Agricultural Productivity Potential Assessment by Using Rainfall Contribution Index in Sub-Sahara Africa

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Abstract: - Food deficit alleviation is the most important aspect for poverty reduction in the entire Sub-Sahara African (SSA) region. This alleviation can be achieved by increasing agricultural productivity. The deficit is in one way or the other attributed to inefficient and insufficient use of rainwater. This paper therefore, examines the scope for meeting the crop water demand under rainfed condition based on the suitable planting period approach in SSA, in order to take advantage of the favorable climatic condition. Climatic data collected from 1996 to 2005 in Ouagadougou and Ngabu, located in Burkina Faso and Malawi, respectively were used in this study. The rainfall contribution index and yield estimation model were introduced to examine the availability of rainwater to suffice the crop water demand and then predicting the yields. Rainfed agriculture in the study sites is characterized by a short and monomodal rainy season starting from May to September and November to April, in Ouagadougou and Ngabu respectively. Ngabu receives annually, an average of 912 mm rainfall, while Ouagadougou receives 698 mm. Based on the index, it has been realized that there is higher crop water requirement in Ouagadougou than in Ngabu regardless of the crop and planting dates. It was also observed that, the rainwater is more sufficient in Ngabu than Ouagadougou. Following the suitable planting periods determined in this study might increase the yield of maize, bean, millet, and groundnuts by 10.31, 16.22, 10.57, and 4.82 % in Ouagadougou, and 5.00, 7.41, 7.14, and 4.30 % in Ngabu, respectively. The suitable planting periods should therefore be recommended for reducing the gap between supply and demand for the selected crops under rainfed condition, so that crop productivity may increase.

Key-Words: Agricultural water, food deficit, planting period, rainfall contribution index, effective rainfall, productivity

1 Introduction

The magnitude and frequency of food deficit events in Sub-Saharan Africa (SSA) has increased with the decrease in production mainly due to changes in weather patterns. The current world food crisis has aggravated the raising of food price and threaded the regional stability particularly in the SSA. In the search for solutions to the problem of food crisis, the international community aid has been solicited. According to [1], the only smart short-term response is to throw money at the problem. Food security problems in SSA need to be urgently addressed, in order to cope with galloping global food prices. This region is most heavily dependent on food imports. For long term solution, SSA needs to move from the international food assistance to agricultural assistance by a real agriculture sector development policy. To tackle the problem, FAO focused on access to fertilizers and seeds for boosting domestic food production and insulate them from price shocks when they fluctuate. It has been also stated by [2] that one of the major reasons for food insecurity in SSA is the low agricultural productivity which is under the direct influence of climate pattern.

However, it is well known that the low income and food deficit countries in SSA face another challenge of water resources limitation. In SSA, the yields from rainfed agriculture which present 95% of agriculture land are low [3]. Therefore, an efficient use of rainwater coupled with the international community support on inputs could obviously reduce the food crisis tension. It is evident that inadequate rainfall and water shortages limit crop production, the management based on matching the rainwater supply and crop water demand can improve the crop productivity. Various management strategies have been suggested to increase yields under rainfed environment. It has been indicated by [4] that the sowing dates can be adapted to make optimum use of rainwater and increase the yield. Studies done by [5] suggested a management practice based on matching water supply and crop demand in African semi-arid region for efficient use of agriculture water. As the SSA struggles to feed a rapidly growing population with finite water resources, rainwater efficient use aims at improving agricultural productivity while reducing the raising of the food price. Study done by [6-7] reported that, there is missing information on crop water balances and rainfall variability which is important for further technology development and farmer decision making in Burkina Faso. According to the report by [8], changes in rainfall for many areas in Malawi have resulted in changes in the growing seasons as well as in crops grown. In the past farmers used to plant their crops after the first rains, but since they started experiencing frequent droughts and floods they are planting their crops much earlier. This is to allow the crops to meet the first rains with the hope that they will mature before the end of the rainy season and to prevent the crops from being washed away by the floods. Instead of planting local varieties, they have opted for hybrid varieties of crops that take a shorter period to mature. Clearly, farmers are now uncertain of when to plant. Several studies have investigated the effects of planting dates on water supply and grain yield [9]. Knowledge of the impact of sowing and irrigation management on crop yield, water balance, crop water use and requirement can help to identify management options for maximizing crop water productivity. Recently, [10] stated that planting date is an important management factor in the production of all crops.

