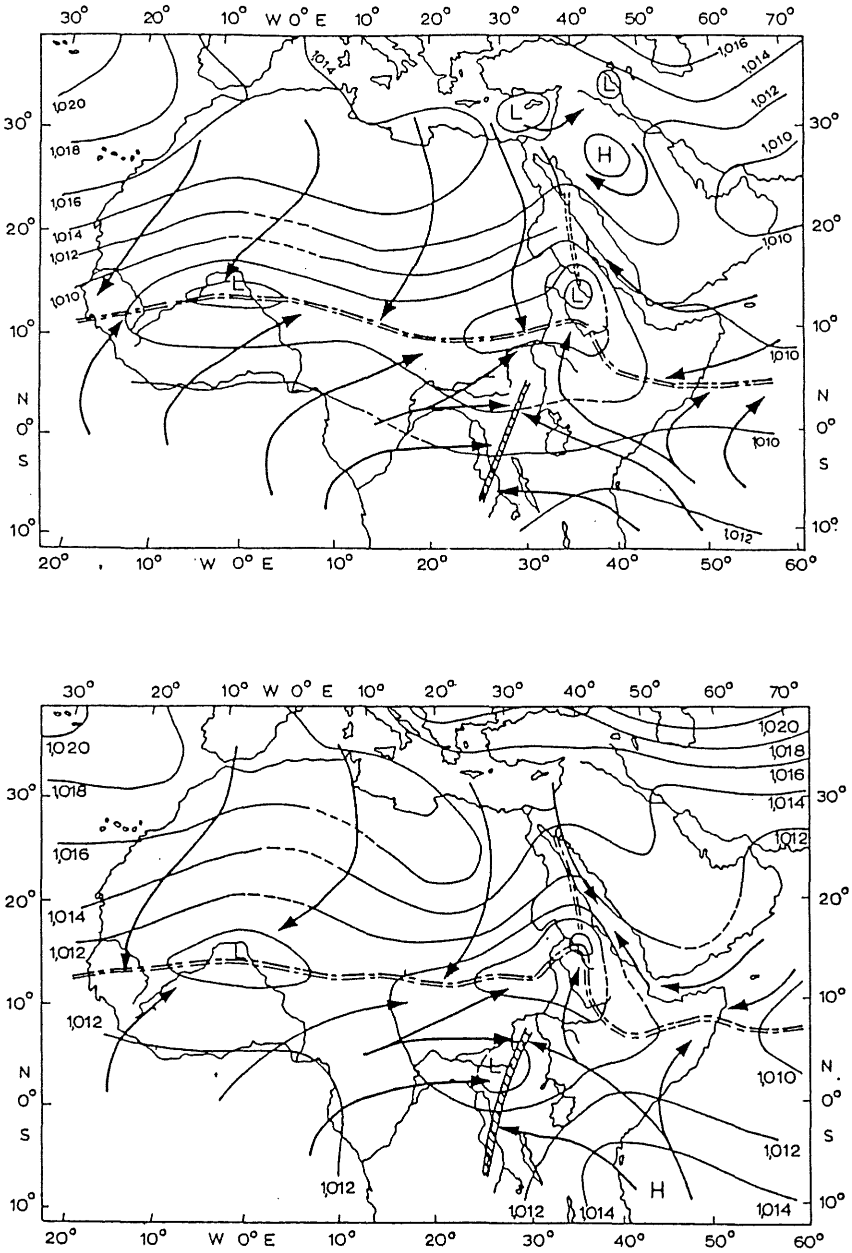


Figure 38. Pressure and wind during intermediate seasons.

3.4 DATA CALIBRATION

For the derivation of physical parameters (for instance with the purpose of estimation of precipitation) it is essential to convert pixel count values into temperature values. Conversion of the thermal infrared channel digital values to radiation temperatures is based on data provided by ESOC. The relation is plotted in figure 39.

Radiance can be converted into pixel count values by means of the following formula:

$$R = F \times MIEC \times (C - C_0)$$

where R is the radiance ($W.m^{-2}.sr^{-1}$), F the fine adjustment of gain (calibration factor ≈ 1.0), MIEC a calibration factor (≈ 0.077), C the pixel counts and C_0 the count offset (≈ 5).

Figure 40 shows the relation between pixel count and temperature, according to the above equation. For the figure a value of 0.077 was used for the total calibration factor and a value of 5 for the count offset. The relation between pixel count and temperature can be approximated by a quadratic function. This results in the following relation:

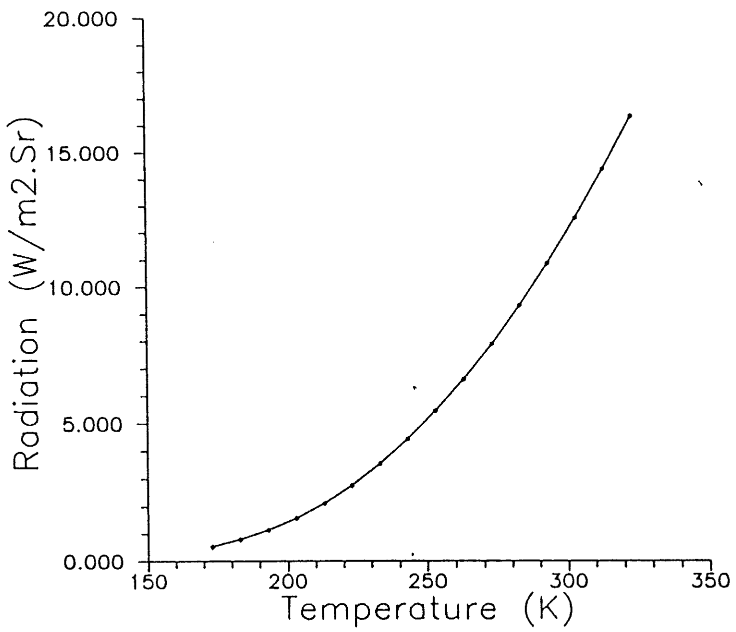


Figure 39. Relation between radiation and temperature.

