Associating multivariate climatic descriptors with cereal yields: A case study of Southern Burkina Faso

Mwenda Borona, Cheikh Mbow, Issa Ouedraogo and Richard Coe

**World
Agroforestry
Centre**

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Photos

Increasing tree density using a simple drip irrigation technique. Water is put manually into the bottles and let to drop out gradually. Photo by Cheikh Mbow/World Agroforestry Centre.

Tree seedling planting in Cassou area, Burkina Faso. Photo by World Agroforestry Centre

Impact of fires and ecosystem fragmentation in a community-managed forest in Burkina Faso. Photo by Cheikh Mbow/World Agroforestry Centre

Cattle drinking from a river in Burkina Faso. Photo by Cheikh Mbow/World Agroforestry Centre

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Abstract

In the Sahel, climate variability and change have resulted in a diversity of direct and indirect impacts largely affecting rain-fed farming. Populations in this area mainly rely on rain-fed farming and natural resources to sustain their livelihoods which heightens their risk. The association between occurring climate variability and staple cereal yields has not been systematically addressed. With reference to these interactions and gaps, this paper initially explores the occurrence of climate variability in southern Burkina Faso and shows how district-scale cereal yields respond variably to inter-annual variation of climate variables. This relationship is primarily explored by use of statistical models and non-parametric correlations. Results mainly show that the cereal yields widely depict sensitivity to the length of the growing period and total dry days in the growing season. Based on the results, our recommendations emphasize on strengthening of pre-existing efficient water utilization platforms especially those that have evidently increased yields.

Keywords

Climate variability, cereal yields, climatic descriptors, food security, Burkina Faso

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List of abbreviations and acronyms

A.S.L	Above Sea Level
CDD	Consecutive Dry Days
CGP	Cessation of the Growing Period
COV/CV	Coefficient of Variation
ETc	Crop Evapotranspiration
ETo	Reference Evapotranspiration
FAO	Food and Agricultural Organization
GDP	Gross Domestic Product
GMU	Gregon Mason University
ICRAF	World Agroforestry Centre
IFPRI	International Food Policy Research Institute
IPCC	Intergovernmental Panel on Climate Change
LGP	Length of the Growing Period
OGP	Onset of the Growing Period
PDSI	Palmer Drought Severity Index
RMA	Risk Management Agency
SAI	Standardized Anomaly Index
SPI	Standardized Precipitation Index
TAR	Third Assessment Report
TDD	Total Dry Days
UoA	University of Auckland
WMO	World Meteorological Organization

Executive summary

This work is based on the assumption that crop growth and development and most importantly yields of the staple cereals are to a certain extent influenced by climate variability. This study hence puts emphasis on rainfall and temperature as key limiting factors of crop performance and subsequent yield. As such, this study is based on a multivariate approach that initially identifies variation in climate in Southern Burkina Faso and the influence of selected fine time climatic variables staple cereal yields in a selected province. To address this main objective, daily precipitation and temperature records from two synoptic stations dating 30-36 years were used. These included Po (11° 10'N 1° 9'W) and Ouagadougou (12° 22'N 1° 31' W). District level production and area under cultivation data was obtained from Sizilli-Ziro province and applied in computation of annual yields (t-ha⁻¹/year) for maize, sorghum and millet which are staples in the country.

Related studies in the region widely rely on rainfall and temperature averages, with minimal statistical inputs to determine the association of climate variability with crop yields. These studies disregard climatic descriptors and indices such as instances of dry spells and seasonal length variance. In this work we focused on parameters beyond rainfall averages by applying an array of climatic descriptors to account for intra-seasonal variation in climate within the season including season length and dry spells.

To explain the climatological context, a wide range of techniques as presented in Table 1 are employed to compute an array of climatic descriptors including dry spells, crop evapotranspiration estimates and season length.

Crop growth and development is influenced by a wide range of climatic and slowly changing non-climatic factors. To establish the evidence, we initially apply some statistical techniques to control for non-climatic factors that alter crop yield including new farming techniques, market dynamics and soil fertility. Selected climatic variables computed are then loaded into regression models to identify their relative contribution in explaining yield variance and their causal relationship with annual cereal yields. Further, we employ correlation matrices to explore the relationship between the various computed climatic variables and cereal yields anomalies.

Table 1 Summary of computed climatic descriptors

Computed derivative	Data input	Rationale
Total, maximum, minimum and mean annual rainfall	Monthly average rainfall	Defining of the unimodal rainy season in the study area
Rainy days and rainfall intensity	Daily rainfall	Defining the distribution of diurnal rainfall events
Anomalies and rainfall trends	Annual rainfall	Defining the interannual variation of average and monotonic trends in rainfall.
Length of the growing period	Daily rainfall	Defining the onset, cessation and subsequently the duration of the growing season.
Dry spells	Daily rainfall	Defining the influence of consecutive dry days on the growing season and their distribution and probability of occurrence.
Drought events	Daily rainfall	Defining the occurrence and severity of drought events in the study period.
Crop evapotranspiration estimates	Daily rainfall, daily maximum and minimum temperature, radiation.	Estimation of the seasonal crop water demand.
Cereal yield anomalies	Cereal production and harvested area	Estimation of annual yield deviation from the mean with accommodation of non-climatic drivers.

The results reveal high climate variability based on; inter-annual and inter-decade rainfall variations across the time series of Po and Ouagadougou synoptic stations. This variability is, for example, initially expressed by the varying annual rainfall amounts from year to year against a long-term average. In the time series we however note a generally increasing trend in annual rainfall for both stations.

Additionally there are several instances of false starts of the rainy season, in more than 50% of the time series, which could contribute to uncertainty in on-farm decision-making. The analysis also shows that instances of average dry spells (5 to 10 days) are prevalent across the season. Further, the months of May and June, which mark the start of the season, are widely characterized by long dry spells lasting over 10 days.

These dry spells coincide with the sowing/planting season. The study area has experienced drought spells in the past though such events are less frequent in recent decades. On average the area is characterized by more normal years without severe dry or wet conditions. We however emphasize on the uncertainty associated with extreme climatic events whose impacts are amplified by minimal adaptive capacity of poor rural dwellers.

Findings indeed show the risks and uncertainties posed by climatic events in the largely farming dependent community. These risks include a wide range of potential direct and indirect impacts including those associated with food availability and access. We suggest a suite of interventions that target management of scarce water resources especially those that have demonstrated positive outcomes in arid and semi-arid environments.

Introduction

Climate variability refers to the short-term changes in average weather conditions in an area. Climate variability has an array of effects on agro-ecological and growing conditions of crops subsequently leading to food insecurity and low agricultural production (Amikuzuno and Donkoh 2012). In Africa for example, it is widely agreed that climate change will not only have a negative effect on food security on the supply side but also, utilization and stability (Niang et al. 2014). This impact is primarily driven by heavy reliance on rain-fed farming systems. Characteristic events such as erratic rains are common in semi-arid regions FAO (1993) and include instances of unpredictable, off season and irregular rainfall (Simelton et al. 2011). Such erratic rains similarly play a role in occurrence of crop failure and subsequently bring about food shortage. The IPCC in the TAR indeed outlines that in the event of climate change and associated impacts, areas in the tropics largely involving non-irrigated agriculture will experience lower yields which could be worsened by poor market access (Parry 2007). These lower yields could further be compounded by low inputs utilization and minimal mechanization (Kandji et al. 2006).

Climate variability is principally manifested by large or small variations in temperature and precipitation – the most important element in agricultural development (Bhandari 2013). In the Sahel region of West Africa there have been an array of studies on climate change effects such as famine since the 1970s and 1980s droughts (West et al. 2008). Other related topics range from land degradation, poor soils and erratic rainfall (West et al. 2008) to desertification (Kandji et al. 2006). In this study these phenomena are of great concern since in Burkina Faso rain-fed agriculture, the principal employer, is the backbone of the economy accounting for about 40% of the GDP (Jalloh et al. 2011).

While the study area lies in a region that receives relatively higher rainfall than the rest of Burkina Faso, cases of intra- and inter-annual rainfall variability are widely prevalent. This variability is a characteristic of rainfall in the Sudano-sahelian zone (Ati et al. 2002). Such effects of climate variability are likely to lead to a wide range of impacts and as Oluwasegun and Olaniran (2010) indicate, in fragile environments climate variability could eventually translate to lower living standards. Barbier et al.

(2009) identifies examples such as a drop in maize and sorghum yields in Burkina Faso which are the staple grains in the central plateau (West et al. 2008).

The motivation of this analysis is to add to the knowledge depth of climate variability including computation methods and how such variation associates with yields. We refer to related studies such as Lodoun et al. (2013) who recognize the importance of studying climatic descriptors in agriculture while also pointing out the barrier in computation of the same which is mainly limited access to daily climatic data. This analysis is crucial as the cereals in focus are predominant in the dry agro-ecology of Burkina Faso and are a major source of energy, protein and mineral nutrients. At the same time, the study forms a basis for informed on-farm decision support in the climate variability prone study area. Indeed understanding effects of climate change on crop yields aids in making of timely and future responses and choices for cropping and land use planning (Lobell and Burke 2010).

In this analysis, methods and results for all computed and/or estimated parameters are presented followed by a comprehensive discussion. Results on variability are presented and discussed at the station level where similarities in trends are identified while also noting variations. Climate variability and crop yield models as well as correlation matrices refer to one station, Po, which lies in the same climatic zone as the BIODÉV site largely within Cassou District. This is a novel study which includes an array of climatic derivatives such as dry spells and drought instances and how these associate with inter-annual cereal yields in Southern Burkina Faso using statistical models. Related studies such as Mishra et al. (2008) and Sultan et al. (2013) rely on deterministic model based approaches in exploring the relationship between cereal yields and climate variability at a national and regional scale. Other studies pay attention to climate variability for example Lodoun et al. (2013) in the larger Burkina Faso and Emma et al. (2015) in central Burkina Faso.

1.0 Statistical methods and results characterizing climate variability

1.1 The study area

The study targeted Ziro province, Figure 1, (11° 16'N to 11° 45'N and -2° 10'W to -1° 48'W) which is located in southern Burkina Faso. The location is characterized by low altitude with an average altitude of 300 A. S. L. The agro-ecological zone includes the South-Sudanian ecological zone (Fontès et al. 1995) which receives 900mm to 1200mm of annual rainfall. This rainfall is unimodal and falls between May and October. The dominant farming system includes cultivation of sorghum, millet and maize cereals, tubers such as yams and sweet potatoes and animal husbandry. The population density in Cassou is 34.7 inhabitants/km², which is among the highly densely populated rural areas in the country (INSD 2007).

1.2 Unfavorable rainfall years

The analysis of unfavorable rainfall is based on monthly and annual rainfall as well as rainy days and temperature distribution. These precipitation and temperature parameters for Po and Ouagadougou stations were computed from daily precipitation and temperature data for the time series running from 1977 to 2013 (see Table 2 for summary of metadata). Computed parameters and methods applied are presented in Table 3.