To the knowledge of authors, there is very few literature related to crop water demand and productivity information under rainfed condition in Burkina Faso and Malawi. As these areas have low and irregular rainfall, there is a need to develop decision support information based on historical climatic data series to help farmers to optimize the rainwater use and increase the yield of their crops. Therefore, rainfall contribution index [11] and yield estimation model [12] determined previously are introduced in this study to examine the availability of rainwater and predict the crop yield. The objective is to provide information of suitable planting period to farmers for better water management and crop yield in Burkina Faso and Malawi. In this study, important long term climatic data, soil and crop information were collected in two production sites, Ouagadougou and Ngabu located in Burkina Faso and Malawi, respectively.

2 Material and Methods

2.1 Study sites

Two areas explored in this study are Ouagadougou, located in the North Sudano-Sahelian region of Burkina Faso and Ngabu, located in Southern region of Malawi **(Figure 1)**. The data sets were collected from the meteorological stations located in both areas. In North Sudano-Sahelian region at 800 mm isohyets, Ouagadougou Airport Meteorological station situated at 12°37'N latitude, -1°52'W longitude and 306 m altitude. In Southern region at isohyets 930 mm, the meteorological station of Ngabu is located at 16°30'S latitude, 35°21'E longitude and 102 m altitude. The monthly weather data composed of precipitation (mm), maximum and minimum temperature (°C), relative humidity (%), sunshine (hour) and wind speed (km/day) were collected from 1996 to 2005 for both locations in this study.

Rainfed agriculture in the study sites is characterized by a short and monomodal rainy season starting from May to September and November to April, in Ouagadougou and Ngabu respectively. The climatic characteristics of the study sites are given in **Tables 1 and 2**. Ouagadougou receives relatively low annual average rainfall of 698 mm than Ngabu which receives 912 mm. The maximum rain amount falls between July and September in Ouagadougou, while it occurs between December and February in Ngabu. This indicates that, despite the seasonal rainfall amount, there is a difference in term of the rainfall distribution between these two locations. Ngabu has relatively low temperature than Ouagadougou during both dry and rainy season. Both minimum and maximum temperatures in these two study areas decrease from the start of the rainy season towards the end. Minimum and maximum air temperature ranges from 17.72 to 27.43°C and 31.42 to 39.82°C in Ouagadougou, 15.67 to 24.13°C and 27.83 to 35.99°C in Ngabu, respectively. Wind speed is high at the beginning of the rainy season in both Ouagadougou and Ngabu. However, it is much higher in Ngabu during the first two months (October and November) of rainy season. Wind decreases from the beginning toward the end of the rainy season in Ngabu. For Ouagadougou, it gently increases up to July and then starts decreasing. Wind velocity for Ouagadougou, recorded at 2 m above the ground has a maximum monthly average of 181.60 km/day in June and minimum of 103.40 km/day in November. Likewise, for Ngabu the maximum monthly average wind velocity of 284.86 km/day and minimum of 112.90 km/day are recorded in October and May respectively. Similarly to the rainfall pattern, relative humidity is much higher in Ngabu than Ouagadougou. This reflects the differences of precipitation observed between these two locations. Relative humidity increases from the beginning of rainy season until August and February in Ouagadougou and Ngabu, respectively. The relative humidity monthly mean in Ouagadougou is 48.49% while for Ngabu it is 66.60 %.