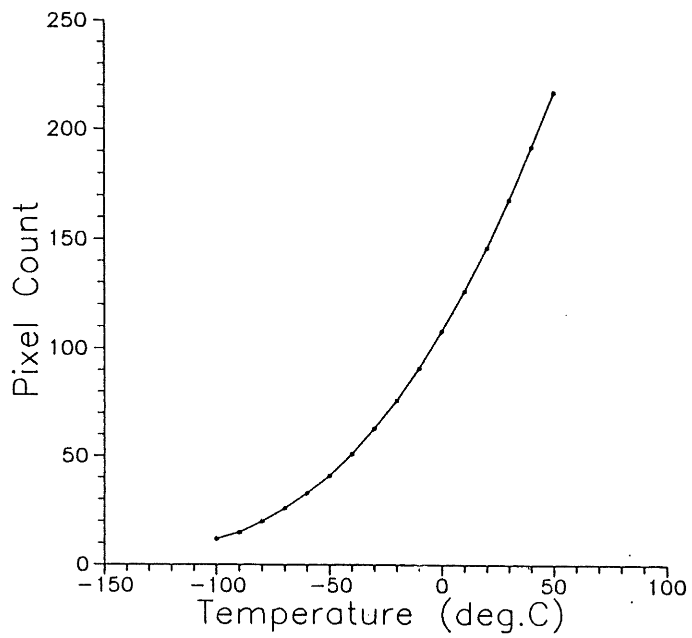


Figure 40. Relation between pixel count and temperature.

$$C = 0.00836 \times T^2 - 2.804 \times T + 250.1$$

where T is the temperature (K). The maximum error in the temperature range between 200 K and 350 K is in the order of 1%.

errors in calibration

From the above formula an estimate in the pixel count value caused by errors in the calibration factor can be derived . One finds:

$$\Delta C \approx 500 \times \Delta MIEC$$

Generally, the error in the calibration factor is in the order of 0.002, resulting in an error of 1 in the pixel count value. On the other hand an estimate of the error in pixel count due to temperature deviations can be found from the approximate formula for pixel count as function of temperature. With T≈250 K, one finds:

$$\Delta C \approx (0.0167 \times T - 2.8) \times \Delta T \approx 1.4 \times \Delta T$$

Thus a deviation in threshold temperature of 0.7 K results in a difference of 1 in the pixel count value. The spreading in temperatures of the clouds which give rain, can easily be several degrees, resulting in a rather large deviation in threshold pixel values. In the practice of applying the CCD method this means that we don't have to bother too much about (small) errors in the calibration.

3.5 COLD CLOUD DURATION METHOD

In most of the Sahel region, rain comes from deep convective instability of the atmosphere, resulting in thunderstorms, which extend high in the atmosphere as *cumulus* and *cumulonimbus* cells. The tops of these cells thus are very cold and can be recognized on METEOSAT-TIR images.

The method is based on the assumption that there is a good relation between the presence of these cells and precipitation, and between the period of the presence and the amount of rain. The longer such clouds are present in a certain region, the more precipitation there will be. From successive images the duration of the clouds can be detected and thus the amount of precipitation estimated.

A problem with this method is the determination of the moment the clouds are actually giving precipitation. It is assumed that if the vertical development has reached a certain value, the cloud will give rain. The vertical development is measured by the temperature of the top of the cloud. Thus if the temperature of the top of the cloud is lower than a certain threshold value, the cloud will give rain. In fact this threshold temperature is not the same for all clouds. There is a natural spread in threshold values. However, as there is no good method to determine for each cloud at which temperature the cloud will give rain, it is assumed that a certain fixed value of the threshold temperature will do sufficiently well for all clouds.

The duration of the rain (and thus the amount of rain) can be detected from successive images. As long as the temperature of the top of the cloud is beneath the threshold value, the rain continues. The moment the temperature exceeds this value, the rain stops. Thus a suitable choice of the threshold temperature is essential. However, this also reveals the difficulty of the method. The threshold temperature should be high enough so that all precipitation clouds are included, but should also be low enough to exclude clouds that are too warm to give rain. Threshold values are choosen mainly in the range between 250 and 200 K.

To average out variations in intensity of individual clouds, the cold cloud duration is determined over a longer period, normally ten days. This period normally will include several rain events.
The Cold Cloud Duration (CCD) method is originally developed by the TAMSAT (Tropical Agricultural Meteorology using SATellite and other data) group of Reading University. The CCD is determined on a pixel by pixel basis. Each pixel represents an area of 5 by 5 kilometers. Pixels showing radiation temperatures below a certain threshold value, are given a score. The scores of successive METEOSAT images are added. Thus the longer the duration of cold clouds over that area, the higher the score.

The relation between CCD and rainfall over the Niger area, has been established by linear regression (McDougall *et al.*, 1988). It was found that a threshold value of 213 K gave optimal results. The following relation was found:

$$R = 4.52 \times CCD + 5.12$$

where R is the amount rain (mm) and CCD the cold cloud duration (h), under the condition that R equals 0 when CCD equals 0.

It seems that this regression depends on the time of the year and the geographical position (latitude). For this research project, the above relation was used to calculate the rainfall from the cold cloud duration.

3.6 RESULTS

Some results of the estimation of rainfall are presented in Figures 41, 42 and 43. These figures present rainfall over the three decades of June 1991. In the figures the following color values are used:

- green: > 15 mm rain
- blue: 50 - 100 mm rain
- red: > 100 mm rain

The range 1 - 15 mm has not been indicated by colors, because the CCD images are rather noisy and a duration value of 1 hour already gives a rain estimate of about 10 mm.

The results could not be verified, because regular rainfall data, measured with raingauges were not available.