Climate data was initially checked for quality to ensure validity of results (Rowhani et al. 2011). Validity check shows that daily rainfall data however exhibits minimal gaps within the rainfall season. Hence in this analysis only daily temperature data was reviewed for missing maximum and minimum temperature data which we estimated using multiple imputations (Markov chain Monte Carlo) for the years running from 2008 to 2013 as well as gaps within the period 1979 to 2007. A sequence $X_1, X_2, \dots$ of random elements of a set is defined as a Markov chain if the distribution of X_{n+1} given $X_1 \dots \dots X_n$ depends on n only (Geyer 2011). Geyer (2011) adds that in the MCMC the Markov chain has stationary transition probabilities when the conditional distribution of X_{n+1} given X_n does not depend on n . Once missing values were estimated, daily minimum and maximum temperatures were computed from the average of the imputed daily temperatures and recorded mean temperatures (Table 3).

In this analysis a rainy day is defined by daily rainfall above 0mm after Mathugama and Peiris (2011).

Five rainfall classes of 10¹ mm intervals, beginning from 1 to 10 mm, were developed to denote the annual distribution of rainy days in the specific precipitation classes within respective years. These classes were arrived at by use of conditional count functions in MS Excel.

Figure 1 Map of the study area

Table 2 Summary of climate data metadata, Po and Ouagadougou

Weather parameter	Po Station	Ouagadougou station
Rainfall data period	1977 to 2013	1977 to 2013
Maximum temperature data period	1977 to 2007	1977 to 2007
Minimum temperature data period	1977 to 2007	1977 to 2007
Mean temperature period	2008 to 2013	2008 to 2013
Coordinates	Lat 11 ⁰ 10'	Lat 12 ⁰ 22'

¹ Method of computing the rainfall classes is not presented here.

Table 3 Summary of methods of computing various parameters

Parameter	Function
Total monthly and annual rainfall	$\text{Total annual rainfall} = \sum \text{of daily precipitation values in the year where } ppm > 0$ $\text{Total monthly rainfall} = \sum \text{of daily precipitation values in a specific month where } ppm > 0$
Annual average precipitation	$\frac{\sum \text{of annual precipitation in the time series}}{\text{Number of years in the time series}}$
Number of rainy days in the year	$\sum \text{of occurrences/counts of precipitation where } ppm > 0$
Monthly maximum rainfall	$\sum \text{of maximum occurrences of total monthly rainfall for specific months in the time series}$
Monthly minimum rainfall	$\sum \text{of minimum occurrences of total monthly rainfall for specific months in the time series}$
Mean monthly rainfall	$\frac{\sum \text{of daily precipitation values for a specific month in the time series}}{\sum \text{of instances of the month in the time series}}$
Average daily, monthly and annual temperature	$\text{Daily mean temperature} = \frac{\text{Maximum daily temperature} + \text{Minimum average temperature}}{2}$ $\text{Mean monthly temperature} = \frac{\sum \text{of daily mean temperature values in a specific month in the time series}}{\text{Number of occurrences of the month}}$ $\text{Annual average temperature} = \frac{\sum \text{of monthly mean temperature values in a specific year}}{\text{Number of months in the year}}$

Figure 2 Monthly rainfall and mean monthly temperature distribution at Po

Figure 2 shows that the maximum rainfall occurs during the July-September period. A secondary axis representing mean annual temperature was added to the precipitation values showing the trend in mean temperature during the rainy season.

Figure 3 Monthly rainfall and mean temperature distribution, Ouagadougou

Figure 3 shows that maximum rainfall is experienced during the July to September period as similarly noted from the Po weather station data. In addition it is apparent that the rain season similarly runs from May to September.

A slight variation is however observed between May and July where the maximum, minimum and mean rainfall drops in June and steeply rises in July.

Figure 4 Annual precipitation sum and number of rainy days, Po

Figure 5 Annual precipitation sum and number of rainy days, Ouagadougou

Figure 4 shows that total annual precipitation distribution, with reference to the Po station, varies over the years with 1990, 1991 and 1994 recording the highest precipitation, 1290mm, 1281mm and 1268mm respectively. Highest recorded precipitation in Ouagadougou includes the years 1991, 2009 and 2012 recording 900mm, 896mm and 1003mm respectively.

In Figure 4 the period 1977 to 1987 experienced a steady increase in total annual precipitation with the 1988 to 1998 decade showing a gently increasing trend. Figure 5 (Ouagadougou station) shows a slightly differing trend in annual precipitation with

the first decadal (1977 to 1987) showing an increasing trend followed by a decreasing trend in the subsequent 10 years (1988 to 1998). This relationship is also presented in scatter plots, Figure 6 and 7 showing a positive relationship in both Ouagadougou and Po stations.

Figure 6 Relationship between the total number of rainy days and annual precipitation, Ouagadougou

Figure 7 Relationship between the total number of rainy days and annual precipitation, Po

Figure 8 presents the distribution of rainy days into increasing rainfall amount categories for Po weather station, depicting more rainy days in the 1-10mm class.

The distribution of rainy days in Ouagadougou tends to express a similar distribution. Figure 9 shows most of the rainy days fall within the 1 to 10mm category followed by fewer days in the 10 to 20mm and 20 to 30mm categories. From both stations it is

observed that there is consistency of extreme events of greater than 50mm in the last decade and a similar distribution in the mid-1980s through mid-1990s.

Figure 8 Distribution of rainy days into rainfall amount classes, Po

Figure 9 Distribution of rainy days into rainfall amount classes, Ouagadougou

1.3 Length of the growing period, methods and results

Initially climate records for the time series for both stations were unstacked/rearranged and loaded onto INSTAT+ for analysis. The LGP with reference to each synoptic station data is computed as a difference between the onset of the OGP and the CGP.

The definition of the OGP is adopted from Sivakumar (1992)², as applied by Lodoun et al. (2013) in a study in Burkina Faso and discussed in studies such as (Ati et al. 2002) and Roncoli et al.(2002).

In this study OGP is a time when rainfall over three consecutive days is at least 20mm³ after 1st May. In addition, onset dates without instances of dry spells (in this case seven days) in the next 30 days were computed to identify instances of false starts in the time series. The cessation date of the growing period is the date after 1st September (Maikano 2006) when the soil water holding capacity was 60mm⁴ (Traore et al. 2000) with a daily evapotranspiration of 5mm (Maikano 2006). The dates also fit to the season (May to September) identified in Figures 2 and 3 in section 1.2.

Further, descriptive statistics such as the mean, standard deviation and the median are computed to identify the central tendency and variation of OGP, CGP and LGP in the time series. Date codes (Julian days) are applied in computing of measures of central tendency as well as identifying OGP, CGP and LGP dates.

In addition the SAI (equation 1) is computed for OGP, CGP and the LGP for the time series to identify annual trends from the time series averages. In this case Z is the SAI, x is the respective year's OGP, CGP or LGP; μ is the respective mean for the time series and δ is the standard deviation for the respective time series.

Results show that for the Po weather station (Table 3), on average the OGP is 15th May and 27th May when instances of dry spells after onset are excluded. The cessation date for the Po weather station was on average 14th October. Further, the earliest and latest cessations were 12th September and 30th October. The earliest

² Onset date is suitable for crop planning in West Africa (Sivakumar, 1992) and applied in recent studies such as Lodoun, 2013.

³ This volume is also reported in perception studies among smallholder farmers in central Burkina Faso.

⁴ The water holding capacity threshold varies by the soil texture. From review majority of the soils in the study area/block/co-ordinates the soil class is *lixisols*, mainly silt-clay-loam with water holding capacity range of 1.2 to 2.0 inches (about 60mm). R scripts (Appendix 1) are applied to extract the dominant soil type from the International soil reference and information centre (ISRIC) database.

starting dates, minimum records, for the OGP in the time series were 1st May including when the dry spell is excluded. In the Ouagadougou station, Table 3, the average onset date noted as 26th May and 15th June when dry spells are excluded.

The average cessation date is 27th September, with earliest and latest dates recorded as 1st September and 15th October. Figures 10 and 11 show unsuccessful instances or false starts where the onset of the season without dry spells varies from the “onset date”. To further bring out the variation in the OGP, CGP and LGP, Figures 10 and 11 also demonstrate anomalies which are variations from respective study period averages.

Table 4 Distribution of Onset, cessation dates and length of the growing period in Po and Ouagadougou

Po	Minimum Julian day (Date)	Maximum	Median
Onset	122 (May 1 st)	181(June 29 th)	136.5 (May 15 th)
Onset Including dry spell	122 (May 1 st)	203 (July 21 st)	148.5 (May 27 th)
Cessation	250 (September 6 th)	296 (October 22 nd)	278 (October 14 th)
LGP	117 days	167 days	143 days
LGP (excluding spell)	61 days	159 days	123 days
Ouagadougou			
Onset	122 (May 1 st)	184 (July 2 nd)	147 (May 26 th)
Onset Including dry spell	123 (May 2 nd)	208 (July 26 th)	167 (June 15 th)
Cessation	245 (September 1 st)	289 (October 15 th)	271 (September 27 th)
LGP	63 days	155days	121 days
LGP (excluding spell)	63 days	152days	100 days

Figure 10 Onset cessation and LGP anomalies, Po

Figure 11 Onset cessation and LGP anomalies, Ouagadougou

1.4 Anomalies and trends in annual precipitation, methods and results

To determine variability of the climate data series for both stations, the SAI and CV were computed. Annual precipitation anomalies were computed through the time series as presented in Figures 14 and 15. The anomalies indicate an index, SAI, which is a standardized difference between the annual precipitation total of a specific year and the average of the time series. This is presented in equation 1 adopted from Hadgu et al. (2013).

$$Z = \frac{(x-\mu)}{\delta} \dots \dots \dots \text{Equation 1}$$

Where Z is the SAI, x is the respective year annual precipitation; μ is the mean precipitation for the time series and δ is the standard deviation for the time series.

In addition, the CV was computed by division of the standard deviation of the time series to the mean as shown in equation 2 modified from Mustapha (2013).

$$CV = \frac{\delta}{\mu} \dots \dots \dots \text{Equation 2}$$

Where δ is the standard deviation of the time series and μ is the time series mean.

The CV was computed for the time series at intra station and inter station level.

To determine the trend in the data the non-parametric Mann-Kendall's trend test was worked out for the time series of each synoptic station. The Mann-Kendall statistic is applied to test for monotonic and/or increasing and decreasing trends as well as significant changes in the time series (Karabulut et al. 2008).

The Mann-Kendall's statistic was computed using TREND 1.02 Chew and Siriwardena (Chew and Siriwardena 2005) as shown in equation 3 to 5 adopted from Hadgu et al.(2013).

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^N \text{sgn}(x_j - x_i) \dots \dots \dots \text{Equation 3}$$

Where S is the Mann-Kendall's test statistic, x_i and x_j represent sequential values for the time series in the years i and j with $j > i$; and N represents the length of the time series.

When the S value is positive there is an increasing trend with a negative value showing a negative trend.