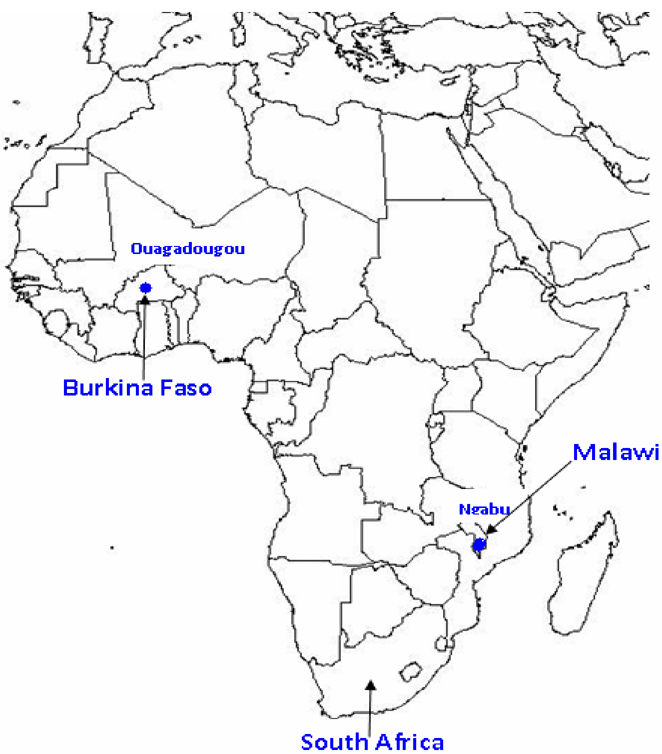

Figure 1. Sketch of the present study areas

Table 1. Summary of average climatic characteristics of 10 years data for Ouagadougou

Month	T_{min} (°C)	T_{max} (°C)	Humidity (%)	Wind speed (Km/day)	Sunshine (Hours)	Rainfall (mm)
Jan	17.91	33.83	28.67	152.95	8.89	0.00
Feb	20.03	36.05	26.17	166.09	8.82	0.22
Mar	23.92	38.82	24.83	156.18	7.99	6.57
Apr	27.45	39.82	33.00	147.57	8.05	22.65
May	27.00	38.30	49.17	175.79	8.50	52.88
Jun	24.98	35.39	59.50	181.60	8.28	68.83
Jul	23.40	32.69	69.50	147.57	7.53	176.23
Aug	22.92	31.42	77.50	125.16	6.67	196.04
Sep	23.08	32.63	74.83	123.65	7.37	140.04
Oct	23.91	35.83	65.00	123.65	8.95	34.15
Nov	20.35	36.41	40.83	103.40	9.62	0.89
Dec	17.72	34.41	32.83	130.12	9.42	0.00
Average	22.72	35.47	48.49	144.48	8.34	58.21

Table 2. Summary of average climatic characteristics of 10 years data for Ngabu

Month	T_{min} (°C)	T_{max} (°C)	Humidity (%)	Wind speed (Km/day)	Sunshine (Hours)	Rainfall (mm)
Jan	23.25	32.37	73.83	160.21	5.59	196.77
Feb	22.76	31.71	73.93	117.16	5.74	223.82
Mar	23.00	32.61	72.37	129.00	6.54	159.26
Apr	20.74	31.40	70.83	121.22	7.16	69.59
May	17.87	29.93	69.97	112.90	7.42	1.71
Jun	15.97	28.58	70.68	116.71	7.00	0.00
Jul	15.67	27.83	69.20	135.18	6.67	1.80
Aug	17.35	30.79	61.37	174.76	7.98	0.00
Sep	19.90	34.09	54.57	243.51	8.50	1.57
Oct	22.59	35.99	52.03	284.85	8.72	2.60
Nov	24.13	36.70	57.67	283.42	8.22	46.56
Dec	23.93	34.41	72.77	211.08	6.36	208.12
Average	20.60	32.20	66.60	174.17	7.16	75.98

2.2 Crop and soil information

Soil water depletion factors for no stress, and yield response factors were based on the procedures given by [13] and [14]. According to [15], for Ouagadougou in North Soudano-Sahelian zone, the surface layer (0 to 30 cm) is loamy which has 20% clay, 30% silt and 40% sand, approximately. The soil bulk density varies from 1.6 to 1.7 g/cm^3. In Ngabu soils are medium to course textured alluvial and colluvial as reported by [16].

Maize, dry bean, millet and groundnut are the main staple food crops grown in the study areas. The crop growth parameters such as duration, height and rooting depth provided by the agricultural extension services were obtained from local information. Then, the crop coefficients were derived by the numerical determination approach and adjusted as described by [13].

$$k_{ci} = k_{c.prev} + \left[\frac{i - \sum (L_{prev})}{L_{stage}}\right](k_{c.next} - k_{c.prev}) \quad (1)$$

where i is the day number within the growing season; k_{ci} is the crop coefficient on day i; L_{stage} is the length of the stage under consideration (days); $k_{c.prev}$ is the crop coefficient at the previous stage; $k_{c.next}$ is the crop coefficient at the next stage and L_{prev} is the length of all previous stages (days).