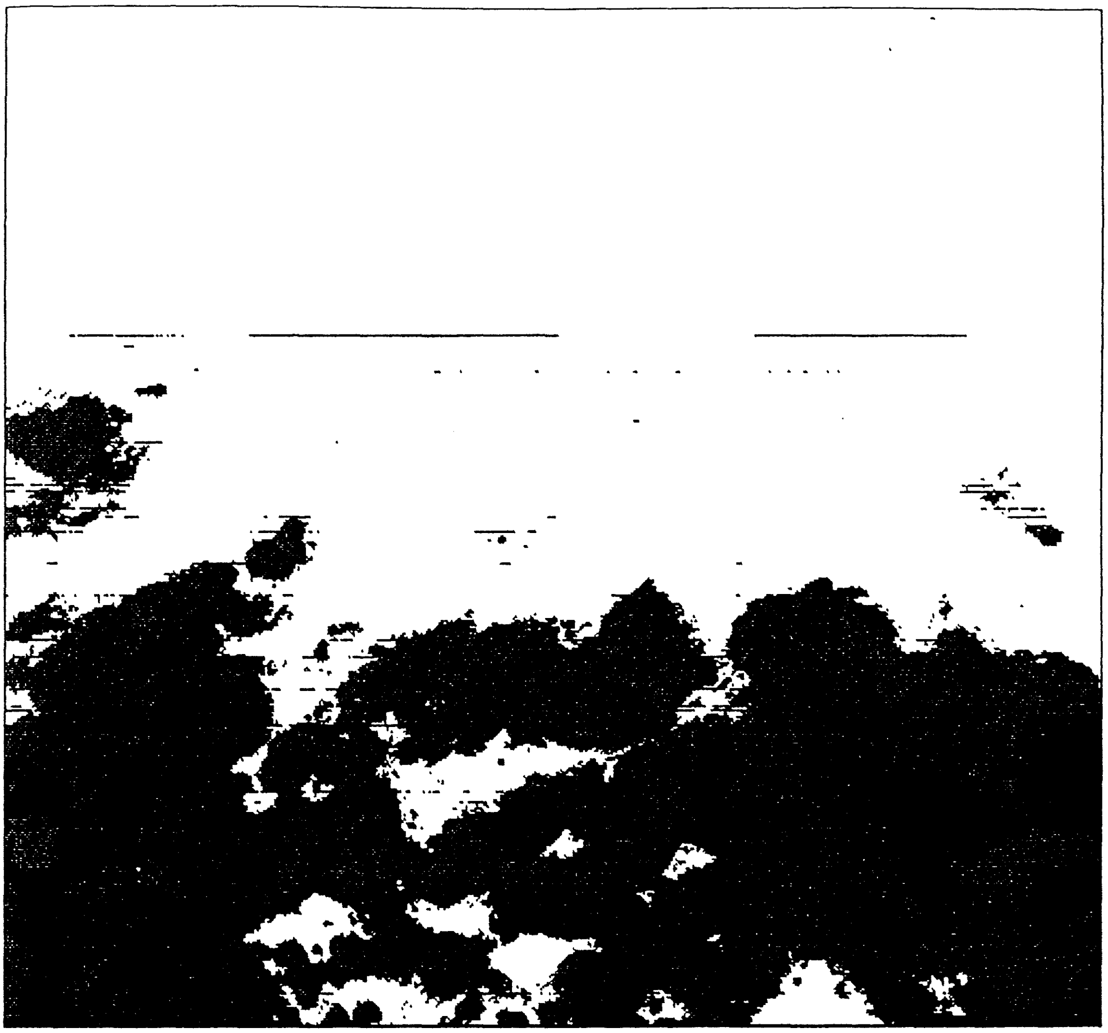


Figure 41. Rainfall over the first decade of June 1991.

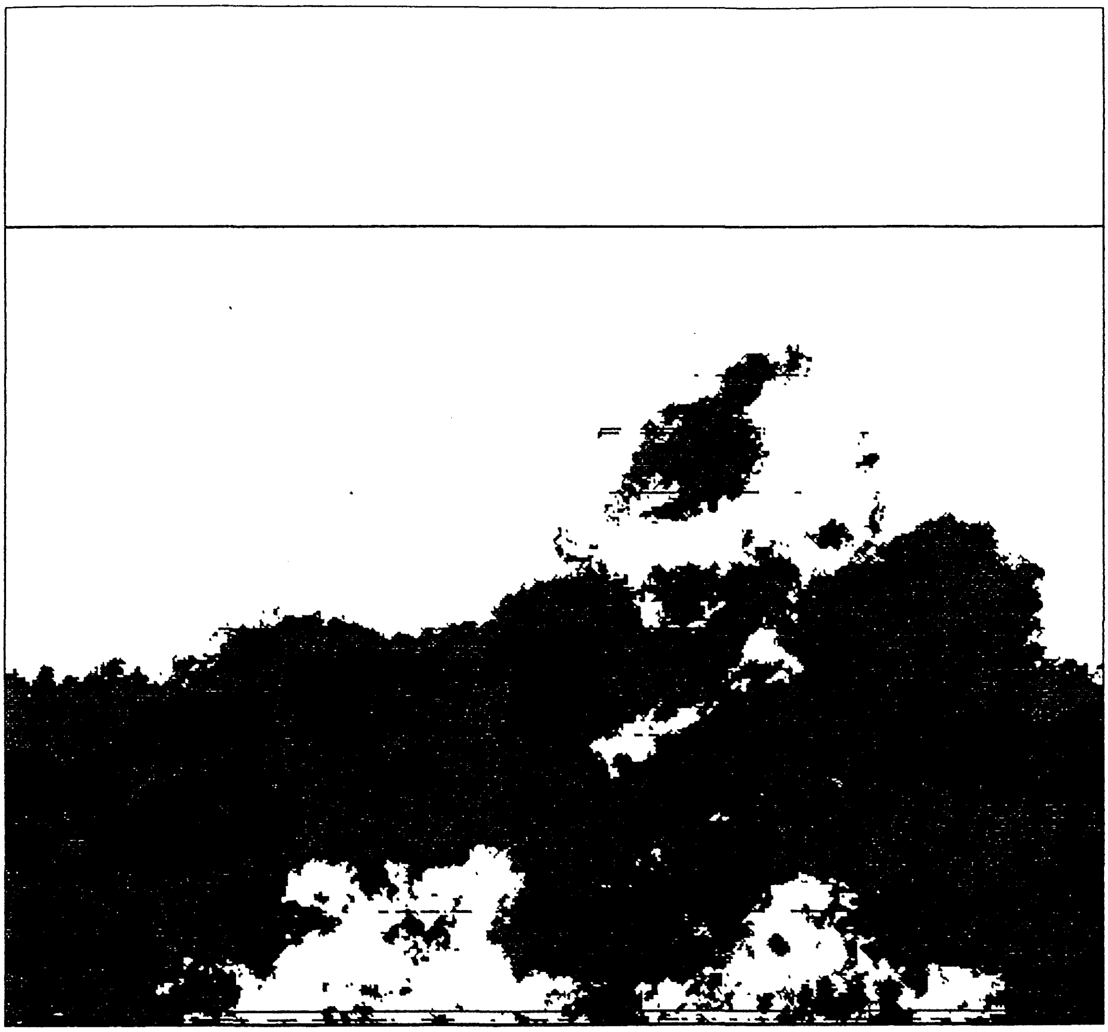


Figure 42. Rainfall over the second decade of June 1991.

