Agricultural Drought Analysis for Sustainable Smallholder Maize Production in Semi-arid Areas: A Case Study of the Lower Moshi Irrigation Scheme, Tanzania

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Abstract

Rainfed maize (Zea mays) in semi-arid Sub-Saharan Africa is subject to many climate-related risks—including agricultural dry spells and droughts. Effectively selecting appropriate agricultural water management strategies must first begin with evaluation of the potential climate-related risks. This article evaluates dry spell occurrence in the Mabogini Village—located within a semi-arid area in Tanzania—using a water balance approach with nineteen years of historical daily precipitation data. The water balance equation was related to crop water requirements to evaluate both the prevalence of agricultural dry spells as well as estimate the water deficits throughout the same time period. Only four of the nineteen seasons did not experience a dry spell of at least five consecutive days. 37% of the seasons had at least one dry spell of 6-10 days while 63% had at least one dry spell of greater than 15 days. Soil water deficit in relation to crop production ranged from 0-140 mm. This study concludes that dry spells lasting greater than 15 days throughout 63% of the past 19 growing seasons represent a high risk to smallholder farmers in the area. The high prevalence of long dry spells suggests that rainfed maize production is not sustainable in the region without interventions. However, relatively small water deficits suggest that proper water capture, storage, and supplemental irrigation methods could help to bridge the gap between dry spells. It is therefore recommended that water management practices be put in place immediately to support productive and sustainable maize production in the area.

Introduction

Tanzania is a country of 48.8 million people located in Sub-Saharan Africa in the eastern region (United Republic of Tanzania (URT), 2015). Future climate change in Tanzania is expected to cause extreme disruptions in agricultural production because 75%-80% of the Tanzanian population is involved in agriculture and 70% live on less than $2 per day (NAPA, 2007; World Bank, 2015). Mean annual temperatures in Tanzania are predicted to increase between 2°C-4°C and rainfall to decrease by 5%-15% by 2030—though this is highly variable throughout the country (NAPA, 2007; Paavola, 2008). The effects of climate change will undoubtedly increase the number of food-insecure people unless dramatic and quick steps are taken to adapt new climate resilient agricultural systems (Ahmed *et al.,* 2011). However, local areas will need to be assessed for climate related risks and appropriate agricultural management strategies assessed for their sustainability to produce more grain with less water. Adaptation of agroecosystems is subject to local conditions including biophysical constraints, socioeconomic dynamics, and localized future climate scenarios (Thornton *et al.,* 2009).

Types of drought include meteorological, socioeconomic, hydrologic, and agricultural (Wilhite and Glantz, 1985). Meteorological droughts are typically defined as a particular timeframe in which an area receives less than a predetermined amount of precipitation (Mwangi *et al.,* 2014). While meteorological droughts can impact agricultural production over long periods of time, the presence of a meteorological drought does not always signify a threat to crop growth. However, agricultural droughts do pose a serious threat to crop production. Definitions of agricultural droughts seek to link meteorological droughts to their direct impact on agricultural production (Wilhite and Glantz, 1985). Most commonly this takes places through linking meteorological assessments with soil water balances throughout a crop growing season—often evaluating soil water deficits in relation to crop growth (Barron *et al.,* 2003; Wang, 2005). Due to the uneven distribution of rainfall throughout crop-growing seasons, crops can experience dry spells that can inhibit growth. Agricultural dry spells are analyzed similar to agricultural droughts—typically relating soil water deficit to crop growth. However, agricultural dry spells are analyzed on a much shorter time frame—typically days—compared to droughts being analyzed over more than one year.