The relative impact of climate on crop required the adjustment of kc. For specific adjustment of kc for mid and late season in climates where the minimum relative humidity differs from 45% or where wind speed is larger or small than 2.0 m/s, the procedure is given by [14] was used as the following:

$$k_{c.mid} = k_{c.mid(Tab)} + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)](\frac{h}{3})^{0.3} \quad (2)$$

Where $k_{c.mid(Tab)}$ is the value for kc of mid season taken from [13]; u_2 is the mean value of wind; RH_{min} is the mean value of relative humidity and h is the mean plant height during the mid-season.

Table 3 shows details for the length of growing stages for maize, bean millet and groundnuts. The values of mid and late season crop coefficient were adjusted from the ones given by [13] because both the study sites have more daytime relative humidity than 45%. Ouagadougou and Ngabu are also less and more than 2m/s windy condition areas respectively **Tables 4 and 5** give the adjusted crop coefficients for the selected crops, in Ouagadougou and Ngabu respectively.

Table 3. Length of growing stages for the selected crops in the study sites.

Crop	Growth	Crop growing stages			
	days	Initial	Development	Mid	Late
Maize Massongo	105	20	30	35	20
Bean KVX61-1	95	15	25	35	20
Millet	140	20	30	55	35
Groundnut	130	25	35	45	25

Table 4. Adjusted crop coefficients for selected crops in Ouagadougou at different stages of growth

Crop	Crop coefficients			
	Initial	Development	Mid	Late
Maize Massongo	0.30	0.84	1.16	0.53
Bean KVX61-1	0.40	0.75	1.14	0.33
Millet	0.30	0.53	0.94	0.24
Groundnut	0.40	0.61	1.12	0.56

Table 5. Adjusted crop coefficients for selected crops in Ngabu at different stages of growth

Crop	Crop coefficients			
	Initial	Development	Mid	Late
Maize Massongo	0.30	0.84	1.11	0.51
Bean KVX61-1	0.40	0.75	1.10	0.30
Millet	0.30	0.53	0.91	0.21
Groundnut	0.40	0.61	1.10	0.55

2.3 Yields Modeling

This study used the model recently developed by [11] for estimating yields, only in rainfed condition under different planting dates. The model is presented as:

$$Ye = Yp \sum_{i=1}^{n} \frac{[1 - ky_i(1 - RCI_i)]}{n} \quad (3)$$

Where Ye and Yp are the estimated and potential yield, respectively; ky is the yield respond factor to drought; i is the time step and n is the total time step for the growing period; RCI is the rainfall contribution index. The general form of RCI is expressed as the following:

$$\mathrm{RCI} = \sum_{i=1}^{n} \frac{\mathrm{PE_i/ETm_i}}{n} \quad (4)$$

where PE is the effective rainfall (mm); ETm is the crop water requirements (mm). Crop water requirement (ETm) is established as a function of reference evapotranspiration (ETo) and crop coefficient (kc):

$$\mathrm{ETm} = \mathrm{kcETo} \quad (5)$$

The Penman-Monteith equation given by [13] was used for the calculation of ETo as the following:

$$\mathrm{ETo} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (6)$$

Where ETo is the reference evapotranspiration (mm/day), R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T is the mean daily air temperature at 2 m height (°C), e_s is the saturation vapour pressure (kPa), u_2 is the wind speed at 2 m height (m s^{-1}); e_a is the actual vapour pressure (kPa), e_s - e_a is the saturation vapour pressure deficit (kPa), Δ is the slope vapour pressure curve (kPa°C^{-1}), and γ is the psychrometric constant (kPa °C^{-1})

Effective Rainfall (PE) representing the portion of total rainfall that plants use to help meet their consumptive water requirements has been calculated by the USDA soil conservation method as followed [17]:

$$\mathrm{PE} = P_{tot}\frac{125 - 0.2P_{tot}}{125} \quad \text{for } P_{tot} < 250\text{mm} \quad (7)$$

$$\mathrm{PE} = 125 + 0.1P_{tot} \quad \text{for } P_{tot} > 250\text{mm} \quad (8)$$

Where: PE is the Effective rainfall (mm) and P_{tot} is the total rainfall (mm).

