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Spatial and temporal aspects of agricultural sustainability in the semi-arid tropics: a case study in Mbeere district, Eastern Kenya

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Abstract *A study was conducted in the semi-arid Mbeere district, Eastern Kenya, to determine spatial and temporal variability of crop yields and climatic factors and their impacts on sustainability of semi-arid agriculture. Spatial aspects were assessed by conducting a survey of on-farm crop yields and using a computer model (QUEFTS) to predict maize yields from soil chemical indices. Temporal aspects were studied using time-series data (rainfall, temperature and crop yields). The study did not find a significant correlation between farmers' actual yields and QUEFTS predictions, and soil nutrients were thus not the only factors influencing maize yields in the study area. Other yield-reducing factors (climate and management) not accounted for in the QUEFTS model played a role. Grain yields of staple food crops were highly variable, fluctuating in time and space, and suboptimal. Particular aspects of rainfall (e.g. the short rains, for cowpeas and beans) were more important than mean annual rainfall in determining crop yields, and factors other than rainfall and soil fertility apparently played a role. The observed low grain yields, large yield gaps and high rainfall variability challenge the sustainability of these farming systems.*

Key words: dryland cereal crops, dryland legume crops, production risks, QUEFTS model, spatial variability, temporal variability

Introduction

Semi-arid lands occupy 17.7% of the earth's surface and are home to about one billion people (Harrison and Pearce 2000, Syngenta Foundation for Sustainable Agriculture 2006). The increasing human population and inappropriate use of natural resources in semi-arid lands have resulted in land degradation and have put food security in jeopardy. Moreover, agricultural production in many semi-arid areas is constrained by poor inherent soil fertility, erratic and low rainfall, shortage of cash for investment, inadequate extension services, insecure land tenure, lack of sufficient credit schemes, inadequate implementation of government policies and lack of political will to guide the implementation process (Harrison 1987).

Efforts to increase food production in semi-arid lands using high external-input systems have had limited impacts. This is because these technical options require relatively high capital investments, a well-functioning infrastructure, and a conducive policy and market environment, all of which are constraining factors in semi-arid areas. Furthermore, the economic efficiency of these proposed capital-intensive options are hindered by the low economic returns for most agricultural produce, existing market risks (such as unpredictable price fluctuations), and the costs and difficulty of access to external inputs (de Jager et al. 2001).

It is increasingly acknowledged that solutions to such challenges lie in sustainable agricultural production systems (Francis 1990), which remain productive over time and provide for the needs of current as well as future generations, while conserving natural resources (Sivakumar et al. 2000). Sustainability has both temporal and spatial dimensions (i.e. it is multi-scalar). The concept that sustainable agricultural systems can maintain output in spite of major disturbances or shocks (i.e. they remain productive over time) is particularly relevant to semi-arid lands where high variability of rainfall causes fluctuations in agricultural productivity, with profound impacts on the ecology, economy and social welfare of people. Sustainability also depends on spatial scales, since factors determining agro-ecological sustainability can be specific to a locality and can be variable in space (Dumanski et al. 1991, Zinck and Farshad 1995).

The development of sustainable agricultural systems requires understanding of the inter-relationships between natural resources (e.g. climate, soil, plant and animal genetic materials) and socio-economic factors. Some of these factors are beyond farmers' control, such as climate (rainfall, evaporation, solar radiation, temperature, relative humidity and wind) and temporal or spatial variations in the severity of pest attacks or outbreaks, especially of migrant pests, airborne diseases and some vector-borne diseases. Others – such as soil fertility, some pests (insects, diseases and weeds), management (timing of operations, planting density, etc.) and selection of germplasm – are influenced by choices that farmers make (Gitari et al. 1996, Mulder 2000). Each of these factors has a spatial and temporal dimension and is associated with risk that influences agricultural sustainability. Risk is generally viewed as uncertainty that affects an individual's welfare, and is often associated with adversity and loss (Harwood et al. 1999). Farming in semi-arid lands is inherently risky due to production uncertainties and price fluctuations (Hanson et al. 2004).

In this study, spatial aspects of agricultural sustainability in the semi-arid Mbeere district were assessed by conducting a survey of on-farm crop yields and using a computer model to predict maize yields from soil chemical indices. Temporal aspects of agricultural sustainability were studied using time-series data (rainfall and crop yields). The study, however, did not take into account other factors (varieties grown, changes in crop management, pest outbreaks, etc.) which may have affected past yields but for which time-series data were not available. The objective of the study was to investigate spatial and temporal variability of on-farm crop yields and climatic factors and their impacts on sustainability of semi-arid agriculture.