The sign function is computed as shown in equation 4

$$sgn(x_j - x_i) = \begin{cases} +1 & \text{if } (x_j - x_i) > 0 \\ 0 & \text{if } (x_j - x_i) = 0 \\ -1 & \text{if } (x_j - x_i) < 0 \end{cases} \dots \dots \dots \text{Equation 4}$$

When N is larger than 10, for example more than 10 years in a time series, the Z_{MK} approximates the standard normal distribution for the time series (equation 5).

$$Z_{MK} = \begin{cases} \frac{S-1}{\left[\sqrt{VAR(S)}\right]} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\left[\sqrt{VAR(S)}\right]} & \text{if } S < 0 \end{cases} \dots \dots \dots \text{Equation 5}$$

The presence of a statistically significant trend in the time series is then defined with reference to the Z_{MK} value. In a two sided test, the null hypothesis H_0 should be accepted if $|Z_{MK}| < Z_{1-\alpha/2}$ at a specific significance level. $Z_{1-\alpha/2}$ is the critical value of Z_{MK} from the standard normal Table for example for 5% significance level ,the value is 1.96.

We further computed the Kendall's tau (τ), equation 6, adopted from Tian and Fernandez (2000) as a measure of the strength of association between time (years) and annual rainfall. This statistic is a measure of the strength of association between two variables (Przytycki 2001).

$$\tau = \frac{S}{n(n-1)/2} \dots \dots \dots \text{Equation 6}$$

The SAI in Figures 12 and 13 identifies wet and dry years along the time series for the two synoptic stations. Wetter years are presented by positive deviation from zero which is the time series average. Drier years on the other hand are characterized by negative anomalies or deviations from the season average.

Figure 12 SAI Po

Figure 13 SAI Ouagadougou

Table 5 shows descriptive summary of the time series monotonic trends computed using the Mann-Kendall approach as well as the level of variation in seasonal and annual rainfall. These are measures of the general trend of the rainfall as well as the extent of variation at seasonal and annual level.

Table 5 Mann-Kendall trend test for annual and seasonal Precipitation, Po and Ouagadougou

	Ouagadougou station		Po station	
	Seasonal	Annual	Seasonal	Annual
S Score	133	144	236	246
Z_{MK}	1.726	1.87	3.074	3.204
Critical value	1.645	1.645	2.576	2.576
Kendall's tau	0.2	0.216	0.3746	0.3904
Significance level (α)	0.1	0.1	0.01	0.01
Coefficient of Variation (CV)	15.9%	13.4%	20.8%	20.4%

The results in a glimpse show the differences in variation in seasonal and annual rainfall at intra-station and inter-station level while also showing a characteristic positive trend based on the S score.

1.5 Frequency of dry spells, methods and results

Climate records for the time series for both stations were unstacked/transformed using MS Excel and loaded onto INSTAT+ for analysis of dry spells. The dry spell was defined as the maximum number of consecutive days with minimal precipitation (0 to 0.85mm) from the onset of rains (OGP from section 1.2) for the season (May to September) for each year in the time series. This threshold is mentioned in related dry spell studies such as Mathugama and Peiris (2011) and Karambiri et al. (2011). Dry spells are computed up to September which constitutes the near end of the season. This length of days also corresponds with the critical growing stages for the cereals considered in this analysis and also the length of growing for the cereals as reported by Wang et al. (2008) in their work in western Burkina Faso.

The sum of dry days within the season in each year in the time series was subsequently computed by aggregating the maximum dry spells for each month (CDD). In addition the distribution of dry days per month across the time series was computed by aggregating the maximum instances of dry days. Following Ibrahim et al. (2012), maximum dry days were further grouped into categories and counted to denote short spells (less than 5 days), average spells (5 to 10 days) and long dry spells (above 10 days). Further review of related work such as West et al. (2008) we reveal that presented categories are consistent with farmer perceptions in the central plateau where they consider a dry spell as a 7-day or longer period of absence or modest rainfall.

Figures 14 and 15 indicate the distribution of short, average and long dry spells in the time series at Ouagadougou and Po station characterized by more average and short dry spells. In following Figures 16 to 19, the distribution of dry days in monthly time scales is further presented and further outlines the distribution of dry spell categories in the season, with longer dry spells at onset and towards the end of the season. Figures 20 and 21 demonstrate the relationship between the LGP and the proportion of total dry days and how the dry days alter the distribution of the LGP.

Figure 14 Dry spell categories, Ouagadougou

Figure 15 Dry spell categories, Po

Figure 16 Distribution of dry days, Ouagadougou

Figure 17 Distribution of dry days, Po

Figure 18 Distribution of dry spells across months, Ouagadougou

Figure 19 Distribution of dry spell across months, Po

Figure 20 Relating total dry days and the length of the growing period, Po

Figure 21 Relating total dry days to the length of the growing period, Ouagadougou

Table 6 LGP and total dry days correlation matrix

		TDD		LGP	
		<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>
TDD	Po	1		-0.353	0.000
LGP	Ouagadougou	-0.5812	0.035	1	

1.6 Most Intense rainfall periods, methods and results

Rainfall intensity is the amount of rainfall per unit time Critchley (1991) measured in mm/day, mm/hour or mm/year for a time series. Rainfall intensity affects the balance of infiltration and runoff at the soil surface. In the two synoptic stations, rainfall intensity was computed as a ratio between the total annual precipitation and the number of rainy days (equation 7) in the year (where ppm>0mm), with the mean intensity computed by averaging the time series annual average rainfall values.

$$\text{Average rainfall per day} = \frac{\text{Annual precipitation}}{\text{Number of rainy days}} \dots\dots\dots \text{Equation 7}$$

Results, Figure 22 and 23, showed a varying trend in rainfall intensity in the time series for both stations with several instances of oscillating peaks and drops along the study period time length. These characteristic oscillations are evidence of inter-annual variability in the rainfall intensity. Trend lines were included along the time series mean to explain the overall direction of rainfall intensity in the period.

Figure 22 Rainfall intensity distribution along the time series, Po

Figure 23 Rainfall intensity distribution along the time series, Ouagadougou

1.7 Drought sequences in the time series, methods and results

In this study drought is defined on the basis of dryness or intensity in comparison to some normal or average amount and the duration of the period. To determine drought sequences and/or spells, a 6-month SPI was computed. In this analysis, the SAI in section 1.3 allows one to identify the years as drier or wetter while the SPI goes further to identify the category of the drought and wetter periods. The SPI is a probability index that involves expression of precipitation for a month or longer in terms of the corresponding climatological records Wilks (2011) by fitting of a gamma probability density function McKee et al. (1993) which is then transformed into a normal distribution (WMO 2012).

Hayes et al. (1999) in their review state that the SPI has key advantages over other indexes, e.g. PDSI, such as requiring precipitation input, versatility-enabling monitoring of agricultural conditions and also being normally distributed. Since it is normalized, the SPI can equally be used to monitor wet conditions. We recognize the approach has limitations however including not accounting for soil, crop growth and temperature anomalies also important for drought monitoring (Narasimhan and Srinivasan 2005). Ntale and Gan, (2003) however states that SPI requiring rainfall as the only input ensures consistency. The probability density function as discussed by Huang and Kahraman (2013) is defined by:

$$g(x) = \frac{1}{\beta^\alpha \Gamma(\alpha)} x^{\alpha-1} e^{-\frac{x}{\beta}} \quad \text{For } x > 0 \dots \dots \dots \text{Equation 8}$$

Where α is a shape parameter, and β is a scale parameter x is the amount of precipitation, and Γ is the gamma function.

Initial estimations for the scale as well as shape parameters are computed by:

$$\alpha = \frac{1}{4A} \left(1 + \sqrt{1 + \frac{4A}{3}} \right) \dots \dots \dots \text{Equation 9}$$

$$\text{and } \beta = \frac{\bar{x}}{\alpha} \dots \dots \dots \text{Equation 10}$$

$$\text{with } A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n} \dots \dots \dots \text{Equation 11}$$

Where $\bar{x}$ the precipitation mean, x is the average value at any time scale, while n represents the number of observations.

By linking the probability density function with estimated parameters, the cumulative probability $G(x)$ of a given precipitation value for each month is computed by:

$$G(x) = \sum_0^x g(x) dx = \frac{1}{\beta^\alpha \Gamma(\alpha)} \int_0^x x^{\alpha-1} e^{-\frac{x}{\beta}} dx \quad \text{For } >0 \dots \dots \dots \text{Equation 12}$$

Since the gamma distribution is undefined at 0, the probability of no precipitation is not yet included in this value. This is adjusted for by use of the modified cumulative probability function shown on equation 13;

$$H(x) = q + (1 - q)G(x) \dots \dots \dots \text{Equation 13}$$

Where q is the probability of zero precipitation. The probability distribution $H(x)$ is then transformed into a standard normal distribution using a conversion approximation to generate the SPI values.

The severity index applied in this study as presented in Table 7 was adopted from Behnassi et al. (2013). The level or magnitude of departure from zero denotes a probability of occurrence such that appropriate decisions can be made with reference to the SPI value. The red-yellow-green colour scale, replicated in the annual distribution of droughts, represents the respective category of severity of dry or wet events.

Table 7 Standardized precipitation indices and categories showing severity

Category	SPI Range	Colour Scale
Extreme drought	-2.0 or less
Severe drought	-1.5 to -1.99
Moderate drought	-1.0 to -1.49
Mild drought	-0.99 to 0
Normal	+0.1 to +1.49
Severe wet	+1.5 to +1.99
Extreme wet	2 and above

The six months were preferable since this presents a typical agricultural cycle covering sowing, planting and harvesting season a modification from Behnassi et al. (2013) 9 month SPI. The SPI relies solely on precipitation which is indeed heavily depended upon in rain-fed-agriculture. Initially a time series of the monthly precipitation data for 36 years for Po and Ouagadougou weather stations was developed and input into an SPI computation tool (WMO 2012). The resulting indices were then grouped with reference to the Table 8. The SPI range is such that positive values indicate greater than median precipitation while negative values indicate less than median precipitation (Hayes et al. 1999). Ω

To further explain distribution of drought events, a simple binary code (dummy) system was adopted where years with mild to extreme drought conditions were coded as 1 while those with normal to wet conditions coded as 0 implying they did not experience drought conditions. These codes were developed with reference to the computed 6-month standardized precipitation index and are later used in the regression models. In the Po and Ouagadougou stations our results (Table 9 and 10) show most of the years fall in the normal category without extreme events though instances of extremes are experienced in some years.

To further outline the annual variation in precipitation a bar chart for the time series for the specific events was developed for both stations. The charts present the trend in

occurrence of drought events in specific years as well as identifying years with extreme precipitation.

Table 8 SPI categories distribution, Po

Drought category	SPI range	Frequency of occurrence	% of occurrence
Extreme drought	-2.0 or less		
Severe drought	-1.5 to -1.99	3	9%
Moderate drought	-1.0to -1.49	1	3%
Mild drought	-0.99 to 0	11	31%
Normal	+0.1 to +1.49	19	54%
Severe wet	+1.5 to +1.99	1	3%
Extreme wet	2		

Figure 24, Po station, shows in the recent decade running from 2003 through 2013 is composed of relatively good years as there were no instances of drought events only followed by an instance of mild drought in the year 2013.