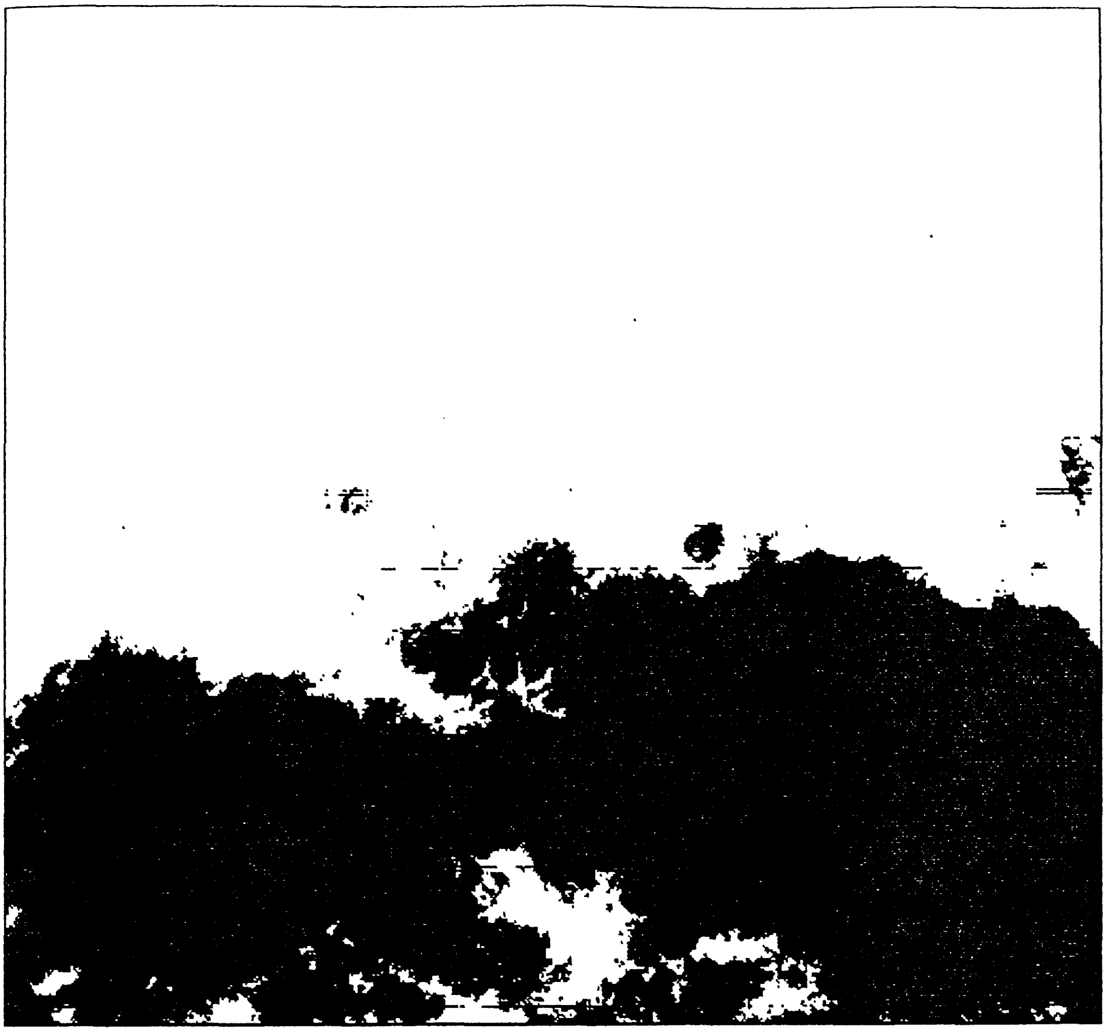


Figure 43. Rainfall over the third decade of June 1991.

4. CONCLUSIONS

This study shows that it is possible to make a reasonable estimate of the water-limited yield potentials of millet using the crop growth simulation model WOFOST. The crop growth simulation models incorporates for complex crop growth-environment relationships which can not be accounted for in simple regression analysis. For an important parameter as the daily precipitation amount a reasonable estimate can be made from METEOSAT images. Such a system could operationalized. It is recommended to refine the parameterization of the millet growth simulation model, especially with respect to the several cultivar characteristics. For application within a system following the yield trend within and between years, it should furthermore be validated whether the simulated water-limited millet production follows the actual millet production.

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REFERENCES

- Adamou, A. (1980). Agriculture. pp. 36-42. In: E. Bernus & S.A. Hamidou (eds.). *Atlas du Niger.* Paris, Editions Jeune Afrique. Les Atlas Jeune Afrique.
- Azam-Ali, S.N., P.J. Gregory & J.L. Monteith (1984). Effects of planting density on water use and productivity of pearl millet (*Pennisetum typhoides*) grown on stored water. I. Growth of roots and shoots. *Experimental Agriculture* 20:203-214.
- Bernus, E., & S.A. Hamidou (eds.) (1980). *Atlas du Niger.* Paris, Editions Jeune Afrique. Les Atlas Jeune Afrique. 64 pp.
- Black, J.N., C.W. Bonython & J.A. Prescott (1954). Solar radiation and the duration of sunshine. *Quarterly Journal of the Royal Meteorological Society* 50:231-235.
- Cadet, D., W.Thiao & M. Desbois (1988). *Estimation of precipitation over west Africa.* EUMETSAT 7th METEOSAT Scientific Users Meeting, Madrid, September 1988.
- Chadwick, A.F., G. Dugdale, A.F. Traore & J.R. Milford (1986). *Operational Rainfall mapping over the Sahel.* EUMETSAT 6th METEOSAT Scientific Users Meeting, Amsterdam, November 1986.
- Daouda Ousmane, S., M. Sicot & P. Marini (1991). Caractérisation de la diversité hydrodynamique d'un sol ferrugineux tropical, differencié sur sable dunaire en milieu soudano-sahélien. pp. 209-216. In: M.V.K. Sivakumar, J.S. Wallace, C. Renard & C. Giroux (eds.). *Soil water balance in the Sudano-Sahelian Zone - proceedings of the Niamey workshop, February 1991.* Wallingford, Oxfordshire, International Association of Hydrological Sciences (IAHS) Press, Institute of Hydrology. IAHS publication no. 199, 1991.
- Dembélé, Y., & L. Somé (1991). Propiétés hydrodynamiques des principaux types de sol du Burkina Faso. pp. 217-227. In: M.V.K. Sivakumar, J.S. Wallace, C. Renard & C. Giroux (eds.). *Soil water balance in the Sudano-Sahelian Zone - proceedings of the Niamey workshop, February 1991.* Wallingford, Oxfordshire, International Association of Hydrological Sciences (IAHS) Press, Institute of Hydrology. IAHS publication no. 199, 1991.
- Diepen, C.A. van, C. Rappoldt, J. Wolf & H. van Keulen (1988). *CWFS crop growth simulation model WOFOST - documentation version 4.1.* Wageningen etc., Centre for World Food Studies. Staff working paper SOW-88-01.
- Diepen, C.A. van, J. Wolf, H. van Keulen & C. Rappoldt (1989). WOFOST: a simulation model of crop production. *Soil Use and Management* 5:16-24.
- Dijk, P. van, & J. Bremmers (1987). *Niger.* Amsterdam, Koninklijk Instituut voor de Tropen. 48 pp. Landendocumentatie 3.
- Dudhia, A. (1986). *A Possible Improvement to the 11 μm Calibration of METEOSAT-2.* EUMETSAT 6th METEOSAT Scientific Users Meeting, Amsterdam, November 1986.
- Duivenbooden, N. van, & L. Cissé (1989). *L'amélioration de l'alimentation hydrique par des techniques culturales liées à l'interaction eau/fertilisation azotée.* Wageningen, Centre de Recherches Agrobiologiques (CABO). CABO report no. 117. 136 pp.
- ESOC (1991). *METEOSAT-4 Calibration Report, issues 10-13 - annexe to the METEOSAT-4 Calibration Report.* ESOC, 1989.
- Fechter, J., B.E. Allison, M.V.K. Sivakumar, R.R. van der Ploeg & J. Bley (1991). An evaluation of