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Materials and methods

The study was carried out in Mbeere district (0º20´ to 0º50´ S and 37º16´ to 37º56´ E), Eastern Kenya, with a population density of 82 persons km^{-2} (CBS 2000). The district has an altitude range of 500–1200 m asl and a mean annual temperature range of 20ºC to 30ºC depending on altitude. Rainfall in the district is bimodal, unpredictable and unreliable, with most parts of the district receiving less than 750 mm annually. The 67% rainfall reliability (amounts surpassed in 20 out of 30 years) is estimated at 150 mm and 450 mm for the first and second rains, respectively (Jaetzold and Schmidt 1983). The district has two growing periods with a total length of 90–119 days (Kassam et al. 1991), and the farming is mainly under rain-fed conditions. Farmers grow maize, beans, cowpeas, sorghum, sweet potatoes and cassava for subsistence, and raise indigenous breeds of cattle, goats and poultry.

Assessments of temporal aspects of agricultural sustainability were carried out at district level while assessments of spatial aspects were done at farm level. The latter were conducted in Muthanu village, in Siakago division, with a group of 30 farmers. The soils in Muthanu are well-drained, shallow to deep, yellowish-brown, loamy sand to sandy loam, luvic arenosols (Muya 2003). They are low in organic carbon (C), total nitrogen (N) and extractable phosphorus (P), and are strongly acid to slightly acid (Table 1).

Assessment of agricultural sustainability requires the use of indicators (i.e. variables that measure change in a given phenomenon) (Smyth and Dumanski 1993). Maize-grain yields (and yield gaps) were selected as indicators of spatial variability and agricultural sustainability. Maize is the main staple food crop in the study area. Crop yields are the result of genotype and climate, and are affected by growth-limiting and growth-reducing factors present in a particular environment (Lövenstein et al. 1995), including water and nutrients,

Table 1. Average characteristics of 30 farm households studied (standard deviation or range in parentheses for general or soil characteristics, respectively)

Characteristic	Mean (SD or range)
General:	
Total farm area (ha)	1.4 (1.2)
Cultivated area (ha)	1.2 (0.8)
Average slope (%)	18.5
Livestock (TLU[a])	1.1 (1.7)
TLU[a] per person	0.2 (0.4)
Area (ha) per TLU[a]	2.5 (2.1)
Households below poverty level[b] (%)	100.0
Soils:	
pH–H_20 (1.0 : 2.5 suspension)	5.6 (4.8–6.3)
Organic C (g kg^{-1})	6.1 (2.9–11.1)
Total N (g kg^{-1})	0.6 (0.3–0.9)
Extractable P (Mehlich-1) (g kg^{-1})	8.8 (2.0–20.0)
Exchangeable K (cmol kg^{-1})	0.4 (0.2–1.0)

[a]Tropical Livestock Unit (1 TLU = 250 kg live weight). [b]Poverty level: below US$1 a day.

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pests and diseases, and farm-management practices. Spatial variability of yields is a reflection of the effect of these factors. Similarly, temporal variability in yields is an indication of dynamic changes in soils, management and climatic factors over time.

Temporal aspects were assessed using temperature, crop yields of major food crops (maize, beans, cowpeas and sorghum), agricultural productivity indices and rainfall. Temperature influences physiological processes in crops, and thus crop development and yields. Although seasonal variations in temperature close to the equator are small, temperatures at higher altitudes may be too low for production of semi-arid crops such as sorghum and cowpeas (Rowland 1993). Temporal changes in crop yields can be used as a proxy indicator of environmental change and land degradation (Muchena et al. 2005, Mazzucato and Niemeijer 2001, Tiffen et al. 1994). By using a base value to compare yield data, an agricultural productivity index allows analysis of changes in yields of different crops over time from the same starting date. Rainfall is the least dependable of all the weather variables and dictates crop production in the semi-arid lands (Stephens and Hess 1999).