In the recent decade the Ouagadougou station indicates a near similar distribution characterized by more instances of wetter years and minimal drought occurrence.

Table 9 SPI categories distribution, Ouagadougou

Drought category	SPI range	Frequency of occurrence	% of occurrence
Extreme drought	-2.0 or less	1	3%
Severe drought	-1.5 to -1.99	2	5%
Moderate drought	-1.0to -1.49	3	8%
Mild drought	-0.99 to 0	14	38%
Normal	+0.1 to +1.49	14	38%
Severe wet	+1.5 to +1.99	2	5%
Extreme wet	2	1	3%

Figure 24 Annual distribution of 6-month SPI, Po

Figure 25 Annual distribution of 6-month SPI, Ouagadougou

1.8 Evapotranspiration estimates, methods and results

Evapotranspiration is defined as the combined evaporation from all surfaces as well as transpiration from plants (Chang 1974). Evaporation from cropped soil is a fraction of the solar radiation reaching the soil, a fraction that decreases as the crop develops canopy. Ideally when the crop is small, water is lost by soil evaporation but as the crop develops foliage transpiration becomes predominant (Allen et al. 1998). Allen et al. (1998) add that an array of factors influence evapotranspiration including; weather parameters, crop characteristics as well as environmental and management factors. Such weather factors include radiation, air temperature, wind speed and humidity.

In computation of evapotranspiration from meteorological data, the FAO Penman-Monteith method is recommended over other suggested approaches Allen et al. (1998), such as Hargreaves, Thornthwaite and Hamon. However, the FAO Penman-Monteith method requires more variables, including; radiation, air temperature, air humidity and wind speed. In many synoptic stations these parameters are not readily available more so for longer time scales. In instances where there is insufficient weather data, the Modified Hargreaves method a reduced data approach, which requires precipitation, temperature and radiation, is one of the recommended alternatives as studies such as Alkaeed et al. (2006) show.

The evapotranspiration concept, reference evapotranspiration (ET_0) applied in this analysis is computed from weather data and denotes evapotranspiration from a reference surface without water scarcity (Allen et al. 1998). In this study radiation, daily rainfall and air temperature are considered in computation of daily ET_0 using the Modified Hargreaves method, equation 14, as discussed by Droogers and Allen (2002) and adjusted by Farmer et al.(2011);

$$ET_0 = 0.0013 * 0.408(T_m + 17) * (T_{max} - T_{min} - 0.0123P)^{0.76} * R_a \dots \text{Equation 14}$$

Where T_m is the daily mean air temperature in $^{\circ}C$, T_{max} and T_{min} represents the daily maximum and minimum air temperature respectively. R_a is the extraterrestrial radiation in $MJ m^{-2} day^{-1}$. The coefficient 0.408 is used in converting $MJ m^{-2} day^{-1}$ into mm/day.

In the Hargreaves equation mean air temperature is an average of the maximum and minimum temperature while the R_a is calculated with reference to location of the site (latitude) and time of the year (month). To this end we computed R_a with reference to equation 15 adapted from Samani (2000);

$$R_a = \frac{1440}{\pi} (G_{sc} \cdot d_r) [\Psi_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\Psi_s)] \dots \text{Equation 15}$$

Where G_{sc} is the solar constant ($0.0820 MJ/m^2/min$)

$$D_r \text{ is the inverse relative distance from earth to sun } D_r = 1 + 0.003 \cos \left[\frac{2\pi(JD)}{365} \right]$$

JD is the day of the year

Ψ_s is the sunset hour angle (rad), $\Psi_s = \arccos[-\tan(\varphi)\tan(\delta)]$

δ is the solar declination (rad) computed as $\delta = 0.409\sin(2\pi \cdot \frac{JD}{365} - 1.39)$

φ Represents the latitude of the location (rad)

$MJ\ m^{-2}\ day^{-1}$ can be converted to mm/d as follows: $mm/d = MJ\ m^{-2}\ day^{-1} / 2.43$

The daily ET_0 values computed with reference to the above equations were aggregated to represent total ET_0 for each month. Monthly ET_0 values were subsequently added for each year in the time series to denote annual ET_0 estimates for each synoptic station. In addition seasonal ET_0 for each year in the time series was computed for each station by aggregating daily ET_0 values for the period May to September.

We further modified the ET_0 values (evaporation power of the atmosphere) to reflect the crop water requirements for the different cereals at initial, development and mid-season growth stages by referring to modified crop coefficients from Wang et al. (2008) in their related work in Burkina Faso. In this analysis we paid attention to the development stage ET_c since this is the water shortage sensitive stage for the cereals (Brouwer et al. 1985). The crop evapotranspiration is computed as a function of reference evapotranspiration (ET_0) and crop coefficients (K_c), equation 16.

$$ET_c = ET_0 \times K_c \dots \dots \dots \text{Equation 16}$$

Computed monthly R_a values for Po ($11^0\ 10'N$) and Ouagadougou ($12^0\ 37'$) are presented in Tables 10 and 11;

Figures 26 and 27 indicate the distribution of reference evapotranspiration (ET_0) across the years in the time series for both stations in relation to recorded rainfall and mean temperature. In these distributions the reference evapotranspiration is lower in the wetter months. Figures 28 and 29 show the inter-annual variation of smoothened seasonal evapotranspiration in the time series with lesser variability observed in the Po station.

Table 10 Extraterrestrial radiation values, Po and Ouagadougou

Month	Extraterrestrial radiation (Ra) in mm/day	
	Po	Ouagadougou
Jan	12.52	12.27
Feb	13.42	13.22
Mar	14.62	14.49
Apr	15.38	15.37
May	15.49	15.56
Jun	15.27	15.41
Jul	15.20	15.34
Aug	15.33	15.42
Sep	15.28	15.28
Oct	14.65	14.55
Nov	13.54	13.35
Dec	12.59	12.59

Figure 26 Distribution of monthly ET0 at Po along monthly rainfall and temperature

Figure 27 Distribution of monthly ETo at Ouagadougou along rainfall and temperature

Figure 28 Seasonal ETo anomalies, Po

Figure 29 Seasonal ETo anomalies, Ouagadougou

2.0 Implications of climate variability on cereal yields: methods and results

Sorghum and millet are major staples in Burkina Faso while maize is an important crop (Somé et al. 2013). Figure 30 shows the trend of annual yields of selected key cereals in Burkina Faso measured in kilograms per hectare. This demonstrates that maize has the higher yield in the country followed by sorghum and millet. The data shows a generally increasing trend in yields for the three crops with a few instances of drop in yields. For instance, yields in maize steadily increase at the beginning of the second decade in the time series followed by instances of rising and falling yields in subsequent years. The moving averages of yields in sorghum and millet indicate a resonating trend in yields with increases and drops occurring concurrently. In this analysis the three cereals yields anomalies for a selected province are independently regressed against selected climatic factors among them; evapotranspiration, dry spells and the number of rainy days. This relationship is informed by the fact that crop growth, yield quantity and yield quality are influenced by climate variability and change driven by changes in temperature and precipitation (Rosenzweig et al. 2001; Prasad et al. 2008).

Figure 30 Yields of selected cereals in Burkina Faso (figures adopted from FAOSTAT (2014))

In this study, production (tons) and harvested area (Ha) data records are used to compute annual yields in Kg/Ha for the period 1984 to 2011 using equation 17.

$$Yield \left(\frac{Kg}{Ha} \right) = \frac{Annual\ cereal\ Production(Kg)}{Cereal\ harvested\ area(Ha)} \dots \dots \dots Equation\ 17$$

Resulting annual yields included missing data for the years 2005, 2012 and 2013. Instances of missing annual yield data were then estimated using a generalized additive model (GAM), equation 18, adopted from Wood (2006), by fitting of available yield records in the function.

$$g(\mu_i) = X * _i \theta + f_1(x_{1i}) + f_2(x_{2i}) + f_3(x_{3i}, x_{4i}) \dots \dots \dots Equation\ 18$$

Where $\mu_i \equiv E(Y_i)$ and $Y_i \sim$ some exponential family distribution

Y_i is a response variable, $X * _i$ is a row of the model matrix for any strictly parametric model components, θ is the corresponding parameter vector, and the f_j are smooth functions of the covariates, X_k .

The GAM applied in this study is implemented in the R software *mgcv*.

Figure 31 shows the distribution of resulting cereal yields in the area of study, Sissili-Ziro province, for selected years between 1984 and 2013.

Figure 31 Cereal yields, Sissili-Ziro province

The yields show a similar trend to the national yield (Figure 30) with steady increase in millet and sorghum yields. This steady increase is notable in the second decade and is however interrupted by a break after the year 2008. Maize yields in the province similarly show a steady increase in the first and second decade with the second decade showing higher yields in the time series.

Cereal yield anomalies were computed for each of the cereals with reference to equation 19 modified from equation 1

$$Z = \frac{(x-\mu)}{\delta} \dots \dots \dots \text{Equation 19}$$

Where Z is the standardized yield, x is the respective years yield, μ is the time series mean and δ is the time series standard deviation.

Yield anomalies presented in Figure 32 indicate that millet yields in the years 1985 and 1988 had the highest positive deviation from the mean for the time series. Subsequent years indicate yields lower than the time series average for several years in the period 1990 to 2002 though this era is characterized by rises and drops in millet yields. Subsequent millet yields depict a mostly near average anomaly. Other cereals display a generally increasing trend with an exception of a below average records of maize yields in the years 2004 and 2007 in the last decade.

In normal circumstances crop production and acreage and subsequent yields tend to increase due to technological advancement and modern farming methods among other non-climatic drivers. These slowly changing factors additionally influence yields over years in association with weather events. To accommodate influence associated with such factors Gaussian smoothing, discussed in the next section, is applied on the annual yield data. In Figure 32 we present the smoothened cereal yields where the Gaussian smoothing function was applied to reduce noise within the data (instances of spikes) while maintaining the overall trend.

The aim of this smoothing technique, including other statistical approaches such as double exponential smoothing or first differences approach Lobell and Field (2007) , is to a certain extent eliminate bias by excluding effects of other non-climatic factors

apart from those related to weather changes (Bannayan et al. 2010). These factors include among others new cultivars, organic matter use, technological changes as well as population dynamics (Behnassi et al. 2013).

Our detrending approach does not exactly handle yield changes associated with interventions such as technological inputs among other non-climatic drivers but we view it as an appropriate method to exclude non-climatic influences. As Rowhani et al. (2011) mention, we also argue that we handle these deficiencies by relying on sub-national yield data.