3 Discussion of Results

3.1 Rainfall Contribution Index

Two production sites have been investigated in this study, Ouagadougou and Ngabu located in Burkina Faso and Malawi, respectively. These two Sub-Sahara African (SSA) countries are low rainfall areas with a difference in the period of their rainy season. From **Figure 2**, the values of RCI found in this study were higher in Ngabu (0.74 to 1.00) than Ouagadougou (0.58 to 0.93). The closer the index value is to one, the higher the rainwater supply and vice versa. By considering only the rainwater availability, it is conclude that, most of the crops were potentially favorable to the agro-ecological climate of Ngabu.

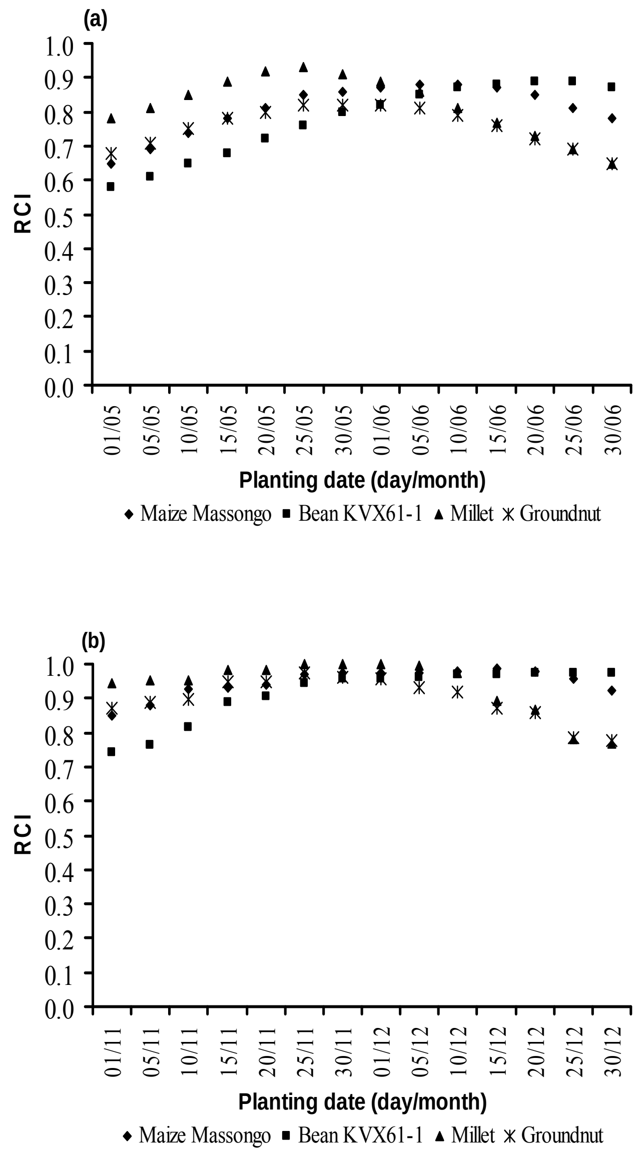

Figure 2 Plot of rainfall contribution index for different planting dates in Ouagadougou (a) and Ngabu (b).

While in Ouagadougou, only millet could be least water stressed among the crops considered in this study. Appropriated planting information might help Burkina Faso and Malawi farmers for a better uses of the rainwater supply. According to [18-19], Burkinabe farmers need more information for staggering planting dates to avoid exposing crops to water deficit during vulnerable crop growth stages. Additionally, based on the crop water and irrigation water requirements comparison of these two locations, it is found that agricultural potential is significantly different. The crop water and its associated irrigation requirements are much higher in Ouagadougou than Ngabu. **Figure 3** shows the comparison of crop water and irrigation requirement for Ouagadougou and Ngabu. This implies that supplementary irrigation is extremely required to fulfill the crop water demand in order to compensate the evapotranspiration losses.