A survey of crop yields and farmers' rates of nutrient application to various crops was carried out in 2004 through one-time recall semi-structured interviews. A nutrient monitoring (NUTMON) questionnaire was used, as described by Vlaming et al. (2001). Composite soil samples (0–30 cm sampling depth) were taken from each study farm and analysed for pH, organic C, total N, extractable P and exchangeable potassium (K). The pH was determined with a conventional glass electrode meter in a 1.0:2.5 soil:water suspension (Hinga et al. 1980). Organic C was oxidised with concentrated sulphuric acid and potassium dichromate, followed by colorimetric determination (Anderson and Ingram 1993). Total N and P were determined by wet digestion followed by colorimetric measurement (Novozamsky et al. 1983). Extractable P was determined colorimetrically after extraction with Mehlich-1 solution (Mehlich et al. 1962). Exchangeable K was extracted with ammonium acetate and then determined by flame photometry (Hinga et al. 1980, Okalebo et al. 2002).

Soil chemical characteristics (pH, organic C, extractable P and exchangeable K) and nutrient inputs for maize were used in the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) computer model (Janssen et al. 1990) to predict attainable maize yields for each study farm. The yields were predicted at three application rates of N, P and K: at the farmers' actual application rates; at half the recommended application rates; and at the full recommended fertiliser application rates. The recommended fertiliser rates for maize in the study area are 50 kg ha^{-1} N, 50 kg ha^{-1} P_2O_5 and 0 kg ha^{-1} K. The values of extractable P (Mehlich-1) were fitted to the model after dividing them by three (B Janssen, personal communication) for comparable model outputs with those for available P-Olsen estimated as described by Olsen and Sommers (1982). QUEFTS predicts yields from soil nutrient supply, takes interactions between N, P and K into account, and determines nutrient-limited yields, assuming that all other production factors are optimal (optimal water supply and crop management). Janssen et al. (1990), Smaling (1993), Smaling and Janssen (1993) and Mulder (2000) have described the empirical equations used in the QUEFTS model.

The QUEFTS-predicted attainable nutrient-limited maize yields were compared with actual maize yields reported by farmers, and also with an average on-station research yield

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potential of 5 t ha^{-1} (range 2.7 to 7.1 t ha^{-1}) for maize varieties in the study area. Attainable yields are those predicted when crop growth is limited by water and nutrient deficiencies, and by physical and biological health of the soil. Maize yield gaps were determined as the difference between attainable yields and actual yields.

Temperature records in Mbeere district (at the British American Tobacco (BAT) weather station, Siakago) were examined for the period 2000 to 2004 inclusive (5 years in which such records were available for the study area). Mean monthly temperatures and seasonal maximum and minimum temperatures, and their variability over time, were analysed to determine whether such variability presented risks to agricultural production and sustainability.

Crop yields of major staple food crops (maize, beans, cowpeas and sorghum) for the period 1980 to 2004 inclusive (25 years) were used in the analysis of temporal variability of agricultural production and production risks. The yield data were extracted from the records of the Mbeere district agricultural office (for 1996–2004) and from Embu district records (for 1980–90 and 1991–95). Mbeere district was created from part of the former larger Embu district, and the earlier data extracted from the Embu records were therefore restricted to those administrative divisions that correspond to the present Mbeere district. Analyses of temporal variation in crop yields and production risks were performed by two inter-related methods: calculation of agricultural productivity indices from time-series data; and analysis of coefficient of variation (CV) of grain yields. Grain yield trends were investigated over the 25-year period for which data were available.

The risk posed to agricultural sustainability by rainfall was studied by analysing rainfall characteristics and their relation to yields of main staple food crops (maize, sorghum, beans and cowpeas). Data on monthly rainfall for the period 1980 to 2004 inclusive were obtained from the BAT weather station, Siakago. The collected data were analysed for: (i) mean annual rainfall and its reliability (variability); (ii) monthly rainfall trends (distribution and reliability); and (iii) seasonal rainfall trends and variability. The analysis was undertaken to identify periods with risks to crop production when rainfall was low, resulting in the possibility of agricultural drought. An agricultural drought occurs when extended periods without rainfall are experienced and the crop water requirements (potential evapotranspiration) exceed the available soil moisture within the crop rooting zone (Biamah 2005).

In addition to the analysis of rainfall characteristics, a trend analysis of crop yields and rainfall over the 25-year period was carried out to determine the effects of rainfall trends, fluctuations and risks on staple food crop production. The relationship between rainfall and staple food crops was further explored using regression analysis, and the equations derived from these analyses were used to determine the strength of relationships between rainfall and crop yields.