the SWATRER and CERES-millet models for southwest Niger. pp. 505-513. In: M.V.K. Sivakumar, J.S. Wallace, C. Renard & C. Giroux (eds.). *Soil water balance in the Sudano-Sahelian Zone - proceedings of the Niamey workshop, February 1991.* Wallingford, Oxfordshire, International Association of Hydrological Sciences (IAHS) Press, Institute of Hydrology. IAHS publication no. 199, 1991.

- Flitcroft, I.D., V. McDougall, J.R. milford & G. Dugdale (1986) .*The calibration and interpretation of METEOSAT based estimates of Sahelian rainfall.* EUMETSAT 6th METEOSAT Scientific Users Meeting, Amsterdam, November 1986.
- Frère, M., & G.F. Popov (1979). *Agrometeorological crop monitoring and forecasting.* Rome, Food and Agriculture Organization of the United Nations (FAO). FAO Plant Production and Protection Paper 17.
- Gaertner, V. (1988). *MIEC IR Calibration Coefficients derived from Cloud Free Sea Pixels.* EUMETSAT 7th METEOSAT Scientific Users Meeting, Madrid, September 1988.
- Glover, J., & J.S.G. McCulloch (1958). The empirical relation between solar radiation and hours of sunshine. *Quarterly Journal of the Royal Meteorological Society* 84:172-175.
- Gopinathan, K.K., & M. Baholo (1987). Applicability of empirical correlations for estimating global solar radiation. *International Journal of Tropical Agriculture* 5:122-126.
- Gregory, P.J., & G.R. Squire (1979). Irrigation effects on roots and shoots of pearl millet (*Pennisetum typhoides*). *Experimental Agriculture* 15:161-168.
- Heemst, H.D.J. van (1988). *Plant data values required for simple crop growth simulation models: review and bibliography.* Wageningen, Centre for Agrobiological Research (CABO-DLO) & Department of Theoretical Production Ecology, Wageningen Agricultural University. Simulation Report CABO-TT nr. 17. 100 pp.
- Hoogmoed, W. (1986). *Some physical and mechanical characteristics of a sandy soil at ICRISAT's Sahelian Center, Sadoré, Niger.* Wageningen, Tillage Laboratory, Agricultural University. 33 pp. Report 86-6.
- Hoogmoed, W.B., & M.C. Klaij (1988). Tillage and planting strategies for sandy soils in Niger, West Africa. pp. 562-564. In: *Challenges in dryland agriculture - a global perspective. Proceedings of the International Conference on Dryland Farming, August 15-19, 1988, Amarillo/Bushland, Texas, U.S.A.*
- Hoogmoed, W.B., & M.C. Klaij (1990). Soil management for crop production in the West African Sahel. I. Soil and climate parameters. *Soil & Tillage Research* 16:85-103.
- Huygen, J., W. Simons & J.A.A. Berkhout (1988). *Estimation of rainfall over Zambia, using METEOSAT data and raingauge measurements.* EUMETSAT 7th METEOSAT Scientific Users Meeting, Madrid, September 1988.
- Keulen, H. van, & J. Wolf (eds.) (1986). *Modelling of agricultural production: weather, soils and crops.* Wageningen, Pudoc. Simulation Monographs.
- Lahuec, J.P., B. Guillot & B. Bellec (1986). *Relationship between deep convection and rainfall in west Africa.* EUMETSAT 6th METEOSAT Scientific Users Meeting, Amsterdam, November 1986.
- Lal, R. (1991). Current research on crop water balance and implications for the future. pp. 31-44. In: M.V.K. Sivakumar, J.S. Wallace, C. Renard & C. Giroux (eds.). *Soil water balance in the*

Sudano-Sahelian Zone - proceedings of the Niamey workshop, February 1991. Wallingford, Oxfordshire, International Association of Hydrological Sciences (IAHS) Press, Institute of Hydrology. IAHS publication no. 199, 1991.

McDougall, V.D., M. Saunby, G. Dugdale & J.R. Milford (1988). *Relationship between rainfall and cloud top temperature in tropical Africa seasonal and regional Effects.* EUMETSAT 7th METEOSAT Scientific Users Meeting, Madrid, September 1988.

