Chapter 6

CLIMATE CHANGE AND DROUGHT RISKS FOR AGRICULTURE

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Abstract: Changes in rainfall patterns and risk of crop failure are discussed in this chapter. Agriculture is by far the most important economic activity in the region. The success of this economic activity relies heavily on water availability during the growing season. For rainfed production systems timing and the amount of precipitation determine to a large extent the success of the growing season. The projected changes in the variability and total amount of rainfall are expected to worsen the situation.

1. CLIMATE CHANGE AND CLIMATE VARIABILITY

Agriculture is by far the most important economic activity in sub-Saharan West Africa (SSWA). It is still the main source of income and livelihood in this region. A large section of the population is active in subsistence agriculture. In sub-Saharan West Africa the arid and semi arid regions are among the harshest and vulnerable production environments in the world. Combined with a fast growing and mobile population, the pressure on the natural and societal resource base will increase.

The rainy season is crucial for agricultural production; it is during this period that conditions determine whether there are going to be food shortages or not. As indicated by the GCM-scenarios, climate change may confront dryland West Africa with even lower and more variable precipitation, higher temperatures and higher evaporation. This may result in even higher risks for crop production, with the ultimate consequence being a decrease in food availability. However, consequences of climate change on agricultural production are highly

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speculative. Partly due to the uncertainties related to the magnitude of climate change, but also due to highly dynamic socio-economic and institutional context that has direct and indirect effects on agricultural production. Whatever the causes, less food, water and fuel means that the local population is forced to adopt and develop alternatives and that all kinds of institutions and organisations will have to adapt to this changing situation as well.

Shifting cultivation, land clearing for crop production, is the main system. Some crop rotation is customary but the intrinsic low soil fertility does not allow continuous cropping without external inputs such as fertiliser. Increasing soil fertility will enhance the production capacity of the land and increase water use efficiency. Labour availability is another constraint in crop production as the continuous fight against weeds and pests is carried out mainly by hand. This section deals with questions related to climate change and climate variability in the region and their effect on crop production with the focus on rainfall, as this is the main driver of the agricultural production systems. The important link between the arable and livestock component in sub-Saharan West Africa is not included in this assessment but will be addressed in the detailed regional studies.

The concept of climate is dynamic and includes short-term variations. Climate variability refers to inter-annual variability of individual climatic parameters around longer-term mean values. Climate variability is inherent in dryland areas (Le Houérou, 1996). Climate variability can occur no matter whether the longer-term climate is stable or changing. For example, inter-annual rainfall values may fluctuate around an overall trend towards wetter or drier conditions.

2. DROUGHT

The encyclopaedia Britannica gives the following definition of drought: it is the lack or insufficiency of rain for an extended period that causes a considerable hydrologic imbalance and, consequently, water shortages, crop damage, stream flow reduction and depletion of groundwater and soil moisture. Drought is a normal, recurrent phenomenon, which occurs in virtually all climatic zones, although its characteristics vary significantly from one zone to another (Hulme, 1995).

The interaction between the natural event and the demand people place on water supply determines the impact of a drought event. Recent droughts in both developing and developed countries have underscored the vulnerability of all societies to this natural hazard, although some groups are more vulnerable than others. It is possible to differentiate the drought impact according to a number of disciplinary perspectives:

meteorological, hydrological, agricultural and socio-economic drought. (see National Drought Mitigation Center: www.enso.unl.edu)

Meteorological drought

Meteorological drought is usually defined on the basis of the degree of dryness and the duration of the dry period. Thus, Hulme (1995) defines meteorological drought as a reduction in rainfall supply compared with a specified average condition over some specified period. Definitions of meteorological drought must be considered as region-specific since the atmospheric conditions that result in deficiencies of precipitation are highly variable from region to region. This study uses a definition based on actual precipitation departures from average amounts on a monthly, seasonal, or annual time scale.