Results and discussion

Farmers' actual maize yields (Figure 1) were lower than the on-station research yield potential of 2.7 to 7.1 t ha^{-1} for common semi-arid maize varieties (MoARD 2002, KARI 2004). The differences in yields between farmers' fields and on-station research yield potential can

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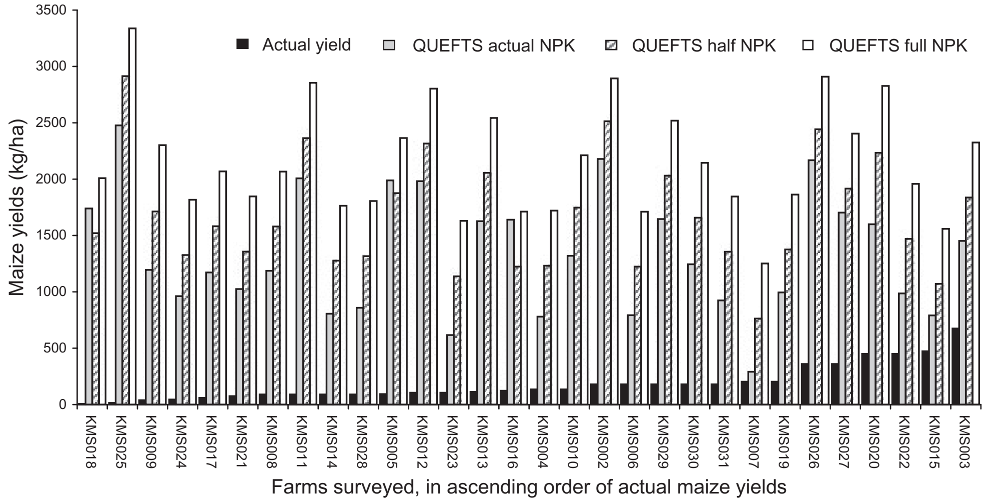

Figure 1. Maize yield gaps in Mbeere district. Comparison, for 30 farms surveyed, of actual maize yields with yields predicted by the QUEFTS model on the basis of: actual NPK used; half the recommended NPK rate; and the full recommended NPK rate.

be attributed to various constraints, which are biophysical or socio-economic in nature. Previous studies in Eastern Kenya have identified low soil fertility, low adoption of recommended varieties and low plant populations to be the main biophysical factors contributing to low maize yields at farm level (Gitari et al. 1996), and limited cash availability within farming households limits the use of essential inputs such as mineral fertilisers for crop production.

The QUEFTS model failed to account for the actual levels of maize yields: QUEFTS-predicted yields were higher than actual maize yields on farms (Figure 1). There were also poor correlations between the actual maize yields and the QUEFTS-predicted yields based on: actual NPK rates (r = –0.039, $p < 0.8$); half the recommended NPK rate (r = +0.029, $p < 0.9$); and the full recommended NPK rate (r = +0.039, $p < 0.8$). The poor correlations suggest that factors other than soil fertility were limiting in the study area, causing actual yields to be lower than QUEFTS yields. QUEFTS was designed to give an estimation of fertility-bound yield, assuming that crop growth is not hampered by other factors such as moisture deficit, waterlogging, restricted root penetration, poor crop husbandry or other yield-reducing factors (Linnemann et al. 1979). Specifically, the QUEFTS model does not consider factors such as water supply, pests, diseases, plant population, varietal choice, weed infestation, sowing time and other crop management practices, despite their importance in determining crop yields at farm level (Bontkes and Wopereis 2003).

Previous studies in semi-arid areas of Kenya have indicated that improved crop yields are obtained when soil fertility and soil moisture are managed in an integrated manner (Kiome 1998). This study has shown that the QUEFTS model alone was not sufficient to explain actual yields, and that soil fertility was therefore not the only factor limiting crop production.

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Similar studies in Benin, West Africa, have also shown that QUEFTS-predicted yields were much higher than, and not correlated with, actual yields obtained by farmers (Mulder 2000). Thus, the determination of crop yields in Mbeere and similar areas may require a general model that takes many factors (including climate and management) into account besides soil fertility.