The Gaussian smoothing function was chosen for this study since this provides cleaner results than other approaches such as median filter from our analysis. The one dimension Gaussian function used to remove noise is presented in equation 20 adopted from UoA (2010) where σ is the standard deviation of the distribution.

$$G(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{x^2}{2\sigma^2}} \dots \dots \dots \text{Equation 20}$$

Figure 32 Cereal yield anomalies Sissili-Ziro

Figure 33 Smoothened cereal yield anomalies

Yield anomalies for smoothened cereal inter-annual cereal yields constituted the dependent variables applied in this analysis. Subsequently regression models and non-parametric correlation (Spearman rho) matrices were applied to define the association between climatic and cereal yield variables. The correlations identify the level of significance as well as the direction of the relationship between climatic variables and cereal yields. Prior to linear regression, curve estimations were computed to detect the nature and strength of the relationship between cereal yields and climatic derivatives. In these estimations we sought to detect whether the climatic variables exhibited a linear, cubic, quadratic or power relationship with yield anomalies.

From these estimates we noted a dominant linear relationship between our variables and climatic derivatives. We thus applied linear regression models to determine the casual relationship between cereal yields and selected climatic parameters for the period 1984 to 2013. In this analysis, yields data for selected common and staple cereals in Sissili-Ziro provinces of Burkina Faso were regressed against certain climatic descriptors.

A simple linear regression model involves a single regressor/independent variable, x , that has a relationship with a response variable/dependent, y . The model is given by equation 21 adopted from Montgomery et al.(2012) and Yan (2009).

$$y = \beta_0 + \beta_1 x + \varepsilon \dots\dots\dots \text{Equation 21}$$

Where y is the dependent variable, β_0 is the intercept, β_1 represents the slope or gradient, x is the independent variable and ε denotes a random error component.

We further applied a multiple linear regression model to evaluate the relationship between multiple climatic predictors and smoothened cereal yields. In these models we are interested in identifying the strength of the contribution of climatic variables in explaining cereal yield variance.

A multiple regression model allows prediction of a continuous dependent variable (Y) based on several continuous or categorical variables (X_1 to X_p) (Afifi et al. 2003) and is an extension of linear or bivariate regression (Tabachnick and Fidell 2001) as shown in equation 22 .

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_m x_m + E, \dots \dots \dots \text{Equation 22}$$

Where y is the dependent, target or response variable, in our case cereal yield anomalies

$X_j, j = 1, 2, \dots, m$, represent m different independent or explanatory in our case climatic descriptors

β_0 is the intercept value when all predictors are 0, also denoted as α in other cases

$\beta_j, j = 1, 2, \dots, m$, denote the respective m regression coefficients

E is the random error or disturbance term, usually assumed to be normally distributed with mean zero and variance and is also denoted as μ in other cases.

The linear models for assumptions were additionally tested for presence of influential points, multicollinearity as well as independence of errors to maintain the validity of our results. The regression parameters and plots as well as correlation matrixes in the next section, relied on smoothened cereal yield data. We present selected scatter plots showing representativeness and strong relationship among predictors and dependent variables. We also note that we refer to the Po station data for regression models since this station falls within the agro-ecology of the study area.

In Tables 11 to 14, simple linear regression standardized model parameters are presented followed by Figures 34 to 45 showing plots of cereal yields against selected climatic derivatives. Similarly, multiple linear regression plots are presented showing standardized coefficient plots indicating the relative contribution of climatic predictors. The R coefficient, in multiple regressions for our case, is a generalization of the correlation coefficient r and can be looked at as one of the measures of the prediction capability of the dependent variable as Martella et al. (2013) explain. The R square is the coefficient of determination which indicates the percentage of the variance of the dependent variable that is predicted on the basis of the predictor (Dewberry 2004).

2.1 Simple linear Regression parameters and scatter plots

Table 11 Evapotranspiration and cereal yield model parameters

Source	Value	Standard error	t	Pr > t
Intercept	-6.867	2.137	-3.213	0.003
Maize ETc	0.520	0.161	3.222	0.003*
Intercept	-8.647	1.875	-4.611	0.0001
Sorghum ETc	0.658	0.142	4.624	0.0001*
Intercept	-7.557	2.066	-3.657	0.001
Millet ETc	0.570	0.155	3.667	0.001*

Table 12 Rainy days and cereal yield model parameters

Source	Value	Standard error	t	Pr > t
Intercept(Maize)	-3.745	1.804	-2.077	0.047
Rainy days	0.367	0.176	2.086	0.046
Intercept (Sorghum)	-2.033	1.900	-1.070	0.294
Rainy days	0.521	0.161	3.234	0.003
Intercept (Millet)	-1.441	1.919	-0.751	0.459
Rainy days	0.141	0.187	0.754	0.457

Table 13 Length of the growing period and cereal yield model parameters

Source	Value	Standard error	t	Pr > t
Intercept (Maize)	-0.892	1.649	-0.541	0.593
LGP	0.102	0.188	0.544	0.591
Intercept (Sorghum)	0.219	1.657	0.132	0.896
LGP	-0.025	0.189	-0.133	0.895
Intercept (Millet)	1.849	1.620	1.141	0.264
LGP	-0.212	0.185	-1.148	0.261

Table 14 Consecutive dry days and cereal yields model parameter

Source	Value	Standard error	t	Pr > t
Intercept (Maize)	-0.289	0.917	-0.315	0.755
CDD	0.061	0.189	0.321	0.750
Intercept (Sorghum)	0.306	0.917	0.333	0.741
CDD	-0.064	0.189	-0.340	0.736
Intercept (Millet)	0.746	0.908	0.822	0.418
CDD	-0.157	0.187	-0.839	0.409

*Relationship is significant at 95% C.I

Further, standardized beta coefficients are presented which in the multiple regressions denote the relative contribution of each climatic variable to the prediction of the respective cereal yields, when variance explained by other climatic variables is held constant regardless of the sign (Pallant 2013). These coefficients are presented by charts and error bars (Figures 46 to 48). In the next section we dwell on an in depth review of the observed relationships between cereal yields and climatic variables.

a) Maize

b) Sorghum

c) Millet

Figure 34 Yields and ETc plot

a) Maize

b) Sorghum

c) Millet

Figure 35 Yields and rainy days plot

Figure 36 Yields and LGP plot

Figure 37 Yields and total CDD plot

Figure 38 Yield model beta coefficients

2.2 Correlation matrix

Bivariate correlations identify the relationship between continuous variables and denote whether such relationship is positive or negative and further denote significant relationships. To this end correlations between cereal yields and climatic derivatives are presented in this section in Tables 16 depicting high, medium and low relationships.

		Rainfall average	Dry days	Dry days first 120 days	LGP Dry spell included	LGP	Reference evapotranspiration	SPI	Drought codes	SAI	Long dry spells	Short dry spell	Average dry spell	Number of rainy days
Maize yield	r	-.093	-.030	.343	.015	.330	.387*	.039	-.204	.129	.141	-.017	.279	.290
	p	.625	.875	.064	.936	.075	.035	.837	.278	.494	.453	.928	.134	.120
Sorghum yield	r	.227	.092	.307	-.113	.390*	.502*	.398*	-.376*	.344*	.204	.023	.093	.233
	p	.226	.628	.098	.552	.034	.005	.030	.041	.063	.277	.903	.621	.214
Millet yield	r	-.071	.104	-.114	-.242	.057	.267	.205	-.139	.037	-.055	.055	-.282	.135
	p	.710	.581	.547	.198	.762	.153	.275	.463	.846	.772	.770	.132	.476

Table 15 Cereal yield and climatic variables correlation matrix, Po

High

Medium

Low

*Correlation is significant at 95% C.I

3.0 Discussion of results

3.1 Identifying climate variability

In this section findings from results in the previous sections are discussed. We refer to related work in adjacent areas and the region at large and outline similarities or deviations from presented findings.

3.1.1 Monthly and inter-annual rainfall distribution

Analysis from, Figures 2 and 3, indicates the seasons with reference to the Po and Ouagadougou stations runs from May to September although there are minimal records of rainfall in April and October. These outlying records can be denoted as off season rainfall due to recorded minimum rainfall records and low rainfall means. The peak rainfall is experienced in the month of August when maximum rainfall records are recorded. Results further show in both reference stations, highest temperatures are experienced during the relatively dry period running from March to April with mean temperatures lower in the rainy season. This relates to studies on local climatic knowledge studies in central Burkina Faso by Roncoli et al. (2002).

Results show near similar characteristics in climatic conditions considering the stations are located in neighboring zones. Analysis results are also compared with related work, for example a recent comprehensive analysis on Burkina Faso's agriculture and climate change by IFPRI Somé et al. (2013) and related work in Burkina Faso by Ingram et al. (2002) and West et al. (2008). The presented results show similarity on the basis of annual distribution of rainfall with the season ranging from three to five months based on the eco climatic zone. A similarity is also noted with a previous detailed agroclimatlogy analysis of Burkina Faso by Sivakumar (1988) mainly in the respective stations mean rainfall.

Figures 4 and 5 on total annual precipitation show evidence of variation in the trend of decadal rainfall amounts over the years. The Ouagadougou station indicates lower records of total annual rainfall which could be associated with the drier agro ecology. While there are variations in the years in both stations, the trend is such that the mean annual precipitation, acting as a threshold for both stations, shows several instances of years with above and below average rainfall for the respective time series.

These observations demonstrate the inter-annual and decadal variability in annual rainfall as West et al. (2008) show in their study in central Burkina Faso. The secondary axes representing the total number of rainy days ($\text{ppm} \geq 0$) gives evidence of a positive relationship between the total annual precipitation and the number of rainy days in the respective year, and by extension the importance of rainy days in defining the total precipitation. In the Po station, for example, we also observe an increasing number of rainy days which can be associated with the wetter climate. This direction is also explained by the positive correlation between the annual rainfall and rainy days

with the Po station showing a significant relationship ($p=0.0000$) which is less than $\alpha=0.005$.

The approach on rainfall classes relates to Ibrahim et al. (2012) in their rainy season characterization for Burkina Faso. With reference to results, Figures 8 and 9, it is evident that the number of rainy days primarily falls in the 1 to 10mm range in the Po and Ouagadougou stations. From the findings, the 10 to 20mm and the 20 to 30mm categories follow closely, with fewer rainy days in the respective years. Subsequent classes are characterized by even fewer rainy days. The area bars indicate the rainfall is largely characterized by more rainy days with smaller rainfall amounts and fewer days with large rainfall amounts in a typical year. In some years however, for example in last decade and subsequent years from both stations, there are instances of rainy days with over 50mm indicating occurrence of extreme rainfall. This distribution is also evident in the larger part of the second decade in the Po station.

These rainfall categories are important since instances of minimal or higher rainfall volumes extending over longer periods, during the growing period, have considerable influence on-farm activities as well as crop production. This is because such distribution influences rainfall effectiveness and intensity, subsequent soil water seepage and eventual crop water uptake (Brouwer et al. 1985).

3.1.2 Length of the growing period

The average dates for the start of the season, OGP, in both synoptic stations range from the beginning of May to early June (Table 4). The season dates also show that rains start later in Ouagadougou when compared to Po. For purposes of definition, as other studies such as Roncoli et al.(2001) point out; onset dates are additionally considered as the sowing or planting dates.

The end of the season or as we have identified as CGP, displays a similar characteristic with the Po station showing a later end of the season. On average the LGP, including and excluding the dry spell at onset, is longer at Po when compared to Ouagadougou. These findings relate to the biogeography of the area around Po which is towards the south of the country (Somé et al. 2013). This region lies within the South-Sudanian agro-climatic zone and receives more reliable precipitation and has more agricultural activity.