Hydrological drought

Hydrological drought is associated with the effects of periods of precipitation shortfalls on surface or subsurface water storage systems (i.e. streams, lakes, reservoirs, and ground water) (Wilhite, 1993). Although the origin of all droughts is a deficiency of precipitation, hydrologists are more concerned with how this deficiency plays out through the hydrologic system (a watershed or river basin). Hydrological droughts are usually out of phase with meteorological droughts since it takes longer for precipitation deficiencies to show up in components of the hydrological system

Agricultural drought

The driest climates with sparse vegetation that is adapted to aridity are characterised by permanent drought. In these areas agriculture is impossible without continuous irrigation. Semi-arid regions are characterised by seasonal drought during the so-called dry season. In areas such as sub-Saharan West Africa the growing season for rain-fed agriculture is restricted to the rainy season. More commonly, the drought is related to abnormal rainfall failure, which may occur in all climate zones but is regarded as a characteristic of the humid and sub-humid climate zones. Such failures are erratic and hard to predict and the effect is often limited to small areas. The so called invisible drought is characteristic for areas which appear to have enough water but in which crops suffer water shortage related stress due to high temperatures resulting in high evaporation and transpiration rates.

Socio-economic drought

Socio-economic definitions of drought associate the supply and demand of some economic good with elements of meteorological, hydrological and agricultural drought. It differs from the aforementioned types of drought because its occurrence depends on the time and space processes of supply and demand to identify or classify droughts. Socio-economic drought occurs when the demand for an economic good exceeds supply as a result of a weather-related shortfall in this good.

3. CLIMATE DATA

Long-term average (1960-1990) monthly data of cloudiness, temperature and precipitation taken from the Leemans & Cramer (1991) dataset were used for the baseline calculations. The spatial resolution of this global dataset is 30×30 arc minutes. The degrees of cloudiness in combination with the geographical position were used to calculate solar radiation. The evapo-transpiration was calculated using Makkink's method. The monthly data could be used directly to calculate the Drought Index. The climate scenarios, MPI-GCM and GFDL-GCM were delivered in the same format as the Leemans & Cramer (1991) dataset.

To arrive at the daily climatic information required for the simulation model the monthly data had to be converted. Linear interpolation was used for radiation and temperature data. Daily rainfall was derived from the combination of the number of rainy days and the total amount of rainfall. The 'number of rain days' was taken from the database compiled by Müller (1996) and subsequently translated to a 30×30' grid.

In rain-fed agriculture, the timing and distribution of rain is essential for crop growth and yield formation. Especially in semi-arid regions, this daily variability is crucial when addressing drought risk. However, daily data is not always readily available or easy to obtain. However, monthly totals of rainfall are available in most situations. If the daily dynamic of the system is omitted and average values are used based on monthly totals, stress situations due to low or excess rainfall are averaged out and may result in errors (Nonhebel, 1993).

Using weather generators, daily data can be generated based on monthly totals and the number of rain days. The weather generator used in this study was developed for the West African Sahel Zone (de Ruijter, 1990). The generator is based on the combination of a first order Markov chain and a gamma distribution (Geng *et al.*, 1986). The Markov chain is used to establish successive daily precipitation using transitional probabilities. The probability distribution of the amount of rain is described using a gamma distribution. A random number generator is used to determine the amount of rain for a given wet day. The parameterisation of both the Markov chain and gamma distribution is region-specific. Parameterisation was applied to 7 stations in Mali, using long-term (30 years) daily datasets. After successful parameterisation the rainfall generator was built into a crop growth model

Information on evapo-transpiration is crucial when quantifying the effect of drought stress on crop performance. Evapo-transpiration is a complex process combining transpiration and evaporation. Transpiration is the process of water transport via the root system to the stem and leaves into the atmosphere. Evaporation is the upward transport of water from the soil surface to the atmosphere. Both processes are driven by the potential differences between the water in the soil and the atmosphere. The potential rate of evapo-transpiration is a combination of the demand by the atmosphere and the properties of the soil and crop.