Farmers' maize yields were spatially variable between farms (Figure 1). The CVs for actual maize yields and for QUEFTS-predicted yields based on actual NPK rates were high, 87% and 40%, respectively. However, the CVs decreased with increasing amounts of NPK in the model, being 30% and 23% for QUEFTS-predicted yields based on half the recommended NPK and the full recommended NPK rate, respectively. The high variability in actual maize yields and in QUEFTS-predicted yields for actual NPK rates is illustrated by the large differences between their minimum and maximum values in Figure 1. Despite this variability, little is yet known about the spatial pattern of yields across fields, or about the temporal stability of this pattern. According to Anderson and Hazell (1989), variability in farm-level cereal yield results from the interaction of many factors: some physical, such as climate, topography and inherent soil fertility; some economic and political, such as prices and access to inputs; and some from the decision-making of farmers themselves, in their choice of production factors and techniques (e.g. fertilisers, pesticides, varieties and mechanisation). In the present study, soil fertility status was variable across study farms (e.g. soil organic C had a CV of 44%).

The yield gap between QUEFTS-predicted attainable yields based on actual NPK rates and farmers' actual yields was large. On average, QUEFTS-predicted attainable yields were 6.6 times the actual maize yields at the fertiliser application rates used by farmers. QUEFTS-predicted yields of maize at the full recommended rate of fertiliser were 29% higher than predicted yields at half the recommended rate, but were still lower than the on-station research yield potential. The QUEFTS-predicted yields of maize at half the recommended rate of fertiliser were about 8 times the actual maize yields. The nutrient-limited maize yields that farmers could achieve with current soil-fertility management practices with optimal water and crop management was about 30% to 80% of the on-station research potential yields. According to Bontkes and Wopereis (2003), the nutrient-limited yield at recommended rates of nutrients, and with optimal water and crop management, is usually about 80% of potential crop yield and can be regarded as the economic yield target: it is not economic to close the remaining gap of 20% of the potential maximum yield (Fairhurst and Witt 2002).

Analysis of temperatures in the study area (Figure 2) showed that the hottest month was January, with a mean temperature of 27.4°C (minimum 26°C, maximum 29°C), and the coolest month was June with a mean temperature of 17.8°C (minimum 17°C, maximum 19°C). The high temperatures in January occur outside the growing season and thus do not pose risks to crop production. Similarly, the coolest temperatures in June do not adversely affect crop production as they occur towards the end of the long rainy period. Furthermore, the coolest temperature was still within the favourable range for most semi-arid crops. The greatest monthly change in mean maximum temperature was between December and January.

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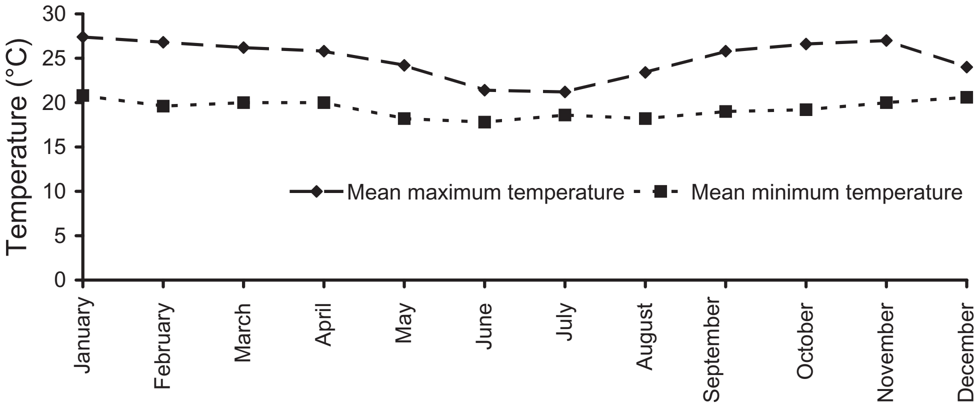

Figure 2. Mean monthly maximum and minimum temperatures (ºC) in the study area (data from BAT weather station, Siakago).

Table 2. Seasonal temperature variability in the study area in 2000–04 (data from BAT weather station, Siakago)

Description		Mean	SD
Long rains:	max. (ºC)	25.4	1.04
	min. (ºC)	19.4	0.72
Short rains:	max. (ºC)	25.9	0.51
	min. (ºC)	19.3	0.60
Annual maximum (ºC)		25.0	0.36
Annual minimum (ºC)		19.3	0.57

Seasonal temperature analysis showed that the mean maximum temperatures during the long rains (March to May) and during the short rains (October to December) were comparable and within favourable ranges of crops grown in the study area (Table 2). This was also true for mean minimum temperatures across the two rainy periods. Thus, temperature variability does not appear to pose any major risk to crop production in the study area.