Research observed yield increasing under high water supply condition by simulating the dynamics of crop seasonal water deficits [20]. These areas have a very low and short rainfall. Hence, inappropriate planting dates over a long period could lead to a mismatch between high crop water demands and high rainwater supply. Accordingly, crops could be under rainwater insufficiency during their high water requirements period. It has been reported by [12], in low rainfall areas, planting dates management might reduce the rainwater stress to crops. Research conducted by [21] indicated that, altering the date of planting to match with the favorable environment conditions seems to be a potential adaptation strategy for sustaining the production. By considering only rainfed condition in this study, the yield deficit was related to the evapotranspiration deficit which is a consequence of rainwater deficit. Hence, the RCI and yields estimated in this study can help for determining the suitable planting period in Ouagadougou and Ngabu.

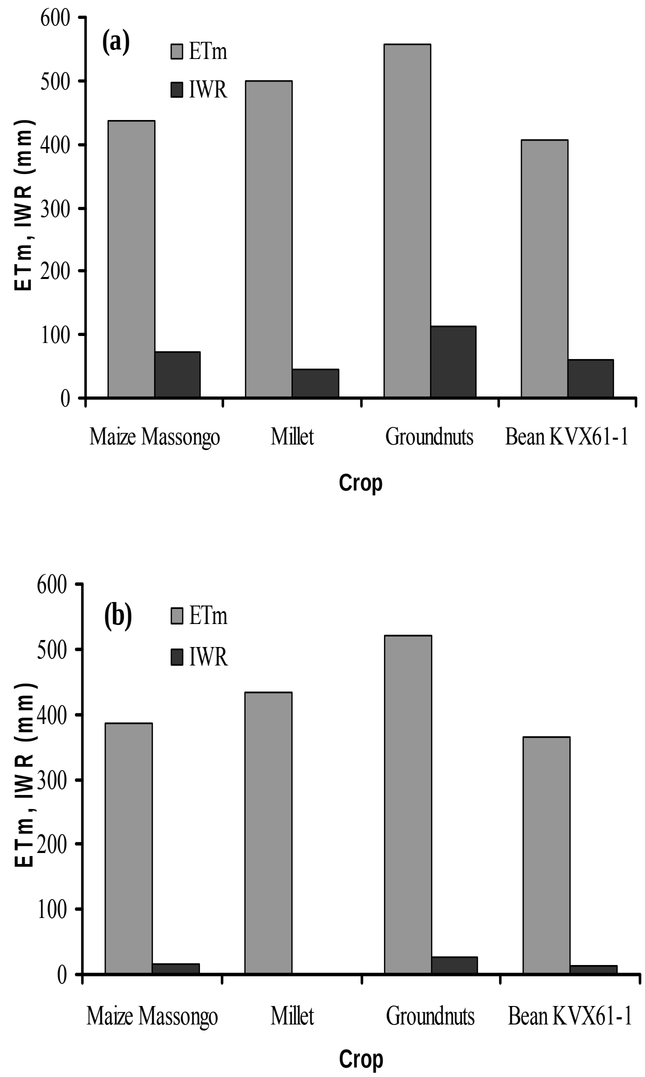

Figure 3. Plot of Crop water requirements (ETm) and irrigation water requirements (IWR) for high rainwater supply condition in Ouagadougou (**a**) and Ngabu (**b**).

3.2 Yields Evaluation

According to [22], as crop yields are sensitive to planting dates and the length of the growing season, planting dates for different regions of the world are an important input parameter that determines regional crop response to climate conditions. He stated that, although some organizations or projects provide information on crop specific planting dates [23-24] this information is not sufficient for a global yield modeling. First, not all countries and not all crops are covered by these databases. Second, planting dates often differ within one country, which is only considered for very large countries in these databases.

Third, planting dates change with climate change, and any project that aims to simulate future crop yields cannot rely on static crop calendars. Thus, this paper explored the potential for improving the rainwater use and increasing the crop yield by manipulating the planting dates.