A number of methods are available for calculating the potential evapo-transpiration. Of these, the most important and best known method is the Penman method (Penman, 1948). Less well-known are the Priestley-Taylor (Preistley & Talor, 1972) and Makkink (Makkink, 1957) methods. All the methods are used to calculate evapo-transpiration for non-restricted conditions; a well-watered short crop. The advantage of the latter two methods is that they require fewer parameters, whereas Penman requires detailed readings of radiation, temperature, vapour pressure and wind speed. Makkink and Priestley-Taylor require only radiation and temperature data and assume that a constant relation exists between evaporative demand by radiation and by wind. All three methods are examined and described in Van Kraalingen & Stol (1997). The Makkink method uses incoming short-wave radiation and temperature, whereas the Priestley-Taylor method uses long-wave radiation and temperature. In this study the more practical Makkink method was used.

4. DROUGHT RISK ASSESSMENT

Several techniques are developed to assess the risk of crop failure in relation to rainfall variability. One approach is the drought index, which provides a composite picture based on a time series analysis of the effect of water deficiency on crop performance. It is a static approach often linked to a given region and crop. In this study a drought index for sorghum and millet is used to assess risk based on a discrete classification for the MPI-GCM scenario and the analysis of historical data records. A modelling approach is followed using a weather generator and a simple crop growth model to quantify the effects of climate change on the crop performance. The modelling approach is more generic than the index approach. Finally, a monitoring tool is assessed which relates the Normalised Difference Vegetation Index (NDVI) time series to a long series of satellite images to characterise vegetation dynamics in relation to climate at regional and continental levels. The NDVI was designed in order to understand the status of vegetation using remotely sensed data. It represents the quantity and activity levels of vegetation. The NDVI is related to the proportion of photo-synthetically absorbed radiation and is calculated from atmospherically corrected reflectance data from the visible and near infrared channels.

A basic approach to determining drought is to use a discrete index. Such an index, as an indicator for increasing drought stress, facilitates communication between scientists of different disciplines, managers and policy makers. Such indicators are quantitative and provide insight into the expected success rate for crop production in a given region and may trigger counteractive measures by policy makers. The drought indicator is static and has no strong predictive value.

The drought index used in this study is based on indices made by Bailey (1979) and the FAO (1980). Bailey uses monthly precipitation and mean monthly temperatures to define a moisture index' in which 'wet', 'neutral' and 'dry' months are differentiated.

It is constructed as follows:

$S = 0.18P/(1.045) \times T$,

where S is the dimensionless drought index, P is the precipitation in cm and T is the temperature in ^{o}C. Months are 'wet' when $S > 0.81$ and 'dry' when $S < 0.53$. In between 0.53 and 0.81, months are called 'neutral'. The FAO approach, developed to define Agro-Ecological Zones, uses monthly precipitation (P) and monthly potential evapo-transpiration (ETP) and allows soil moisture storage from a 'rain' month for a following 'dry' month. For the FAO, a month was regarded as sufficiently wet for a crop that is adapted to dry conditions when $P > 0.5$ ETP. Also when P>ETP, the surplus rainfall can be accumulated for the next month as soil moisture storage with a maximum storage period of one month. Table 6.1 shows the full range of the six indices.

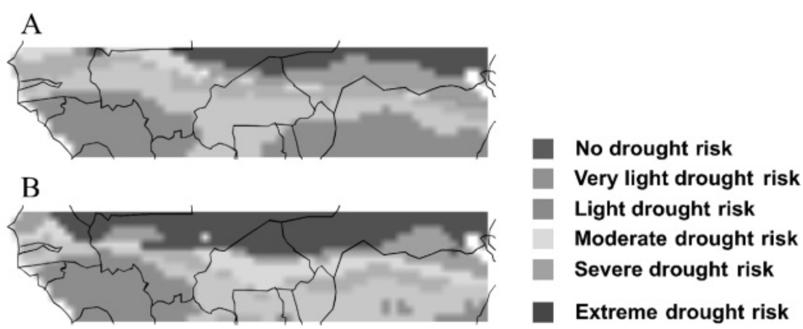
Using average monthly precipitation, average monthly temperature and average monthly daily potential evapo-transpiration, the index distinguishes between 'very wet' (Bailey's 'wet'), 'moderately wet' (Bailey's 'neutral'), 'slightly wet' (FAO's 'rain'), and 'dry' months. For sub-Saharan West Africa we will focus on the rainy season, starting in May and extending to October. As the method uses average monthly data, high-resolution or daily climate variability is eliminated from the equation.