The productivity indices for maize, beans, cowpeas and sorghum were calculated by setting the yield data for 1980 at 100% and comparing other time-series yield data with this base value (Figure 3). The variability was marked by low yields or crop failure in 1984, 1987, 1992–94, 1996 and 2004. The low crop yields or crop failure coincided to a large extent with regional droughts, which occurred in 1984, 1987–88, 1991–92 and 1996–97, with the most severe taking place in 1984 and 1991–92. These drought events have often been punctuated by occasional periods of excessive rainfall that cause havoc to local economies, affecting all aspects of human life and activities (e.g. the El Niño rains of 1997–98).

The mean annual rainfall for the 25-year period 1980–2004 was 1143 mm, ranging from 479 mm to 1970 mm (Table 3). In the study area, as in other semi-arid parts of Eastern Kenya,

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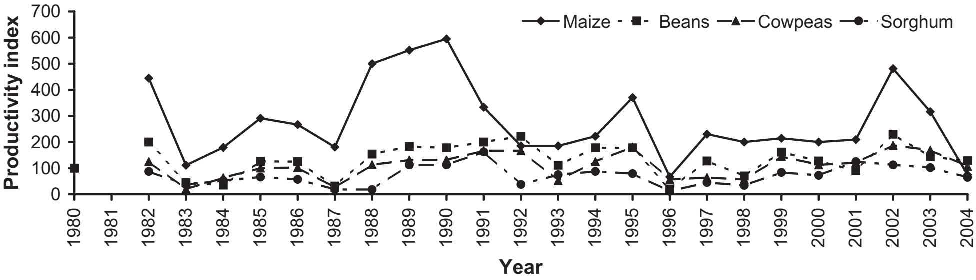

Figure 3. Productivity of food grain crops in Mbeere district during 1980–2004: productivity index calculated from baseline value of 100 for yield of each crop in 1980.

Table 3. Mean annual rainfall (mm) in study area in 25-year period 1980–2004 (data from BAT weather station, Siakago)

Years	Mean	SD	CV (%)	95% confidence interval	
				Lower bound	Upper bound
1980–84	901.51	267.92	29.72	568.84	1234.18
1985–89	1042.51	287.33	27.56	685.75	1399.27
1990–94	1014.16	224.23	22.11	735.75	1292.58
1995–99	1256.81	492.00	39.15	645.91	1867.71
2000–04	1497.80	617.76	41.24	730.75	2264.85
All (25 years)	1142.56	429.75	37.61	965.17	1319.95

severe droughts and near-failure or total failure of crops have been experienced even in periods (1980–92) when annual rainfall ranges from 649 mm to 825 mm (Figure 4). This shows that the mean annual rainfall alone is not adequate to explain the risks posed by rainfall to crop production in these semi-arid areas.

Annual rainfall reliability was estimated from trend analysis of inter-annual rainfall data and CVs of rainfall in 5-year periods during the 25 years (1980–2004) of data studied. There was high variability in rainfall, characterised by high CVs (Table 3), especially in 1995–99 (CV 39.15%) and 2000–04 (CV 41.24%). Such erratic rainfall distribution is a threat to crop production.

It is common experience in marginal rainfall areas that, whereas total annual rainfall may appear adequate for crop production, poor distribution during the growing season may result in highly damaging drought at critical periods of crop growth. Indeed, much of the rain may fall completely outside the growing season in some years.

Monthly rainfall distribution over the 25-year period shows that there is a bi-modal rainfall pattern in the study area: March–May and October–December, with an intermittent period of little to no rain in the months of June to September (Figure 5). The rainy periods in

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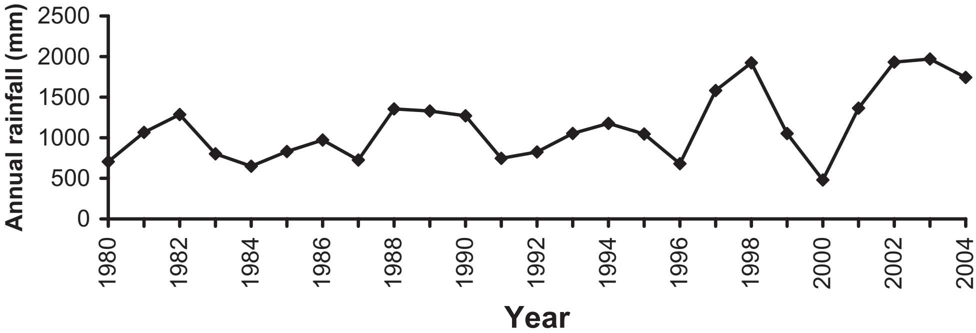

Figure 4. Annual rainfall variability in the study area during 1980–2004 (data from BAT weather station, Siakago).