Figures 10 and 11 show a variation that leads to changes in the LGP which occurs when the condition of a dry spell is included in the computation of the onset of the season. From these figures, successful onset dates are defined as instances where the onset, including and excluding the dry spell, coincide or share the same point in the vertical axis. As such, an instance of an unsuccessful date is characterized by an abrupt dry spell lasting several days (7 days in our case) just after the onset of the

season. This phenomenon has been discussed in related work such as Ati et al. (2002) and has a key effect on farming communities since dry spells at onset contribute to crop failure. From figures 10 and 11, it is clear the LGP is longer in the years when there are instances of late cessation dates with no instances of dry spells during the beginning of the season. Comparing the synoptic stations (Figures 10 and 11) it is evident there are more instances of false starts in the time series of Po (58.3% of the years) than Ouagadougou (40.5% of the years). These proportions point out a concern for Po which lies in an area associated with more reliable annual rainfall and more farming activities.

The study further identifies several deviations in the season length means (anomalies) with reference to the OGP, CGP and LGP among the individual stations. In terms of inter-annual variability, the Po station (Figure 10) in the first decade shows most instances of the variables lying below the average when compared to recent years falling in the last decade and following years. These can be interpreted as widespread instances of early onset and cessation of the season culminating in a shorter season. The cessation dates show a similar above average occurrence increasing through the second and third decades and most of the recent years. These can be interpreted as instances of late cessation of the growing period. As such, the LGP including when the dry spell is considered, shows an above average performance in most of the years in the last decade including the following years.

In the Ouagadougou station (Figure 11), there are several mixed instances of below and above average occurrences in all seasonality variables with no standard trend. However, the cessation period in the last decade is above average in most of the years, except the sharp drop in the year 2000. This implies the LGP is longer in the recent years a similar characteristic at Po. The corresponding onset dates including where dry spells are excluded show sharp oscillations above and below the time series mean, subsequently altering the LGP.

In this section the inter-annual variation and relationship in the three key parameters defining the cropping season over the time scale for both stations in the time series is shown. Further, results reveal that this variation changes with locality and prevailing agro ecological conditions as represented by the two synoptic stations. This variation in the cropping season ultimately influences the performance of the crops by defining the farmer's decisions on sowing and harvesting and more so appropriate input investments (DeBeurs and Brown 2013). Indeed studies in the Sahel have shown that farmers recognize instances of unsuccessful onsets which they term as "false rains" which are associated with seed damaging dry spells (West et al. 2008). Most important though is the LGP: which is influenced by rainfall variability and temperature, and is a key indicator of yield potential and by extension determines the choice of management practices (Steeg et al. 2009).

3.1.3 Anomalies and trends in annual precipitation

In this analysis the SAI is applied to define the wet and dry years with reference to positive and negative anomalies (deviations from the time series mean). To this end, Figure 12 shows a trend of drier years from 1977 through 1985 for the Po station followed by a blend of dry and wetter years from 1986 to 1999. The period 2003 to 2010, falling in the recent decade is characterized by most of the years experiencing wet conditions. This observation is similar to the characteristic rainy days with more than 50mm from Figure 8 in the last decade also indicating wetter years. A similar pattern is found in Figure 13 for the Ouagadougou weather station. In this station however, the years running from 2003 to 2010 experience more pronounced wet conditions or they can be referred to as wetter years in the time series.

The variability in both stations expresses a characteristic sinusoidal pattern including initial drier years followed by wetter years and subsequent batch of drier and wetter years. Both synoptic stations also experience breakpoints characterized by instances of drier years in a series of wet years with the converse also appearing. A key example is the period between 1991 and 1993 for the Po station (Figure 12) where the initial year experienced dry conditions followed by a wetter year and the third year experiencing slightly dry conditions a pattern repeated in the same decade (1988 to 1999).

The time series statistics show that both stations show a positive and significant trends of annual and seasonal precipitation with Z_{MK} greater than the respective critical values, Table 5, $S=236$ ($Z_{MK}=3.074, >2.576$), $S=246$ ($Z_{MK}=3.204, >2.576$) at Po and $S=144$ ($Z_{MK}=1.645, >1.645$), $S=133$ ($Z_{MK}=1.726, >1.645$) at Ouagadougou.

The Ouagadougou station shows a weaker positive trend where we interpret rainfall increase in this time series is lesser. This observation could be further defined as; while there are inter-annual variations in seasonal and annual rainfall, also evidenced by the SAI (Figure 12 and 13) and total annual precipitation (Figures 2 and 3), the monotonic trend has been an increase in annual precipitation in both stations. The variation in annual precipitation is further explained by the coefficient of variation (CV) for the time series showing slightly higher variability in the Po station (CV=20%) compared to Ouagadougou (CV=16%) for seasonal rainfall.

Observed trends exhibit some similarity with rainfall trend studies in the west African Sahel such as Nicholson (2005) and Lebel and Ali (2009) especially in recovery of rainfall when compared to the mid-1900s with the only limitation being the length of the study period. The trend analysis approach has been applied in detecting monotonic directions of rainfall data in related studies for example Hadgu et al., (2013) in their study in Northern Ethiopia. This method gives a glimpse of the long term as well as short term direction of climatic variables such as annual rainfall that are principal in influencing agricultural activities. Exhibited trends in rainfall are also influenced by

changes in the atmospheric environment for example Hoerling et al.(2006) indicate that rainfall changes in the region are also driven by variations in the Atlantic Ocean sea surface temperatures.

3.1.4 Dry spells

Dry spell results indicate that short and average dry spells of up to 10 days dot most of the years in the Ouagadougou and Po stations (Figures 14 and 15). Within the Ouagadougou time series, several instances of long dry spells with more than 10 days are equally prevalent in the study period. In years experiencing long dry spells, the numbers of dry days in the growing season tend to be higher including when the years experienced only short or average spells for example the year 1997 in Ouagadougou. In the Po station, long dry spells of more than 10 days are equally widely evident in the time series indicating several years have experienced instances of long dry spells within the growing season.

We further found out that the number and instances of dry days and spells are prevalent at onset in both stations. For example, in the Ouagadougou station the larger proportion of dry days mainly occurs during the months of May and August (Figure 16) with fewer drier days in the months of June and July. A similar characteristic is observed in the Po weather station (Figure 17); the numbers of dry days are higher in the first 30 days of the season with subsequent days and months experiencing an almost even distribution of dry days.

The monthly distribution of dry spells in the time series further indicates in both stations the distribution of long dry spells is concentrated in the months of May and September which principally marks the onset and end of the season respectively. Referring to the Po station, long dry spells largely appear in the first two months of the season, while the Ouagadougou station shows long dry spells in the months of May and August and even longer instances in September. This observation can account for the earlier end of the growing period in the drier agro ecology around Ouagadougou.

Another common similarity is that shorter dry spells tend to increase across the months with average spells remaining evenly distributed in the season in both synoptic stations. In Figures 20 and 21 the existing proportionality of instances of total dry days to the LGP is exhibited. These results show that years experiencing longer dry spells are characterized by shorter season lengths. Primarily, dry days which are derived from dry spells, are a determinant of the length of the LGP in both stations and further analysis in Table 6 further reveals; a negative and significant relationship between the LGP and TDD for both stations.

In this analysis instances of dry spells are identified through their length or as Muthaguma and Peiris (2011) call this indicator, the length of dry spells (LDS). From

these results instances of dry spells are a key concern because such dry spells tend to affect the length of the growing period including raising the likelihood of crop failure at the onset of the season. This is so since in arid environments, soil moisture availability is dictated by the duration and persistence of dry spells particularly at onset of the season (Kisaka et al. 2015). These instances of dry spells pose great risk among the farming community as they influence crop-water deficit during key growth stages (Igbadun et al. 2005). Dry spells are indeed an unresolved challenge among farmers in Burkina Faso as Fox and Rockstrom (2003) mention. In deed this study relates to other studies such as Sivakumar (1992) that indicate the role of dry spells in influencing agricultural applications in decision-making on farm operations such as irrigation and harvesting. Further, West et al. (2008) point out the role of adequate rainfall in enabling crops to withstand dry spells in the Sahel, especially when rains end prematurely.

3.1.5 Rainfall intensity

In the Po station in the first decade, the period between 1979 and 1985 is characterized by a decreasing trend in rainfall intensity. Figure 22 further shows distinct instances of steadily increasing intense rainfall in the last dekad between 2005 and 2007. The same variation is observed in Ouagadougou (Figure 23), characterized by a similar trend of rising and dropping intensity along the mean in the time series revealing cases of variability. The last decade and subsequent years from both stations shows a steep rise in intensity characterized mostly by near and above mean rainfall intensities. This direction can be linked to the increasing occurrences of the number of rainy days and subsequent higher annual rainfall which translates to a good year in terms of rainfall distribution. An additional similarity in both stations includes an increasing trend in the time series (though steeper in Ouagadougou) with reference to the linear trend line.

Rainfall intensity has an influence on the level of rain water infiltration into soil and hence availability of soil water. This is because rainfall intensity relates to the heaviness, velocity, size and energy of falling rainfall, Haggett (2002), which is influenced by the infiltration capacity of the soil and subsequent occurrence of runoff (Brouwer et al. 1985; Haggett 2002).

These interactions are a concern in arid environments with low rainfall as any loss of water could affect yields, Haggett (2002), especially water stress sensitive cereals such as maize (West et al. 2008). Other effects relate to soil loss, for example, ILRI (2009) indicate instances of rainfall characterized by rainy days with more than 15mm are likely to cause soil erosion. Farmers in central Burkina Faso, in a related study on local knowledge and perceptions, indicated the importance and understanding of rainfall duration. In the study they emphasized that rainfall falling over night for several hours, largely infiltrates the soil Roncoli et al. (2002) and facilitates cultivation of moisture dependent cereals such as maize (West et al. 2008).

This analysis refers to intensity at a course scale; nevertheless the inter-annual variability computed as a daily average (*mm/day*) is likely to lead to minimal erosion considering most of our annual rainfall averages fall mostly below the 15mm threshold. However, the inter-annual variability is likely to affect cereal growth and development by influencing availability of water for agricultural production.

3.1.6 Drought spells

In most of the years, 54%, with reference to Po station (Table 8) have been normal that is the area has not experienced many events associated with extreme dry or wet conditions. Nevertheless, it is evident a number of years experienced mild drought conditions (31%). Further, drought instances ranging from mild to severe drought cumulatively account for 43% of the years in the time series. In Ouagadougou (Table 9) there are equal instances of mild drought and normal years (38%), in each category representing the larger instances. Cumulatively, there are more instances of drought related years with mild to extreme drought years represented by 54% of the years. From this analysis we show Po area experiences more favorable climatic conditions characterized by lesser occurrences of extreme events, in this case mild to extreme drought.