Using recorded climate data, the drought index can be calculated for a number of years and so provide insight into how the drought risk index behaves over time (see Chapter 3).

Table 6.1 Drought Index after Bailey (1979) and FAO (1980).

Index	Classification	Method	Criteria
0	No drought	Bailey	At least four consecutive 'very wet' months
1	Very light drought	Bailey	At least four consecutive 'moderately wet' months
2	Light drought	Bailey	Three consecutive 'moderately wet' months
3	Moderate drought	FAO	Three consecutive 'slightly wet' months
4	Severe drought	FAO	Two consecutive 'slightly wet' months and a 'dry' month which is sufficiently compensated by the storage of rain from the previous month (storage: P-ETP; available rain = $P_m + P_{m-1} - ETP_{m-1}$).
5	Extreme drought	FAO	Two consecutive 'slightly wet' months without moisture storage in the third month or less than two consecutive 'slightly wet' months

Changes in precipitation, are used to calculate the drought risk. Map 6.1 clearly shows that changes in precipitation as presented for the Baseline A scenario using the MPI-GCM have a dramatic impact on the spatial distribution of the risk prone areas. When compared to Map 3.2, the picture is similar to that of the dry spells of the Seventies.



Map 6.1. Changes in drought risk for 1990-2050, A depicts the current situation (based on 30-year average) B displays the projected drought risk for baseline A scenario, MPI-GCM *(See colour section, p. 460).*

5. CROP GROWTH SIMULATION MODEL

Crop growth obeys certain physiological principles. These growth processes can be quantified in response to the environment by mathematical formulae (Spitters & Schapendonk, 1990). The environment crop interaction can be described using simple static models without a description of process rates and dynamic models where state variables change in accordance to fluctuating process rates. The drought index is an example. Static models have the advantage of a small number of parameters and a simple algorithm.

The dynamic approach, however, has the advantage of greater flexibility. In addition, it gives a greater insight into the sensitivity of underlying processes interacting with fluctuating climatic factors. Such a mechanistic dynamic model, enables the prediction of crop growth rates and yields under a variety of environmental and management conditions. Crop growth models are useful for understanding and exploring system responses to environmental and management operations. Crop models may also be used for yield forecasting or can be applied in land use evaluation, e.g. to assess the production potentials of new cropping areas as regards dependence on climatic conditions and the availability of water and fertiliser.

The model used in this study is based on the LINTUL-type models (Bouman *et al.*, 1996), it is a simple general crop model, which simulates dry matter production as the result of light interception and utilisation with a constant light use efficiency. Detailed information on how to construct and use crop growth simulation models can be found in e.g. Penning de Vries & Van Laar (1982), van Keulen & Wolf (1986), and Penning de Vries *et al.* (1989). Reviews of the various approaches followed in crop growth simulation and examples of their application have been given by, among others, Loomis *et al.* (1979), Penning de Vries (1983), Whisler *et al.* (1986), and Wisiol & Hesketh (1987), Spitters *et al.*, 1989.

Temperature is the only factor that determines the development rate of the crop. Crop growth is possible within a temperature range of 5 to 35 °C. In order to complete a full growth cycle, a certain amount of accumulated temperature degrees are required. The required degree-days may vary among crops. In this study a standardised cereal crop (wheat, rice, maize, millet or sorghum) is taken as a proxy for a wide range of crops that could be grown. The crop requires a total of 1200 °Cd, divided in two stages. The radiation interception by leaves increases linearly during the first stage of crop development, from zero at emergence to unity at a development stage of 600 °Cd (van Heemst, 1986). Subsequently, interception remains at unity during 600 °Cd and reduces to zero over the last part of the growing period, because of leaf senescence. Intercepted radiation is converted into biomass by multiplication with a constant radiation use efficiency set at 3.0 g MJ-1 (Monteith, 1981, 1990; Gallaghar & Biscoe, 1978; Goudriaan & Van Laar, 1994).