Soil water deficits are a function of the evapotranspiration of the agricultural system, the precipitation received in the area, as well as numerous soil properties including water retention characteristics, water infiltration rate, and deep seepage (Nesmith and Ritchie, 1992; Hudson, 1994; Karl and Trenberth, 2003; Zhang *et al.,* 2004). This is most easily visualized through a general soil water balance equation as given in equation 1.

$$\Delta S=P+I-(R+D+ET)\ldots\ldots\ldots\ldots\ldots\ldots\text{(Eq.1)}$$

ΔS is change in soil water storage, P is precipitation, I is irrigation, R is runoff, D is deep drainage, and ET represents evapotranspiration (Lal and Shukla, 2004). Agricultural dry spells occur when there is a crop-related soil water deficit for a given number of days. Dry spell analysis uses this simple water balance equation and relates it to crop water requirements to identify potential crop growth stress and estimate irrigation requirements. While precipitation is an external variable that is not controlled by farmers, irrigation can be important in addressing agricultural dry spells.

Meteorological dry spell analysis can still be relevant for identifying smallholder farmer water management options (Nyakudya and Stroosnijder, 2011), though studies that analyze agricultural dry spells in semi-arid Sub-Saharan Africa could be more beneficial. For instance, Barron *et al.* (2003) conducted both a meteorological and agricultural dry spell analysis in Kenya and Tanzania and reported that maize was exposed to dry spells exceeding 10 days for 74%-80% of the seasons evaluated while the meteorological dry spell analysis indicated a minimum probability of only 20% of the seasons for this to occur.

The objective of this article is to evaluate the occurrence of agricultural droughts through dry spell analysis using a simple hydrologic balance for Mabogini Village, in the Lower Moshi Irrigation Scheme (LMIS), Tanzania. Specifically, this article assesses the sustainability of rainfed maize production in an effort to explain low yields in the region as well as to identify potential options for managing soil and water resources both immediately and under future climate change to ensure sustainable agricultural production.

Methods

Description of the study area

Mabogini Village is located within the Lower Moshi Irrigation Scheme, northern Tanzania, Moshi District, Kilimanjaro Region, United Republic of Tanzania (3.40° S, 37.36° E) at an elevation of 775 m a.s.l. The average annual minimum temperature is 18.0°C and the average annual maximum temperature is 30.7 °C. The area receives an average annual rainfall of 525 mm - primarily between March and May - with a shorter period of rainfall occurring between November-January.

The Lower Moshi Irrigation Scheme has a total area of 2,300 ha and was identified as having the highest economic viability for irrigation scheme development projects in the area. The Lower Moshi Irrigation Scheme was given priority for implementation, and construction started in May 1984 and was completed in April 1987. Located between 3 and 15 km South-East of Moshi town, the scheme covers the administrative areas of six villages namely Kaloleni, Mandaka, Mabogini, Rau river, Chekereni, and Oria along the right bank of the Rau River. Mabogini Village has the largest population compared to the other villages within the scheme. According to the National Bureau of Statics Census report of 2012, Mabogini Village has a population of 11,855 (United Republic of Tanzania (URT), 2013). Mabogini Village is bordered by the Rau River on the East, the sugarcane plantation of Tanganyika Planting Company (TPC) on the southwest, and in the North by Moshi municipal. The original design of the Lower Moshi Irrigation Scheme in 1984 was aimed at cultivating flooded rice crops twice per year throughout the scheme. However, lower than expected water intake combined with higher water demands at the plot level have resulted in reduced rice production. For this reason, only a portion of the Lower Moshi Irrigation Scheme cultivates rice twice per year (full irrigated rice during dry spell season and with supplemental irrigation during the long rainy season) while a large area within the Lower Moshi Irrigation Scheme infrastructure relies on rainfed maize production during the long rainy season only due to insufficient water.

Data collection

Weather data for Mabogini Village from 1997 to 2015 were collected from the Kilimanjaro Agricultural Training Centre (KATC) in Chekerini Village - a nearby village. Daily precipitation and minimum and maximum temperature were also collected. Data was collected daily by a manual rain gauge and thermometers located on the KATC compound. Data gaps within the collected weather data were filled using estimated daily calculated values from National Air and Space Administration's (NASA) Prediction of Worldwide Energy Resource (POWER) Agro-climatology database (NASA, 2015). Daily potential evaporation estimates (Epotential) were generated using the Food and Agriculture Organization's (FAO) CLIMWAT Database (Smith, 1993). Seasonal characteristics were calculated for each year from March 20 until July 17 for 120 days. The average characteristics are reported in Table 1. This data range is representative of the average maize planting date each year as well as the average crop growth period of maize varieties used in the area (Table 2). Season rainfall was determined for each year by summing the rainfall received during the growing season for March 20 until July 17 (Table 1).