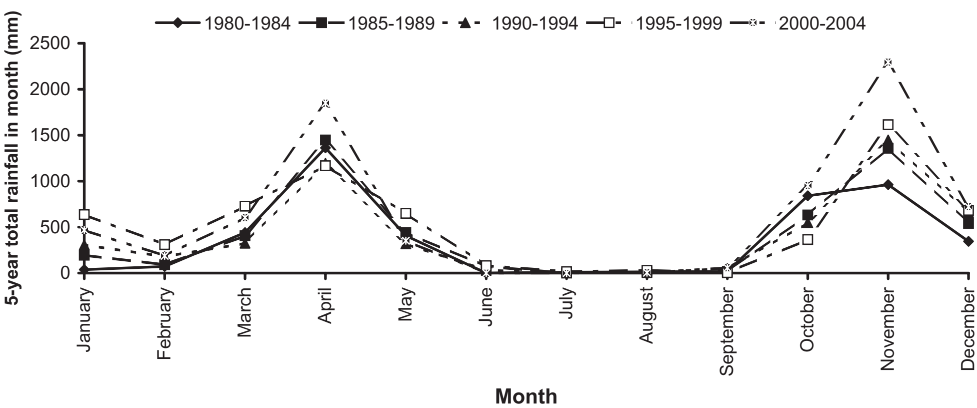

Figure 5. Five-year totals of monthly rainfall in the study area for each 5-year period during 1980–2004 (data from BAT weather station, Siakago).

March–May and October–December are referred to as the long and short rains, respectively, with peak rains in April and November.

The mean monthly rainfall during the long rains ranged from 86.65 mm to 280.96 mm (Table 4), and the corresponding mean monthly rainfall in the short rains ranged from 117.81 mm to 307.08 mm, during the 25-year period for which data were analysed. On the basis of the CVs, monthly rainfall reliability was in the order April ≥ November > December > March > October > May.

Seasonal rainfall distribution showed that the short rains provided, on average, 19% more rainfall than the long rains (Table 5) over the 25-year period: about 90% of the annual rainfall occurred in the two rainy periods, with the short rains contributing 468 mm (41%) and the long rains 552 mm (49%) of the total annual rainfall (1143 mm). The CVs in the two rainy periods ranged from 49% to 92% (long rains) and 50% to 89% (short rains). Owing to this

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Table 4. Mean monthly rainfall distribution in the study area during 1980–2004 (data from BAT weather station, Siakago)

Month	Monthly rainfall			
	Mean (mm)	CV (%)	Min. (mm)	Max. (mm)
January	65.73	186.11	0.00	585.80
February	33.53	161.65	0.00	223.50
March	100.13	86.31	0.00	304.00
April	280.96	49.24	85.40	544.00
May	86.65	92.02	0.00	260.50
June	7.28	212.67	0.00	70.00
July	1.44	243.51	0.00	12.70
August	2.58	176.03	0.00	16.00
September	5.86	152.49	0.00	32.20
October	133.51	89.08	0.00	408.00
November	307.08	49.61	37.50	669.00
December	117.81	71.90	0.00	320.00

Table 5. Mean seasonal rainfall distribution in the study area in the 25-year period 1980–2004, with coefficients of variation and 95% confidence intervals (data from BAT weather station, Siakago)

Years	Long rains (March–May)				Short rains (October–December)			
	Mean (mm)	CV (%)	95% conf. interval		Mean (mm)	CV (%)	95% conf. interval	
			Lower	Upper			Lower	Upper
1980–84	441.96	53.67	147.41	736.51	429.59	37.61	228.97	630.22
1985–89	458.91	20.30	343.25	574.57	506.24	42.08	241.72	770.76
1990–94	367.32	128.18	208.17	526.47	530.92	17.01	418.80	643.04
1995–99	509.12	35.19	286.64	731.60	532.24	59.53	138.82	925.66
2000–04	561.34	59.41	147.23	975.45	793.02	45.87	341.32	1244.72
All years	467.73	43.76	383.25	552.21	558.40	46.65	450.88	665.93

variability in seasonal rainfall, drought periods will occur even when seasonal rainfall averages are high.