In the Po time series (Figure 24), key spells of consecutive drought events are evident in the period 1979 through 1985 where mild to extreme drought conditions are widely experienced. This can be interpreted as a lengthy drought running through the six year period. The lengthy period between 1986 and 2002 is characterized by a blend of dry, normal and wet years with an instance of severe drought in the years 1990. The recent decade is however characterized by more instances of consecutive normal years with minimal instances of rainlessness.

Figure 25 shows a slightly differing trend in Ouagadougou with the period running from 2003 to 2013 exhibiting mainly normal years with three instances of severe and extreme wet conditions and two instances of drought (moderate and mild). In this station several instances of mild to extreme drought appear from the period running from 1992 through 2002. This period represents a typical drought spell in the 10-year period interrupted by the normal rainfall in the year 1999. These results correspond with the geographical descriptions for the two areas; Po has a better climatic environment with higher precipitation as it lies much to the south.

Drought is a complex phenomenon and as such a non-universal definition is an extended period of reduced, erratic or below normal precipitation over a season (Zargar et al. 2011), an event also associated with high temperatures, strong winds and low relative humidity which aggravate the drought (Oliver 2005). Drought is also associated with timing (delays in the start of the rainy season, principal season of occurrence, occurrence of rains in relation to principal crop stages) and effectiveness of rains (intensity and number of rainfall events). To this end, droughts vary with

impacts, characteristics and spatial extent (Oliver 2005). Droughts are further classified into meteorological, agricultural, socioeconomic and hydrological (WMO 2012). These characteristics widely relate to our results and also perception studies by West et al. (2008) in the central plateau of Burkina Faso where households likened drought to delayed onset, shorter rain season or early cessation.

Dry spells and drought occurrences have a close relationship; dry spells of more than 40 CDD can be effectively termed as a drought instance when this occurs within the growing season (Mathugama and Peiris 2011). Indeed droughts are a common occurrence in the Sahel including Burkina Faso (Olaniyan 1996). Such droughts have severe impacts on livelihoods largely dependent on agriculture. The most immediate effects impact crops and as Toulmin (1986) outlines, these include a fall in crop production, resulting from poor rainfall distribution.

While presented results depict more instances of normal years, we should be concerned about the likely occurrence of drought events without notice due to uncertainties and complexities associated with climatic events. Studies such as Kadji et al. (2006) point out that terminal droughts are becoming a common occurrence in the Sahel. Further, Reij et al. (2009) mention it is likely farmers may not recall on how to cope with such droughts, from past experience, subsequently experiencing devastation when abrupt events strike. Results further identify the usefulness of drought indices in risk management, for example the drought in the year 1997 (in the Po station for our case), is reported by other authors such as Roncoli et al. (2001). Studies such as West et al. (2008), Reij et al. (2009) and Ibrahim et al. (2012) also point out the occurrence of devastating droughts in the 1970s and 1980s for example a key drought in the 1982-84 period that affected the densely populated central plateau of Burkina Faso. Kadji et al. (2006) also outline the extent of these events for example the Sahelian drought of 1984 extended all the way to Ethiopia in the east. These events are associated with an acute human and environmental crisis that cascades into occurrence of improper land use and drop in ground water (Karambiri et al. 2011).

3.1.7 Evapotranspiration

In this analysis evapotranspiration was computed to consider the loss of water from the soil and crop foliage which eventually affects crop performance and growth. Evapotranspiration therefore presents the balance between daily rainfall and water loss resulting from temperature exposure. Results show a similar trend in the ET_0 from both synoptic stations, with the rainy season (May to September) showing lower ET_0 when compared to the driest months (October, March and April). The trend could be associated with higher precipitation but lower temperatures resulting in lower evaporation and transpiration. On the converse the drier months with minimal precipitation experience higher temperatures that perpetuate moisture loss through evaporation and transpiration. This moisture loss could be exacerbated by minimal vegetative cover during the drier period as well as scanty vegetation in arid and semi-

arid environments. Indeed other studies in Burkina Faso such as Some et al. (2006) note the higher instances of evapotranspiration during the drier period. Mean monthly ETo estimates were compared with previous work in the study area by Sivakumar (1988) and confirmed near equal values which validates the applied estimation method.

Figure 28 shows the variation of the reference evapotranspiration at the Po station across the time series with the first and second decade showing most instances of seasonal ETo are below average. The last years, following the second decade, are characterized by several instances of above average ETo with only the last two years showing a decreasing and near average trend. The Ouagadougou station however shows a more varying trend with instances of above and below average ETo in the time series with 1987 showing the highest positive variation from the mean and 1979 showing the lowest negative deviation from the mean.

Results show an explicit relationship between temperature and evapotranspiration. These observed evapotranspiration dynamics at the monthly and inter-annual level are likely to have varying effects on crop growth and development in the Sahel by varying available and limited crop water. Further, vital resources such as reservoirs volumes, necessary for domestic water use and livestock are likely to vary based on prevailing evaporation demand. Indeed, Burkina Faso which lies in this region is characterized by low and highly variable rainfall Some et al. (2006) and such instances of water shortage will tend to variably reduce crop growth (Connor et al. 2011).

In the next section we further explore how inter-annual crop evapotranspiration (ETc) variation relates with cereal yields.

3.2 Relating climate variability to inter-annual crop yield

From Figure 32, year 1998 millet yields depict a steadily increasing trend which falls above average from the year 2002 to 2011. Sorghum yields show a yield trend characterized by years of below average yields from the period 1984 through 1993. The recent decade from the year 2001 breakpoint is characterized by mostly above average sorghum yields. Maize yields show a clearer yield trend in the time series with the period from 1997 characterized by above average yields with minimal instances of drops below average. These are notable examples of how annual cereal yields vary along the time series in the study area and further reveal the generally increasing trend. The following discussion explores how these yield transition is driven by and/or relates to inter-annual adjustments in climatic factors.

Crop-climate variability regression parameters show a positive prediction of cereal yields by the crop evapotranspiration at development stages of crop growth.. Specifically, maize, sorghum and millet anomalies are significantly predicted by

respective development stage crop evapotranspiration where $\beta=0.520$, $t(1)=3.222$, $p=0.003$; $\beta=0.658$, $t(1)=0.142$, $p=0.0001$ and $\beta=0.570$, $t(1)=0.155$, $p=0.001$ respectively. These observations are also displayed graphically in the scatter plots (Figures 34 to 45) with lines of best fit indicating the strikingly positive relationship.

The bar plots representing multiple regression beta coefficients (Figures 46 to 48) further show that the crop evapotranspiration also shows a positive relationship with all cereal yields over other predictors. The multiple regression bar plots indicate that the number of rainy days made positive contribution in prediction of maize yields, implying the cereal is highly responsive to rainfall amounts. On the other hand the explanatory variable indicates a weakly negative prediction and variance of millet yield anomalies. Cereal yields show an interesting response to the CDD and the LGP in the season with for example the CDD negatively predicting millet and sorghum yield anomalies. The relationship is non explicit or milder in the maize yield model.

In the multiple regression plots, coefficients of variation (R^2) similarly show that indeed near half variance in maize, $R^2=51.8\%$, and sorghum yields, $R^2=45.9\%$, is strongly explained by climatic derivatives. This indicates indeed to a certain extent climatic factors do alter crop yield and contribute to yield variability with non-climatic drivers also playing a role in this phenomena.

Regression plots show variation in response of cereal yields to climatic derivatives, implying these cereals respond variably to climatic factors. However, the importance of precipitation as demonstrated by precipitation derived variables shows the critical role of rainfall in explaining crop development. Maize for instance is very sensitive to hydrous stress during the flowering and grain filling stages of growth (Ingram et al. 2002; Kambire et al. 2010). Indeed maize is more sensitive to climatic variability than the other C4 cereals in this study. In these results, the observation that the LGP contributes positively to maize yield could be associated with the moderate nature of drought which as Kambire et al. (2010) mention, leads to a denser root system during the vegetative period subsequently increasing yields.

Contribution of LGP and the CDD in negatively relating to sorghum and millet yields while weakly predicting the yields of maize, indicates the severity of dry conditions and subsequent effects on even drought hardy crops as related studies such as Rowhani et al. (2011) found out.

Another observation is the overall less explanation of millet yields variance by most of the climatic derivatives as demonstrated by the lower coefficient of determination (R^2) in the multiple regression model results. This demonstrates that millet is a hardy crop compared to sorghum as Behnassi et al.(2013) also discuss. In deed millet is more efficient in utilization of soil moisture due to a better root configuration-the cereal can hence effectively thrive in much drier areas. The cereal however has limits

for example susceptibility to water logging when compared to sorghum (Ingram et al. 2002).

Briefly highlighting some correlations from Table 16, we observe that climatic variables associated with drought instances and/or dry spells show weak and negative non-significant relationship with maize yields. Instances of drought in the time series show a negative relationship ($r=-.204$, $p=0.278$). The same observation is made on short dry spells (0 to 5 CDD) where ($r=-.017$, $p=.928$) and the total dry days in the season ($r=-.030$, $p=.875$). The LGP shows a medium positive relationship with the maize yields. When dry spells are experienced in the growing period (LGP with the dry spell included) the maize yield-LGP relationship is lower ($r=.015$, $p=.936$).

Sorghum yields similarly relate negatively to the growing season when dry spells are experienced at onset where ($r=-0.133$, $p=0.552$) when the dry spell is included in computation of the LGP. When we compute the LGP leaving out the dry spell we observed a positive relationship which is further significant ($r=.390$, $p=.034$). A significant negative relationship is however noted with drought instances derived from the SPI where $r=-0.376$, $p=0.041$. The SAI which is directly computed from annual rainfall does similarly show a positive relationship with sorghum yields ($r=0.344$, $p=0.063$). This direction is also observed with the number of rainy days in the season. Instances of short, average and long dry spells including the sum of dry days in the season, all show a weak positive relationship with sorghum yields.

Millet yields also respond negatively to LGP with dry spells at the onset of the growing season, which as per our scale is medium ($r=-0.242$, $p=0.198$). When the dry spell is counted at the onset of the season, the relationship is clearer and in this case for millet the correlation is weakly positive. Millet yields additionally show a negative relationship with the long and average dry spells as well as inter annual drought instances. On the other hand, the correlation with short dry spells and the number of dry days in the season is positive but low.

Instances of positive relationship between crop yields and climatic factors indicate the role of such factors in determining cereal yields. A higher positive relationship, for example sorghum yields and rainfall derivatives such as SAI, is evidence of the key role of rainfall variation from average in even influencing drought hardy cereals. The relationship with LGP shows the importance of seasonality in influencing the cereal yields and more so effects of dry spells during the sowing period which is principally the onset of the season. Indeed, these are the some of the sensitive growth stages of most of the cereals. These results further show that crops adapted to extreme water stress areas also have thresholds or limits when exposed to severe climatic events. The negative correlation between maize and the total number of dry days in the season and the weak positive relationship with millet and sorghum yields indicates the contribution of instances of dry spells and cumulative dry days within the season in altering of crop performance.