A climatic data information model recently proposed by [12] was used in this study to estimate the yields of crops. The results are presented in **Tables 6 and 7** which give the crops yields estimated for different planting dates in Ouagadougou and Ngabu, respectively. From these results, it was observed that the yields vary according to the locations and planting dates. The highest estimated yields found were 5.10, 1.31, 1.40 and 0.87 tons per hectare for maize, bean, millet and groundnut, respectively in Ouagadougou. Whilst in Ngabu, they were 5.92, 1.46, 1.50 and 0.98 tons per hectare for maize, bean, millet and groundnut, respectively. It was observed that, the yields were higher in Ngabu than Ouagadougou. In Ouagadougou, the highest estimated yields for maize, bean, millet and groundnut were found on June 5, June 20, May 25 and May 25, respectively. Whilst in Ngabu, the highest yields were obtained on December 15, December 25, November 25 and November, respectively.

This study considered the planting dates under the highest RCI which gave the highest expected yields, as suitable planting dates. From the results of this study, by comparing the average value of expected yields to potential yields, it was observed that the yields of maize, bean, millet, groundnuts were reduced by 10.31, 16.22, 10.57, 4.82 % in Ouagadougou, and 5.00, 7.41, 7.14, 4.30 % in Ngabu, respectively. These yields decreasing were much higher for planting staggered from the suitable dates determined in this study. This is causally related to the planting dates variation. Study done by [25] attributed this yield reduction to the evapotranspiration deficit due to the shortage of water supply which is affected by the cropping calendar. According to [10], a shift in planting time leads to significant impact on the performance of the crops. The potential yield is the highest possible yield obtainable with ideal management, soil and weather; hence it can only be obtained when irrigation is considered for all the crops studied in both sites except for millet in Ngabu of Malawi. The maximum

Table 6. Estimated yields for suitable planting period for selected crops in Ouagadougou

Crop							
Maize Massongo		Bean KVX61-1		Millet		Groundnut	
Planting dates	Yield (t/ha)	Planting dates	Yield (t/ha)	Planting dates	Yield (t/ha)	Planting dates	Yield (t/ha)
01/06	5.03	10/06	1.28	15/05	1.34	20/05	0.86
05/06	5.10	15/06	1.29	20/05	1.38	25/05	0.87
10/06	5.10	20/06	1.31	25/05	1.40	30/05	0.87
15/06	5.03	25/06	1.31	30/05	1.37	01/06	0.87
20/06	4.88	30/06	1.28	01/06	1.34	05/06	0.87
Traditional av.	4.56		1.11		1.23		0.83
Optimum av.	5.03		1.29		1.36		0.87
Increase (%)	10.31		16.22		10.57		4.82

Table 7. Estimated yields for suitable planting period for selected crops in Ngabu

Crop							
Maize Massongo		Bean KVX61-1		Millet		Groundnut	
Planting dates	Yield (t/ha)	Planting dates	Yield (t/ha)	Planting dates	Yield (t/ha)	Planting dates	Yield (t/ha)
30/11	5.80	10/12	1.45	25/11	1.50	15/11	0.96
01/12	5.81	15/12	1.45	30/11	1.50	20/11	0.96
05/12	5.81	20/12	1.45	01/12	1.50	25/11	0.98
10/12	5.83	25/12	1.46	05/12	1.50	30/11	0.97
15/12	5.92	30/12	1.46	10/12	1.46	01/12	0.97
Traditional av.	5.60		1.35		1.40		0.93
Optimum av.	5.88		1.45		1.50		0.97
Increase (%)	5.00		7.41		7.14		4.30

yield can obtained when crops are planted during the suitable planting periods, while traditional yields are obtained when traditional planting dates are practiced in the respective study sites. **Figure 4 (a and b)** shows that the standard deviations were lower between potential and average maximum expected yields obtained from suitable planting period in Ngabu than in Ouagadougou.

The yield of groundnut, millet, maize and bean would increase if farmers follow the suitable planting period. For these SSA countries, it can be concluded that, the yields deficits under rainfed condition might be attributed to the cropping calendar difference. The future food scenario is not optimistic because the demand for food in developing countries is expected