Table 1: Growing season weather summary for Mabogini Village, Tanzania

	Mean	**Standard Deviation**
Rain days per season	32	13
Rain per rain day (mm day^{-1})	8.3	2.8
Mean season rainfall (mm)	257.9	125.4
Total season potential evapotranspiration (mm)	395	--
Mean daily evapotranspiration (mm day^{-1})	3.3	0.7

For future climate data, the MarkSIM DSSAT weather file generator was used (Jones and Thronton, 2000; Jones and Thornton, 2013). The MarkSIM software generates future climate data through the downscaling of global circulation models used by the Intergovernmental Panel on Climate Change (IPCC). These global circulation models are influenced by future greenhouse gas emission trajectories which are grouped into Representative Concentration Pathways (RCPs) based on four possible greenhouse gas concentration scenarios. Future climate data for each of the four RCPs—2.6, 4.5, 6.0, and 8.5—were generated using a suite of all eighteen models used in the IPCC Assessment Report 5 (AR5) (IPCC, 2013; Barros *et al.,* 2014; Field *et al.,* 2014) (Table 3).

Water balance

The water balance calculation developed by Barron *et al.* (2003)—that is based on the FAO-24 methodology (Doorenbos and Pruit, 1977; Allen *et al.,* 1998)—was used to assess agricultural drought through dry-spell occurrence. This simple water balance calculation takes into consideration precipitation, soil water balance, and crop evapotranspiration throughout the growing season to determine the potential threat to crop production. All equations have been adapted and modified from Barron *et al.* (2003). Crop water requirements were determined on a daily basis throughout the growing season (Eqation 2):

$$E_{\text{actual}} = E_{\text{potential}} \times k_c \text{ ………..................…(Eq. 2)}$$

E_{actual} (mm day-1) is the maximum crop water requirement, $E_{\text{potential}}$ (mm day^{-1}) the potential (non-limited) evapotranspiration for the area, and k_c is the crop coefficient. The crop coefficient changes throughout the growing season to represent changes in water requirements for various crop growth stages (Table 2).

For this simple calculation, R is assumed to be 0 because the area under investigation is within soil bunds designed for flooded rice production. Therefore, Pe is equivalent to all precipitation received. The bunds effectively keep water from running off the plots. A possible issue is that this does not take into account evaporation of water from the surface due to limiting soil infiltration rates in some areas. D was calculated if soil water begins to exceed the soil water storage potential. The latter was set at 175 mm m^{-1} according to the average soil water storage potential suggested for irrigation calculations by Brouwer *et al.* (1985). The initial ΔS_{root} was zero, however, the calculations began 20 days before the start of the growing season using the collected precipitation data.The initial ΔS_{root} was set to zero because land use - and thus potential evaporation - varies widely throughout the area. Additionally, the area typically receives little or no precipitation the two months leading up the beginning of these simulations. It was assumed that during the time before the growing season, the soil was bare and had an average evaporation rate of 0.5 mm day^{-1} according to a study conducted in an area under semi-arid conditions (Wythers *et al.,* 1999). This allowed for the effect of rainfall prior to the growing season - and subsequently changes in soil water storage - to be included in the calculations. Finally, the effective rooting depth (Table 2) dictates how much of the total soil water is actually available to maize plants. The following two conditions were also placed in this calculation:

$$\text{if } \Delta S_{\text{root}} \geq E_{\text{potential}};\ E_{\text{actual}} = E_{\text{potential}} \text{………......(Eq. 4)}$$
$$\text{if } E_{\text{actual}} \geq \Delta S_{\text{root}} \geq 0;\ E_{\text{actual}} = \Delta S_{\text{root}} \text{………(Eq. 5)}$$

Table 2: Crop development stages and corresponding rooting depth (zr) and crop coefficient (kc) used in the water balance model throughout the growing season. Adapted from Barron *et al.* (2003).