Radiation and temperature are, obviously, not the only environmental factors determining crop yield. Water, which is absolutely essential for crop growth, is in most cases equally important. Crop growth might be limited by a shortage of water during all or part of the growing period.

The movement of water through to crop via the stomata into the atmosphere is called transpiration. CO_2 is transported in the opposite direction for the formation of carbohydrates. Most of the water used by the crop is, in fact, lost to the atmosphere. When the uptake of water from the soil through the roots is not sufficient to replace the water lost to the atmosphere, the plant reduces the outflow of water by closing its stomata. However, this reaction also hampers inflow of CO_2 and hence plant growth. The two processes are more or less proportional. In other words for each kilogram of plant material produced (under a given set of external conditions) the same amount of water is required.

The potential evapo-transpiration determines the demand for water. For a closed crop canopy, when the soil is completely covered by leaves, this is in fact the transpiration demand. The amount of water needed to realise the transpiration demand can be calculated on the basis of crop-specific transpiration coefficients (Monteith, 1990).

The availability of water depends on rainfall and soil physical properties. Soil water between field capacity and wilting point is assumed to be available (see Table 6.2). When the soil water content falls below the texture-specific threshold, crop transpiration becomes less than the potential and crop growth decreases proportionally.

Table 6.2 Volumetric water content at field capacity and wilting point, and water holding capacity (cm m^{-1}) source: FAO, 1996.

Soil property	Soil type		
	Coarse	**Medium**	**Fine**
Field capacity	13	32	54
Permanent wilting point	4	10	44
Water-holding capacity	9	22	10

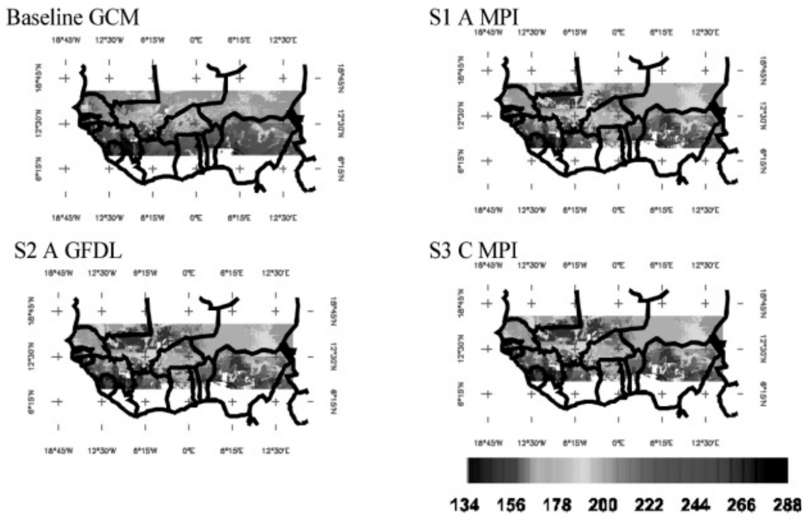
The process of water movement into (rainfall) and out of (evapo-transpiration, and drainage) the soil body is calculated with a capacity type, dynamic soil-water-balance model. Total storage was related to soil depth set at a max of 1 meter. Because of the constant relation ratio between growth and transpiration, a constant transpiration coefficient can be used. The transpiration coefficient may vary between 200 and 350 for cereals. A value of 250 is commonly used. This means that for each 250 l of water 1 kg of crop dry matter is produced. This coefficient is used to calculate the demand for water given the increase in biomass. When the water supply is lower than the demand, the growth rate is reduced proportionally. Crop yields result from the multiplication of the accumulated biomass over the growing period by a harvest index, set at 0.43.