- Michel, P. (1980). Sols. pp. 18-19. In: E. Bernus & S.A. Hamidou (eds.). *Atlas du Niger.* Paris, Editions Jeune Afrique. Les Atlas Jeune Afrique.
- Morel, A. (1980). Climat. pp. 14-17. In: E. Bernus & S.A. Hamidou (eds.). *Atlas du Niger.* Paris, Editions Jeune Afrique. Les Atlas Jeune Afrique.
- Ong, C.K., & A. Everard (1979). Short day induction of flowering in pearl millet (*Pennisetum typhoides*) and its effect on plant morphology. *Experimental Agriculture* 15:401-410.
- Payne, W.A., R.J. Lascano & C.W. Wendt (1991). Physical and hydrological characterization of three sandy millet fields in Niger. pp. 199-207. In: M.V.K. Sivakumar, J.S. Wallace, C. Renard & C. Giroux (eds.). *Soil water balance in the Sudano-Sahelian Zone - proceedings of the Niamey workshop, February 1991.* Wallingford, Oxfordshire, International Association of Hydrological Sciences (IAHS) Press, Institute of Hydrology. IAHS publication no. 199, 1991.
- Penning de Vries, F.W.T., D.M. Jansen, H.F.M. ten Berge & A. Bakema (1989). *Simulation of ecophysiological processes of growth in several annual crops.* Wageningen, Pudoc. Simulation Monographs 29. 271 pp.
- Raulin, H. (1976). Niger. pp. 401-408. In: Committee for the World Atlas of Agriculture (eds.). *World Atlas of Agriculture - under the aegis of the International Association of Agricultural Economists. vol. 4 Africa.* Novara, Instituto Geografico De Agostini. pp. 761.
- Rietveld, M.R. (1978). A new method for estimating the regression coefficients in the formula relating solar radiation to sunshine. *Agricultural Meteorology* 19:243-252.
- Rosema, A. (1990).*Sahelian Vegetation Monitoring Project, Final Report.* BCRS TO-3.15, February 1990.
- Sivakumar, M.V.K. (1988). Predicting rainy season potential from the onset of rains in Southern Sahelian and Sudanian climatic zones of West Africa. *Agricultural and Forest Meteorology* 42:295-305.
- Sivakumar, M.V.K. (1990). Exploiting rainy season potential from the onset of rains in the Sahelian zone of West Africa. *Agricultural and Forest Meteorology* 51:321-332.
- Spitters, C.J.T., H. van Keulen & D.W.G. van Kraalingen (1989). A simple and universal crop growth simulator: SUCROS87. pp. 147-181. In: R. Rabbinge, S.A. Ward & H.H. van Laar (eds.). *Simulation and systems management in crop protection.* Wageningen, Pudoc. Simulation Monographs No. 32.
- Staveren, J.Ph. van, & W.A. Stoop (1985). Adaptation to toposequence land types in West Africa of different sorghum genotypes in comparison with local cultivars of sorghum, millet, and maize. *Field Crops Research* 11:13-35.
- Stoop, W.A. (1986). Agronomic management of cereal/cowpea cropping systems for major toposequence land types in the West African savanna. *Field Crops Research* 14:301-319.
- Stoop, W.A. (1987). Variations in soil properties along three toposequences in Burkina Faso and

implications for the development of improved cropping systems. *Agriculture, Ecosystems and Environment* 19:241-264.

- World Meteorological Organization (WMO)/ Organisation Météorologique Mondiale (OMM) (1971). *Climatological normals (clino) for climat and climat ship stations for the period 1931-1960 - Normales climatologiques (clino) relatives aux stations climat et climat ship pour la période 1931-1960.* Geneva, WMO/OMM. WMO/OMM No. 117 TP. 52.
- Yeboah-Amankwah, D., & K. Agyeman (1990). Differential Ångström model for predicting insolation from hours of sunshine. *Solar Energy* 45:371-377.

Annex A. Long-term monthly precipitation averages and standard deviations for 16 locations throughout Niger, derived from available daily values for these periods. Source data: ASECNA - Direction de l'Exploitation Météorologique, Niamey, Niger.

location	available years	monthly precipitation average (+ σ) month 1	2	3	4	5	6	7	8	9	10	11	12	Σ
Tillabéry	1923-1931	0	1	2	4	20	52	119	173	76	12	0	0	458
	1933-1989	(0)	(4)	(7)	(9)	(22)	(31)	(51)	(78)	(45)	(20)	(1)	(1)	(120)
Niamey-	1944-1989	0	0	3	5	33	73	153	185	94	13	1	0	561
Airport		(0)	(0)	(8)	(12)	(30)	(39)	(66)	(77)	(53)	(15)	(3)	(0)	(149)
Gaya	1932-1933	0	1	3	16	70	118	186	253	157	21	1	0	825
	1935-1943	(0)	(5)	(7)	(19)	(39)	(45)	(82)	(90)	(54)	(22)	(3)	(0)	(147)
	1945-1947													
	1949-1989													
Tahoua	1922-1931	0	0	1	3	15	51	106	135	57	10	0	0	379
	1934-1989	(2)	(0)	(2)	(9)	(15)	(31)	(49)	(59)	(27)	(18)	(0)	(0)	(101)
Birni N'Konni	1934-1989	0	0	0	3	30	70	132	195	95	11	0	0	536
		(1)	(0)	(2)	(7)	(25)	(36)	(55)	(83)	(55)	(19)	(0)	(0)	(145)
Keïta	1955-1965	0	0	0	4	17	44	133	155	67	7	0	0	428
	1967-1972	(0)	(0)	(2)	(10)	(24)	(32)	(65)	(76)	(31)	(17)	(0)	(0)	(123)
	1974-1975													
	1977-1978													
	1980-1989													
Maradi-	1933-1938	0	0	0	4	7	62	152	215	85	9	0	0	534
Airport	1940-1989	(0)	(0)	(1)	(10)	(138)	(36)	(57)	(89)	(45)	(17)	(0)	(0)	(197)
Agadez	1922-1940	0	0	0	2	6	10	41	74	13	0	0	0	146
	1943	(1)	(0)	(0)	(7)	(12)	(14)	(26)	(42)	(16)	(1)	(0)	(0)	(61)
	1945-1989													
Zinder-	1945-1989	0	0	0	1	21	43	134	199	60	6	0	0	464
Airport		(0)	(1)	(2)	(4)	(29)	(32)	(58)	(91)	(35)	(10)	(1)	(0)	(130)
Magaria	1939-1958	0	0	0	3	27	58	175	221	84	9	0	0	576
	1960-1962	(0)	(0)	(2)	(8)	(31)	(37)	(77)	(105)	(43)	(15)	(0)	(0)	(184)
	1965													
	1968-1975													
	1977-1989													
Maïne Soroa	1939-1943	0	0	0	2	11	32	103	161	55	9	0	0	373
	1945-1989	(0)	(0)	(1)	(6)	(14)	(25)	(43)	(84)	(38)	(13)	(0)	(0)	(115)

Diffa	1951-1963	0	0	0	1	8	19	78	143	32	10	0	0	292
	1966-1967	(0)	(0)	(0)	(3)	(13)	(20)	(45)	(90)	(24)	(18)	(2)	(0)	(112)
	1969-1972													
	1976													
	1978-1979													
	1981-1989													
Bilma	1923-1927	0	0	0	0	0	1	3	9	3	1	0	0	17
	1929-1975	(1)	(0)	(0)	(0)	(2)	(2)	(5)	(13)	(6)	(7)	(0)	(1)	(15)
	1977-1989													
N'Guigmi	1922-1926	0	0	0	0	7	9	57	116	17	1	0	0	207
	1928-1932	(0)	(0)	(0)	(2)	(17)	(17)	(42)	(70)	(18)	(3)	(0)	(0)	(97)
	1934-1945													
	1947-1989													
Chikal	1980-1989	0	0	0	0	11	33	76	105	65	4	0	0	293
		(0)	(0)	(1)	(0)	(21)	(26)	(36)	(41)	(39)	(7)	(0)	(0)	(65)
Gouré	1936-1943	0	0	0	1	14	24	114	143	50	3	0	0	348
	1945-1966	(0)	(0)	(0)	(3)	(26)	(19)	(54)	(78)	(36)	(6)	(0)	(0)	(128)
	1968-1976													
	1978-1989													