Days after sowing	Crop Development Stage	Rooting depth, zr (m)	Crop coefficient, kc
1-30	Stage 1: emergence and establishment	0.1	0.4
31-60	Stage 2: vegetative development	0.1-1.0 (interpolated)	0.4-1.3 (interpolated)
61-90	Stage 3: tasseling, flowering	1.0	1.3
91-120	Stage 4: grain filling and drying	1.0-0.8 (interpolated)	1.3-0.55 (interpolated)

E_{actual} is limited by soil water stored within the root zone ($\Delta S_{\text{root zone}}$). Water within the soil profile is determined by:

$$\Delta S_{\text{root zone}} = (\Delta S_{t-1} + P_e - R - D) \text{ x } \textit{effective root depth} \text{ (mm)......................................(Eq. 3)}$$

ΔS_{root} (mm day^{-1}) is the water available in the root zone, ΔS_{t-1} (mm day^{-1}) is the soil water storage left from the previous day, P_e (mm day^{-1}) is the effective rainfall, R (mm day^{-1}) is the surface water runoff, and D (mm day^{-1}) is the deep percolation out of the soil.

This demonstrates that E_{actual} is limited by the water available in the soil within the root zone. To determine dry spell occurrences, the crop index (CI), suggested by Barron *et al.* (2003) was used:

$$CI = \frac{E_{actual}}{E_{potential}} \quad \text{..............................(Eq. 6)}$$

$$\text{if } CI \leq 0.5\text{, dry spell occurs................(Eq. 7)}$$

When E_{actual} only reaches 50% of $E_{potential}$, crop growth and development are negatively affected. A study in Tanzania and Kenya reported that dry spells of 10 days long would significantly damage maize crops (Stroosnijder, 2007). CI for each growing season was evaluated to determine the prevalence of dry spells of 5, 10, and 15-day duration (Table 4). This analysis gives an indication of historical prevalence of agricultural dry spells.

Table 4: Number of dry spells of varying lengths for each growing season from 1997-2015 in Mabogini Village, Tanzania

Year	5 days	6-10 days	11-15 days	>15 days
1997	0	1	0	0
1998	0	0	0	0
1999	0	0	0	0
2000	0	0	0	0
2001	0	2	1	0
2002	0	0	0	1
2003	0	2	0	0
2004	1	1	0	1
2005	1	0	0	3
2006	1	0	0	2
2007	0	1	0	1
2008	0	0	0	1
2009	1	1	1	2
2010	0	0	0	0
2011	1	0	2	1
2012	1	0	0	1
2013	0	0	0	1
2014	0	0	0	1
2015	0	1	0	1
Years with dry spell (%)	31.6	36.8	15.8	63.2

Finally, the following calculations were used to determine the amount of supplemental irrigation water that would be required to limit crop damage during dry spells:

$$\text{daily irrigation}_{req.} = (E_{potential} \text{ x } 0.56) - \Delta S_{root}\text{.(Eq. 8)}$$

The daily irrigation requirement is the amount of water needed to increase ΔS_{root} water content enough so that Eactual is greater than 50% of $E_{potential}$ (i.e. CI>0.5). The total irrigation required for each season was summed and is presented in Figure 1.