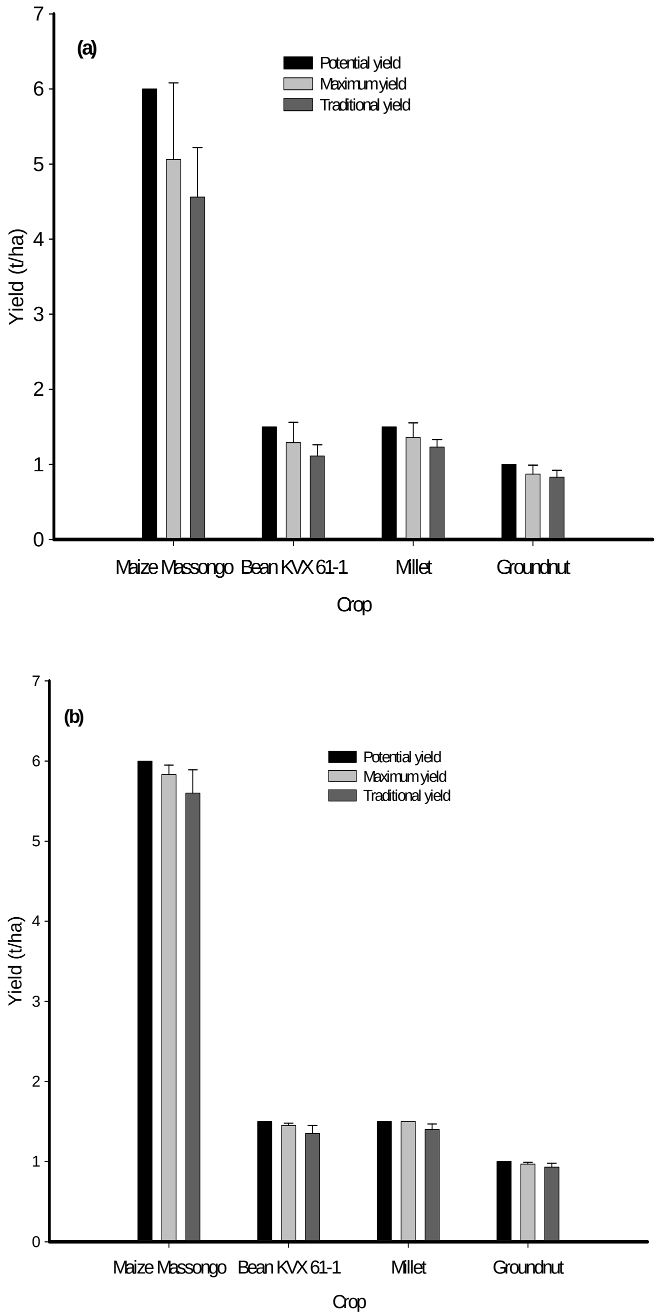

Figure 4. Potential, Maximum and traditional yields estimated from suitable and traditional planting periods in Ouagadougou (**a**) and Ngabu (**b**). Vertical bars indicate the standards deviation calculated between potential yields and estimated yields.

to increase at about 3.6% per year during the coming decade [26]. Therefore, the results of this study might be suggested to alleviate the water shortage and yield deficit in rainfed production, in Ouagadougou and Ngabu. This can help farmers to be able to make practical decisions on the land preparation periods and planting dates of their crops. It is necessary to develop this methodology for different locations and enlarged to other new cultivars release by breeders. Hence, the low agricultural productivity can partially be solved. Discussions about the importance of early yield predictions for agricultural planning and food security issues have also been presented by [27].Then, the food crisis can find a long term solution.

4 Conclusions

Burkina Faso and Malawi located in Sub-Sahara Africa are low rainfall and food deficit countries. Ngabu receives annually, an average of 912 mm rainfall, while Ouagadougou receives 698 mm. This present study explores the cropping calendar approach in order to alleviate the water deficit impact on crop and increase the yields. From the results of this study, the RCI and expected yields determined were found higher in Ngabu than Ouagadougou due to their agro-ecological climatic difference. By considering only the rainwater availability, it is conclude that, most of the crops were potentially favorable to the agro-ecological climate of Ngabu. It is also found that the yields vary according to the locations and planting dates. It was found that, the gap between potential and expected yields was causally related to the planting dates. Rainwater efficient use can therefore be made available to crops by improving management of planting period.

Therefore, the suitable planting period determined for the selected crops in this study, are recommended for reducing the gap between supply and demand under rainfed condition. The planting dates approach is a useful decision support system to help farmers to optimally schedule and manage rainwater for high productivity. The information on expected crop production and rainwater supply can also be used by governments for agricultural management and planning in both Burkina Faso and Malawi.

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