Annex B. Available whole year records of monthly precipitation and average temperature data, indicated in plain characters, for 13 locations throughout Niger, from the World Weather Records of the National Center for Atmospheric Research (NCAR), Boulder, Colorado, United States of America. Source data: National Climatic Data Center (NCDC), United States Department of Commerce, Asheville, North Carolina, United States of America. Orginally incomplete records with values for missing months obtained by interpolation are indicated in *italics*.

location	parameter	available complete and *incomplete* records
Tillabéry	precipitation	1951-1958, *1964*, *1966*, 1967-1968, *1969*, 1970-1971, *1972*, 1973-1974, *1975*, 1976-1980, *1981-1982*, 1983-1985, *1986-1987*, 1987, *1988*
	average temperature	1951-1958, *1959*, *1964*, *1966*, 1967-1968, *1969*, 1970-1971, *1972-1973*, 1974, *1975*, 1976-1980, *1981*, 1982-1985, *1986*, 1987, *1988*
Niamey	precipitation	1905-1910, 1912-1922, 1924-1958, *1959-1960*, 1961-1963, *1964*, 1965-1971, *1972*, 1973-1977, *1978*, 1979-1980, *1981*, 1982-1984, *1985-1986*, 1987, *1988*
	average temperature	1945-1948, *1949*, 1950-1958, *1959-1960*, 1961-1971, *1972*, 1973-1977, *1978*, 1979-1980, *1981*, 1982-1984, *1985-1986*, 1987, *1988*
Gaya	precipitation	1971, *1972*, 1973-1974, *1976*, 1977-1978, *1979*, 1980, *1981*, 1982, *1983-1987*, 1988
	average temperature	1971, *1972*, 1973-1974, *1976*, 1977-1978, *1979*, 1980, *1981*, 1982, *1983-1987*, 1988
Tahoua	precipitation	1922-1932, 1934, 1937-1942, 1945-1960, 1964-1972, *1973*, 1974-1976, *1977*, 1978-1980, *1981-1987*, 1988
	average temperature	1951-1958, 1964-1972, *1973*, 1974-1976, *1977*, 1978-1980, *1981-1987*, 1988
Birni N'Konni	precipitation	1951-1958, *1959-1965*, 1966-1969, *1970*, 1971, *1972*, 1973-1980, *1981*, 1982-1984, *1985-1986*, 1987-1988
	average temperature	1951-1960, *1961-1964*, 1965-1969, *1970*, 1971, *1972*, 1973-1980, *1981*, 1982-1984, *1985-1986*, 1987-1988
Maradi	precipitation	1932-1962, *1966*, 1967-1971, *1972-1974*, 1975-1980, *1981*, 1982-1985, *1986*, 1987, *1988*
	average temperature	1951-1958, *1966*, 1967-1971, *1972-1974*, 1975-1985, *1986*, 1987, *1988*

Agadez	precipitation	1922-1940, *1941*, 1943, 1945-1958, *1959-1960*, 1961, *1962-1963*, 1964-1971, *1972*, 1974-1980, *1981*, 1982-1985, *1986*, 1987-1988
	average temperature	*1941*, 1943, *1945-1946*, 1947-1948, *1949*, 1950-1958, *1959*, 1960-1961, *1962-1963*, 1964-1971, *1972*, 1973-1981, *1982*, 1983-1985, *1986*, 1987-1988
Zinder	precipitation	1905-1906, 1908, 1911-1914, 1916, 1918, 1922-1958, *1959*, *1961*, 1962-1971, *1972-1973*, 1974-1976, *1977*, 1978-1980, *1981*, 1982, *1983-1986*, 1987-1988
	average temperature	1941-1948, *1949*, 1950, *1951*, 1952-1958, *1959*, 1960-1971, *1972-1973*, 1974-1976, *1977*, 1978-1980, *1981*, 1982, *1983-1986*, 1987-1988
Magaria	precipitation	*1981-1983*, 1984-1985, *1986*, 1987-1988
	average temperature	*1981-1983*, 1984-1985, *1986*, 1987-1988
Maïne Soroa	precipitation	1951-1958, 1964-1965, *1966-1967*, 1968, *1969*, 1970-1971, *1972*, 1973-1975, *1976*, 1977, *1978*, 1979, *1980-1986*, 1987-1988
	average temperature	1951-1958, *1964*, 1965, *1966-1967*, 1968, *1969*, 1970-1971, *1972*, 1973-1977, *1978*, 1979, *1980-1981*, 1982, *1983-1986*, 1987, *1988*
Bilma	precipitation	1923-1925, 1927, 1929-1953, *1954*, 1955-1958, 1960-1961, 1964, *1965*, 1966-1968, *1969*, 1970-1971, *1972*, 1973-1974, *1975-1988*
	average temperature	1951-1953, *1954*, 1955-1958, 1960-1961, 1964, *1965-1966*, 1967, *1968-1969*, 1970-1971, *1972*, 1973-1974, *1975-1988*
N'Guigmi	precipitation	1922-1926, 1928-1938, 1940-1945, 1947-1962, *1964-1967*, 1968-1970, *1971-1972*, 1973, *1974*, 1975-1976, *1977*, 1978-1980, *1981*, 1982, *1983-1986*, 1987, *1988*
	average temperature	*1964-1965*, 1966-1970, *1971-1973*, 1974-1976, *1977*, 1978-1980, *1981*, 1982, *1983-1988*

Annex C. Available whole year records of daily precipitation data for 16 locations throughout Niger, from the Meteorological Service of Niger (ASECNA - Direction de l'Exploitation Météorologique); assumed location altitude, longitude and latitude; and years for which millet growth was simulated.

location	available records	latitude	longitude	altitude (m)	simulated years
Tillabéry	1923-1931 1933-1949 1952-1989	14°12' N	1°27' E	210	1952-1959 1964 1966-1988
Niamey-Airport	1944-1989	13°29' N	2°10' E	226	1945-1950 1952-1957 1959-1988
Gaya	1932-1933 1935-1943 1945-1947 1949-1989	11°52' N	2°23' E	150	1971-1974 1976-1988
Tahoua	1922-1931 1934-1942 1944-1950 1952-1989	14°54' N	5°15' E	387	1952-1958 1964-1988
Birni N'Konni	1934-1942 1944-1989	13°48' N	5°15' E	274	1951-1956 1958-1974 1976-1988
Keïta	1955-1961 1967-1972 1974-1975 1977-1978 1980-1989	14°44' N	5°46' E	450	-
Maradi-Airport	1933-1989	13°28' N	7°05' E	369	1951-1955 1957-1958 1966-1977 1979-1988
Agadez	1922-1941 1943 1945-1989	16°59' N	7°59' E	500	-
Zinder-Airport	1945-1989	13°48' N	9°00' E	479	1945-1959 1961-1976 1978-1979 1981-1987