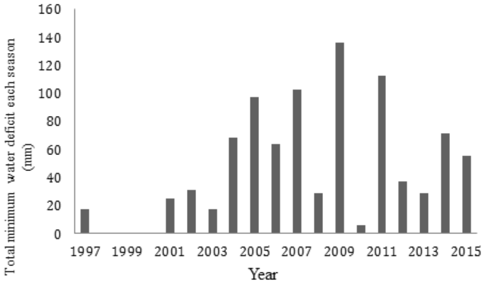

Figure 1: Potential irrigation requirements of each growing season for Mabogini Village, Tanzania

RESULTS AND DISCUSSION

Rainfall Analyses

Mean seasonal rainfall for the 19 years of available data (1997 - 2015) was 257.9 mm while total potential evaporation was 395 mm. However, for mean rainfall, the standard deviation was 125.4 mm. This indicates high variability of rainfall between seasons—often making it difficult for farmers to plan planting and investing strategies for optimal production. This is further highlighted in Figure 2, where total seasonal rainfall for each year is graphed. The apparent high variability of rainfall spans between a high seasonal rainfall of over 600 mm to a low seasonal rainfall amount of below 100 mm. In addition to the high variability, the weather data indicate a general decrease in the total amount of rainfall over the 19 years (Fig. 2). This high variability is typical for southern and eastern Africa. Usman *et al.* (2004) reported that part of this variability is heavily influenced by the El Niño Southern Oscillation (ENSO).

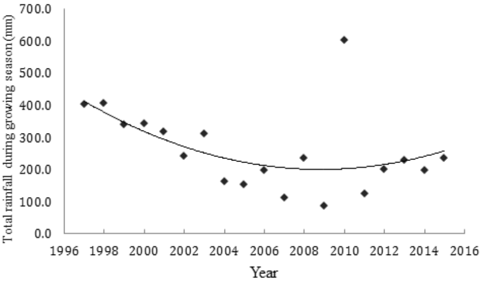

Figure 2: Total seasonal rainfall by year for Mabogini Village, Tanzania. The quadratic equation for the decrease in total seasonal rainfall from 1997-2015 is: total seasonal rainfall = (-1.5 X year^2) – (6111.4 X year) + 6x10^6, R^2=0.26.

Dry Spell Analyses

Even in years where there was sufficient total seasonal rainfall, dry spells were still present. Dry spells of 5 days were present in 32% of the seasons, of 6-10 days in 37%, of 11-15 days in 16%, and of greater than 15 days in 63% of the seasons analyzed (Table 4). This presence of dry spells - especially of the longer duration - indicates the need for future water management techniques to ensure production. Additionally, the presence of the dry spells might help explain the low average yield of maize and the high frequency of crop failure throughout the Lower Moshi Irrigation Scheme area. Of the 19 years analyzed, there were four years in which no dry spells occurred. A meteorological study conducted in Zimbabwe reported that 30% of the years would likely have meteorological dry spells and that dry spells of 6-10 days would be the most common (Nyakudya and Stroosnijder, 2011). However, Barron *et al.* (2003) reported that actual dry spells—which had negative effects on crop growth—were highly dependent on soil water deficits throughout the growing season. This study underlines the importance of water balance evaluations when studying dry spell occurrence. Slegers and Stroosnidjer (2008) argued that rainfall trends in semi-arid East Africa give no proof that meteorological droughts are increasing. Instead, they hypothesize that agricultural droughts are increasing through soil water deficits and therefore this is leading to the higher prevalence of droughts reported by smallholder farmers. The high percentage of dry spells, reported in duration from 5 to greater than 15 days, is similar to typical dry spell ranges for SSA (Barron *et al.,* 1999; Fox and Rockström, 2000). Approaches to drought mitigation and monitoring have focused mainly on vegetation and meteorological analyses (Rojas *et al.,* 2011). Fortunately, recent studies are reporting the inclusion of soil moisture monitoring and agricultural drought predictions based on soil water deficits combined with meteorological analyses (Anderson *et al.,* 2012; Shukla *et al.,* 2014).

Water deficit

The simple water deficit analysis indicates that seasonal deficits are between 0 and 140 mm. The mean deficit was 47.4 mm with a standard deviation of 41.3—again highlighting the high variability (Figure 1). Further studies should be conducted to quantify irrigation efficiency, water availability, and the field crop water use. This information would be valuable to determine feasibility on a large scale of the sustainability of increasing irrigation to this portion of the Lower Moshi Irrigation Scheme.