Reference evapotranspiration estimates positively relate with the yields of all cereals. We explain this observation with reference to our results (Figure 26) as; mean evapotranspiration is relatively lower than the mean rainfall during the peak/mid stage of the growing season implying crops are unlikely to experience water stress. This water balance could be more favorable to drought hardy cereals. Further, the rainy season or growing season experiences lower temperatures that bring about reduced evaporation demand on soil water. In arid and semi-arid environments water loss through evapotranspiration does however present moisture stress especially when there are instances of erratic rains. In principle temperature rise creates high water stress through higher evapotranspiration but these effects can be mitigated or aggravated by rainfall variability (increase or decrease) (Roudier et al. 2011).

4.0 Limitations

Limitations of this analysis fall into two categories including those related to data sources and statistical techniques. To begin with, we experienced limited climate data when computing certain derivatives such as daily evapotranspiration estimates. This variable is influenced by a complex relationship between prevailing weather conditions as well as crop-soil interactions. Based on recommended analysis techniques the computation presented here is deemed an estimate. To ensure these aforementioned estimates are correct we compared results with previous studies that applied recommended approaches. At the same time we estimated missing records while closely referring to available data records to ensure estimates are as close as possible to raw data.

While working with synoptic station data and cereal yields, a key barrier is the complexity associated with crop response to climate dynamics as well as the influence of management and socio-cultural factors. Crop response to climatic factors varies even at the varietal level which is beyond the scope of this analysis. To this end, presented results only capture the general relationship between aggregated cereal yields and annual climate parameter anomalies. We however recognize the importance of a wide range of interactions between crop growth and non-climatic changes and as such employ certain statistical approaches to accommodate the impact of non-climatic drivers.

National cereal yields records in many African countries could be arguably unreliable due to the absence of quality control in ensuring the accuracy of the same at the collection/recording stage. In some instances the accessible records used in yield computation are estimates of crop production and acreage. Annual cereal yields presented in these results were however populated at the district level, which we argue has some level of accuracy and is more reliable. The climate variability analysis is also limited to a small-scale area and hence our results are not to be generalized to a larger area such as a national or regional scale. Nevertheless, these results can be compared to other studies in the larger Sahel or those restricted to Burkina Faso.

5.0 Conclusion

Most of the computed climatic derivatives refer to seasonal rainfall which is a key concern over other factors affecting arable crops including potential evapotranspiration. This study reveals instances of climate variability based on inter-annual rainfall variations across the time series of Po and Ouagadougou synoptic stations stationed in varying agro-ecological environments, where similarities and differences exist. This variability is expressed by the varying rainfall amounts from year to year against a long term average as well as inter-annual variation in rainy days and rainfall intensity.

Further, we paid attention to several climatic derivatives describing seasonality. To this end, results reveal the instances of variation in onset of the rainy season as influenced by occurrence of dry spells at onset in more than 50% of the years in the time series. Subsequently, there are several instances of unsuccessful rainfall starts that could contribute to crop failure due to uninformed sowing. In addition this study shows that instances of average dry spells (5 to 10 days) are prevalent with reference to analysis from both stations and these events occurs widely across the season. Further, the month of May, which marks the start of the season, is widely characterized by long dry spells which is a concern since this time is also considered as the sowing/planting period among other initial land preparation stages. Further on, the study area has experienced drought spells in the past though instances are less frequent in recent years. On average the area is characterized by more normal years without severe dry or wet conditions. It is important to emphasize that while this routine normal distribution is prevalent, there could be disruptions by unforeseen occurrence of drier years. Nevertheless, this study establishes that recent years have experienced an improved rainfall regime based on standardized rainfall anomalies, rainfall averages and drought indices.

The study establishes that cereal yields exhibit a characteristic increasing trend over the years with minimal instances of decreases or below mean records. Correlation matrices and regression models show varying relationships with climatic derivatives. For example correlations show a negative relationship between all three cereal yields with instances of drought, revealing that indeed drought instances whether mild or severe are a concern in the area. Further, it is apparent that while drought conditions are a concern, millet yields show a robust response to such extremes over other cereals. Another interesting observation is the strong relationship between maize and rainfall amount; which shows that maize yields are highly predicted by rainfall measured as the number of rainy days.

Presented results establish evidence of climate variability viewed from different angles in the study area, which evidently has mixed effects on cereal yields. The effect of this variability on the onset of the growing season, which we equate to the start of sowing, is likely to have influence on the farming calendar due to the

difficulty in decision-making on when to engage in principal activities such as land preparation and subsequent planting. Indeed the prevailing climatic environment at the start of the season contributes immensely or signals the anticipated crop performance thorough the rest of season. The nature of climatic conditions throughout the growing period, including the mid-season, equally determines yields quantity and quality. Due to the heavy dependence on farming activities, it is likely that principal livelihoods are likely to be negatively impacted by events such as droughts and dry spells, resulting in widespread food insufficiency and loss of crucial income. In addition uncertainty of rainfall onset and distribution within the season is likely to influence availability of water for livestock consumption and household utilization. While farming communities employ short and long-term counter measures in the face of these events, extreme occurrences such as consecutive droughts and floods pose an immense threat to such investments. In other cases while these communities widely employ traditional weather prediction mechanisms, these are equally and even more subject to uncertainties brought about by the current changes in climate.

6.0 Recommendations from our findings

While we show there is evident increase in rainfall, such positive direction can only benefit farmers if it is effectively utilized because of the semi-arid and near arid nature of the agro ecology. For example West et al. (2008) report efforts by farmers in the central plateau of Burkina Faso to cultivate different cultivars with different water requirements and harvest dates. As such, to ensure smallholder farmers avert instances of dry spells at onset (beginning of sowing), they need timely and well packaged weather data such as the probability of occurrence of dry spells and even drought occurrences. Indeed other studies in Burkina Faso such as Roncoli et al. (2001) have pointed out that farming households are keen on accessing weather information due to uncertainty in rainfall prediction. We concur with their proposal that it is important that weather information should dovetail with the existent cultures and traditions and more so borrow from and merge with farmers' own forecast mechanisms effectively.

We also propose mechanisms aimed at ensuring efficient utilization of water resources such that future needs are put into consideration. A key example could be implementation or enhancement of water harvesting at household and community level and adoption of efficient adjustments such as cost effective drip irrigation aimed at enhancing water use efficiency in the semi-arid environment. Other useful approaches include conservation tillage aimed at reducing soil water loss. There are other effective methods including *zai* pits, grass hedges and stone bunds though some such as *zai* pits (Reij et al. 2009) and "half-moons" Barbier et al.(2009) are labour intensive while others require certain equipment and materials (Ingram et al. 2002). The effectiveness of water conservation approaches such as stone lines, for example, includes increased yields of up to 20% to 30% in Burkina Faso (Jalloh et al. 2011). Farmers could also make an adjustment in their calendar such that some of these tried

and successful but labour intensive means are ready before the farming season when labour is scarce. These approaches have indeed been reported in other studies in the Sahel such as Reij et al. (2009) as being successful in improving soil fertility and cereal production including when dry spells strike.

We further propose adoption of flexible land use such as informed planting of multipurpose trees to enhance food availability, access and utilization and at the same time diversify household income in the face of extreme climatic impacts and market induced shocks. Such alternative income could also be generated through on-farm processing which principally involves value addition by diversification of cereal products.

In this arid area, it is also appropriate to enhance access to affordable credit facilities, through microfinance lenders, to facilitate farmer access to improved varieties and tools for improving farming techniques. Where feasible, it is also appropriate for small holder farmers to form community based organizations where they have a better bargaining power in accessing financial services such as savings and credits as well as farm machinery to enhance on-farm diversification and invest in recovery mechanisms. These groups also form a perfect platform to link and share best practices, innovations and experiences in land rehabilitation and agroforestry. Indeed locally made, available and “long term benefit” interventions in the face of climate variability, are more likely to bring successful results. Nevertheless it is advisable to marry these with novel mechanisms such as crop and livestock insurance which could also be adopted with a close alliance and informed arrangements with the private sector.

At the national level, we propose enhancement of risk reduction programs including food storage, contingency planning and improvement of infrastructure to improve access to markets and market information and even inputs. Such action should be accompanied by incorporation of farmer observations and indigenous mechanisms into seasonal forecasting and early warning systems. Such provision of weather information should be coupled with feedback mechanisms informing on the benefits and relevance of such services. At the same time access to mechanical facilities such as tractors, plows and related technologies could enhance adaptive capacity in a shorter season.

Our analysis recognizes the role of cycles such as CO₂ interactions and nutrient cycles and their influence on crop development but does not refer to these. We further recognize that novel or improved farming techniques and associated technical improvements play a role in boosting of crop yields. It is hence recommend that these interactions are considered in subsequent or similar studies. A possible alternative is application of robust mechanistic models such as APSIM, SARAH_h or DSSAT. In other studies such as soil properties estimation using meteorological data or remote sensing methods (Ahmad et al. 2010), soil mapping (Hengl et al. 2015) and related

reviews (Strobl et al. 2009), certain regression techniques are proposed including support vector machines, artificial neural networks and random forests. These non-parametric prediction approaches exhibit robust prediction power in these applications but similarly demonstrate limitations and varying performance. While we suggest these alternatives, this does not in any way water down our analysis as we validate models for certain assumptions and apply smoothing techniques to accommodate non-climatic effects on cereal anomalies while also relying on district level yield data.

Appendices

Appendix 1 R script for extracting the soil type for the study area

```
> library(rjson)
> library(sp)
> library(GSIF)
> library(rjson)
> library(sp)
> pnts <- data.frame(lon=c(-2.10,-2.48), lat=c(11.16,11.45), id=c("p1","p2")) #you
need to change your points here
> coordinates(pnts) <- ~lon+lat
> proj4string(pnts) <- CRS("+proj=longlat +datum=WGS84")
> soilgrids.r<-REST.SoilGrids(c("TAXGWRB"))
> ov <- over(soilgrids.r, pnts)
> data.frame(ov$TAXGWRBMajor, pnts)
  ov.TAXGWRBMajor lon lat id optional
1    Lixisols -2.10 11.16 p1    TRUE
2    Lixisols -2.48 11.45 p2    TRUE
```

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205. Agroforestry and Forestry in Sulawesi series: Smallholders’ coffee production and marketing in Indonesia. A case study of two villages in South Sulawesi Province. <http://dx.doi.org/10.5716/WP15690.PDF>
206. Mobile phone ownership and use of short message service by farmer trainers: a case study of Olkalou and Kaptumo in Kenya <http://dx.doi.org/10.5716/WP15691.PDF>

The World Agroforestry Centre is an autonomous, non-profit research organization whose vision is a rural transformation in the developing world as smallholder households increase their use of trees in agricultural landscapes to improve food security, nutrition, income, health, shelter, social cohesion, energy resources and environmental sustainability. The Centre generates science-based knowledge about the diverse roles that trees play in agricultural landscapes, and uses its research to advance policies and practices, and their implementation that benefit the poor and the environment. It aims to ensure that all this is achieved by enhancing the quality of its science work, increasing operational efficiency, building and maintaining strong partnerships, accelerating the use and impact of its research, and promoting greater cohesion, interdependence and alignment within the organization.

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