Magaria	1938-1963 1965 1968-1989	12°10' N	8°06' E	450	1981-1986 1988
Maïne Soroa	1936-1989	13°14' N	11°59' E	339	1951-1958 1964-1988
Diffa	1951-1964 1966-1967 1969-1979 1981-1989	13°11' N	12°05' E	300	-
Bilma	1923-1925 1927-1989	18°41' N	12°55' E	357	-
N'Guigmi	1921-1926 1928-1989	14°15' N	13°07' E	289	1964-1976 1978-1988
Chikal	1980-1989	14°16' N	3°28' E	300	
Gouré	1936-1966 1968-1976 1978-1989	13°53' N	9°54' E	450	

Annex D. Latitude and altitude of locations used for calculations on Ångström coefficients.

location	latitude	altitude
Avignon (France)	43°55' N[2]	60 m[2]
Bremen (Germany)	53°00' N[3]	14 m[3]
Nancy (France)	48°41' N[1]	217 m[1]
Niamey (Niger)	13°30' N	190 m
Roskilde (Denmark)	55°37' N[4]	5 m[4]
Rothamsted (United Kingdom)	51°30' N[5]	5 m[5]
Silstrup (Denmark)	56°56' N	10 m
Tel Hadya (Syria)	36°11' N[6]	392 m[7]
Wageningen (The Netherlands)	50°83' N[8]	7 m

1 source: WMO (1971)

2 Nîmes (France) - source: WMO (1971)

3 Hamburg - Fuhlsbüttel (Germany) - source: WMO (1971)

4 Copenhagen (Denmark) - source: WMO (1971)

5 Kew (United Kingdom) - source: WMO (1971)

6 Urfa (Turkey) - source: WMO (1971)

7 Aleppo (Syria) - source: WMO (1971)

8 Uccle (Belgium) - source: WMO (1971)

Table 7. Relationship between measured (RAD_m) and calculated global radiation (RAD_c) ($kJ.m^{-2}.d^{-1}$) for the whole radiation range: $RAD_c = a + b \times RAD_m$, for Niamey, from June up to August, 1985. The Ångström coefficients were calculated following 5 different methods: see Table 2.

regression			method		
coefficient	1	2	3	4	5
n	92	92	92	92	92
a	4,720	13,177	5,192	4,797	2,199
b	0.813	0.463	0.939	0.897	0.824
r	0.896	0.895	0.896	0.896	0.896

The inconsistent results with respect to the different methods to estimate the Ångström coefficients were also obvious when distinguishing between a low and a high radiation range (Tables 5 and 6). The correlation coefficients hardly changed as compared to the whole radiation range, with the exception of Niamey with especially low values for the upper half of the radiation range. It could be concluded that for all methods for all locations the calculated global radiation values deviated considerably from the measured global radiation values.

As for the purpose of this study only calculated global radiation values for roughly the period June up to August are of relevance, just for this period a comparison was made between the different methods for estimating the Ångström coefficients (Table 7). Whereas the correlation coefficients are similar for all methods considerable differences existed between the regression coefficients, however, without an unequivocally best fit. In combination with Ångström coefficients a and b of 0.224 and 0.444, respectively (r = 0.896), derived through linear regression analysis from the June up to August values (n = 92), this observation justified the application of the simple method of Frère & Popov (1979) for the estimation of the Ångström coefficients.

Because no directly measured daily or monthly long-term sunshine duration values were available

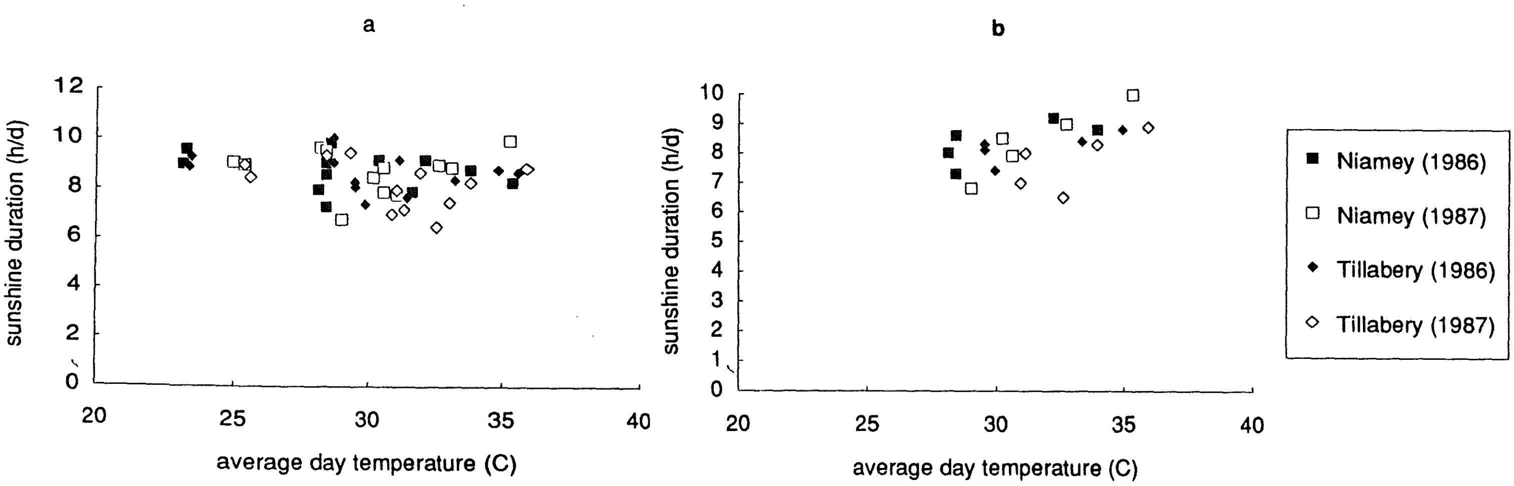

Figure 13. Relation between monthly values of independent variable average day temperature and dependent variable daily sunshine duration, for Niamey and Tillabéry, for 1986 and 1987, considering the whole year (a) and the period from May up to September (b).