Management practices that capture and store more water can be valuable in this region as the water deficit is relatively small. Rainwater harvesting and conservation tillage have been suggested as two practices with high potential to bridge between dry spells through improved water availability and timing of operations (Rockström *et al.,* 2002; Mbilinyi *et al.,* 2005). These low-cost technologies would enable farmers in semi-arid regions to supplement their crops with irrigation to help bridge the dry spell gaps. Net profit from water harvesting and supplemental irrigation increased 170%-260% in a study in Kenya (Fox *et al.,* 2005). This study also reported that water harvesting and supplemental irrigation are best used in conjunction with fertilizer inputs.

Table 3: Change (% increase from past weather) in total annual rainfall and average annual low and high temperatures for 2025, 2035, and 2045 for four Representative Concentration Pathways (RCP) for Mabogini Village, Tanzania

Year	Total Annual Rainfall				Average Annual Min Temperature				Average Annual Max Temperature			
	RCP				RCP				RCP			
	2.6	4.0	6.0	8.5	2.6	4.0	6.0	8.5	2.6	4.0	6.0	8.5
2025	42.5	41.4	42.6	28.3	4.2	4.5	4.1	4.8	1.0	1.3	1.0	1.5
2035	46.2	47.4	23.1	39.6	5.0	5.9	5.3	6.9	1.5	2.1	1.7	2.3
2045	34.9	37.9	43.6	43.6	5.6	7.2	6.5	9.1	1.7	2.7	2.3	3.4

Future climates

For all future climate scenarios and for all three time periods, total annual rainfall is projected to increase 23%-47% (Table 3). Seasonal rainfall was not evaluated in this study because seasonal planting schedules and crop genetics will change both the date of planting and length of season in the future. However, Lo *et al.* (2008) reported increased precipitation during the December-February timeframe for East Africa. This would indicate the need to further evaluate crop planting seasons or possibly evaluating if it would be possible to have two growing seasons in the region in the future. The certainty regarding these predictions is still highly variable. Ahmed *et al.* (2011) reported both increased and decreased maize production depending on the global circulation model (GCM) used. Additionally, Ahmad and colleagues reported that increased precipitation volatility would dramatically increase poverty rates throughout Tanzania—further highlighting the need for agricultural drought mitigation measures. This increase in total annual rainfall highlights the importance of implementing agricultural practices that enhance water infiltration and storage in the soil—may be even eliminating the need to rely on supplemental irrigation in the future.

While rainfall increases in most of the future climate scenarios, temperatures for all scenarios and time periods also increase. The mean annual minimum temperature is predicted to increase 4.1%-9.1% and the mean annual maximum temperature by 1.0%-3.4%, corresponding to an increase of between 0.7°C-1.6°C for average annual minimum temperature and between 0.3°C-1.0°C for average annual maximum temperature. This will likely impact the evapotranspiration rate in the area—thus increasing water need (Trajkovic, 2005). Additionally, these higher temperatures will also increase crop heat stress. Rowhani *et al.* (2011) report that an increase of 2°C in annual average temperature could lead to a 13% decrease in maize production throughout Tanzania.

Conclusion

This article evaluated the occurrence of dry spells within the Lower Moshi Irrigation Scheme with the objective of evaluating the sustainability of rainfed maize and quantifying potential water requirements for future interventions. This study concludes that water management practices must be put in place immediately to support productive and sustainable maize production around Mabogini Village, Tanzania. Dry spells lasting greater than 15 days throughout 63% of the past 19 growing seasons represent a high risk to smallholder farmers in the area. However, the high variability of rainfall - and thus high variability of dry spells - throughout the data analyzed suggest that in some years rainfed production might be feasible.

Thus, solutions must be put in place that both increase water capture and storage and that also would not hinder farmers in years where rainfall is sufficient. This point is especially important regarding future climate change scenarios in the area whereby annual average precipitation is expected to increase - though the variability throughout the growing season is still unknown.

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