Calculations are carried out using a daily time step, on a 0.5°×0.5° spatial grid for the baseline (1960-1990) and the three climate change scenarios for sub-Saharan West Africa. Because a weather generator is used to scale down precipitation figures from monthly to daily values, each soil-weather combination is calculated 20 times. As the start of the growing season is not exactly known (the growing season starts somewhere in May and ends in October), calculations are started at two week intervals from 1 May till the end of October. The resulting database contains the calculated yield for each land pixel of 0.5°×0.5° for 20 rainfall distributions for 12 starting points in the growing season.

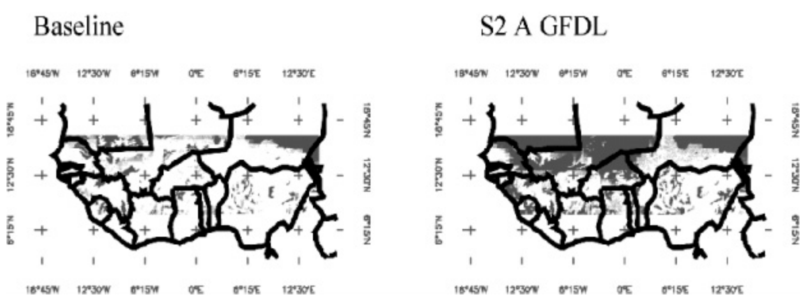
The onset of the growing season is a crucial aspect of agriculture. 'False' starts may cause entire seasons to be lost. Using the database containing the simulated database, the starting data that produce the highest production levels are extracted to establish the spatial variability in the onset of the growing season. Map 6.2 clearly reveals, for all scenarios, an increase in variability, indicating an increased risk in assessing the planting date. The diversification could also mean that the risk of crop failure is spread over the region, with it being possible to shift market infrastructures in order to exploit such opportunities. Baseline GCM Is the 1960 – 1990 average. S1 A MPI Scenario 1 uses baseline A with the Max Planck Institute climate model. S2 A GFDL Scenario 2 uses baseline A with the Global Fluid Dynamics Laboratory climate model. S3 C MPI Scenario 1 uses baseline C with the Max Planck Institute climate model. Baseline A combines a medium population growth with a medium economic growth. Baseline C combines a medium population and high economic growth.

Using the 20 calculated yield levels for each soil-crop-weather combination, including some of the rainfall variability, we can assess the risk of given management practices such as planting date. With regard to yield we will concentrate on the probability that a given yield level is exceeded rather than providing 'exact' yield levels. Map 6.3 shows the consequences of not adjusting the planting data for the baseline and S2 A GFDL scenario.

The highest yields are obtained when planting takes place on around day 190 (beginning of July). If this is applied to the changed situation, a large part of the region, notably sandy soils and (semi)-arid regions, experiences higher risk levels resulting in lower production levels. Adaptations, earlier planting or a change in crop variety require other structures to be in place: e.g. seeds need to be available and labour and markets also need to be in place.



Map 6.2. Start of the growing season, day of year, related to highest water limited production level. Baseline GCM Is the 1960 – 1990 average. S1 A MPI Scenario 1 uses baseline A with the Max Planck Institute climate model. S2 A GFDL Scenario 2 uses baseline A with the Global Fluid Dynamics Laboratory climate model. S3 C MPI Scenario 1 uses baseline C with the Max Planck Institute climate model. Baseline A combines a medium population growth with a medium economic growth; Baseline C combines a medium population and high economic growth *(See colour section, p. 460).*



Map 6.3 Probability of yield exceeding 2250 kg ha-1 for the 1960-1990 baseline and S2 A scenario using GFDL GCM, day of planting is 190. (red = 1, white = 0). Baseline Is the 1960 – 1990 average. S2 A GFDL Scenario 2 uses baseline A with the Global Fluid Dynamics Laboratory climate model. Baseline A combines a medium population growth with a medium economic growth *(See colour section, p. 461).*