Comparison of rainfall and food grain yields over the 25-year period showed that the yields of cereal crops fluctuated and that, in some 5-year periods, they followed the pattern of rainfall (Table 6). For example, maize-grain yields followed the same trends as mean annual rainfall in the first three 5-year periods (1980–94). However, the pattern of maize yields and mean annual rainfall was dissimilar in the period 1995–2004, partly due to the El Niño rains of 1996–97, which destroyed many crops.

Sorghum yield trends did not show any clear relationship with rainfall patterns, indicating that sorghum production could have been affected by other biophysical or management

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Table 6. Mean crop yields (t ha^{-1}) and rainfall (mm) in five consecutive 5-year periods and in the total 25-year period in Mbeere district (CVs as percentages in parentheses)

Period	Maize yield	Bean yield	Cowpea yield	Sorghum yield	Rainfall
1980–84	0.56 (77.15)	0.43 (79.84)	0.37 (59.86)	0.55 (42.71)	901.51 (29.72)
1985–89	0.97 (44.59)	0.56 (45.95)	0.45 (42.90)	0.43 (72.13)	1042.51 (27.56)
1990–94	0.82 (57.05)	0.80 (23.39)	0.62 (36.49)	0.76 (48.88)	1014.16 (22.11)
1995–99	0.58 (49.88)	0.50 (58.95)	0.48 (58.23)	0.40 (60.70)	1256.81 (39.15)
2000–04	0.69 (59.28)	0.65 (36.19)	0.67 (26.12)	0.76 (27.26)	1497.80 (41.24)
All years	0.73 (55.12)	0.59 (45.93)	0.52 (43.85)	0.58 (51.94)	1142.56 (37.61)

factors besides rainfall. The yields of grain legumes (cowpeas and field beans) followed a similar trend to that of rainfall, except during the period 1995–99, in which El Niño rains lowered crop production due to high rainfall intensity and the farmers' poor response to the excessive rains.

A significant relationship was found between maize yields (Y) and mean annual rainfall (X) during the period 1985–89 ($Y = 0.0014X - 0.5396$, $R^2 = 0.93$, $p < 0.01$). However, for the period 1980–84, the relationship was not significant at 5% ($Y = 0.0014X - 0.6209$, $R^2 = 0.85$, $p < 0.10$). Similarly, the relationships between bean yields and mean annual rainfall for the periods 1980–84 ($Y = 0.0011X - 0.4834$, $R^2 = 0.81$, $p < 0.1$) and 1985–89 ($Y = 0.001X - 0.2256$, $R^2 = 0.71$, $p < 0.1$) were not significant at 5%. For the other 5-year periods studied, the relationships between maize or bean yields and mean annual rainfall were not significant ($p > 0.1$). The coefficients of determination (R^2) indicate the proportions of variation in crop yields (Y) accounted for by rainfall (X): thus, in 1980–84, rainfall accounted for 85% of the variation in maize yields. The result for maize in 1985–89, significant at 1%, indicates that, at least in some years, maize yield trends were explained by mean annual rainfall, but other causative factors not identified in the study appear to have been more important in the other years.

For the 25-year period, the amount of rainfall during the short rains was found to be the strongest predictor of cowpea and bean yields. The relationship between cowpea yield and rainfall in the short rains was $Y = 0.0004X + 0.3157$ ($R^2 = 0.08$, $p < 0.05$), and for beans the relationship was $Y = 0.0005X + 0.3189$ ($R^2 = 0.08$, $p < 0.05$). Thus, the short rains were a major determinant of cowpea and bean yields in the study area. The short rains were also more reliable for growing these crops than the long rains: the relationships between yields (of both cowpeas and beans) and rainfall during the long rains were not significant ($p > 10\%$).

Using time-series data, this study has shown that grain yields of staple food crops (maize, sorghum, beans and cowpeas) at farm level were highly variable in time and space, and were suboptimal. The low yields and their variability, exemplified by the large yield gaps observed in this study, challenge the sustainability of these farming systems. Addressing this scenario will require a holistic approach that simultaneously determines yield-reducing factors and

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assesses sources of variation of grain yields – such as technological options (agronomic practices and cultivars), soil moisture, policy and economic factors, and the interactions among them – for effective identification of interventions that will enhance progress towards agricultural sustainability.

The study showed that the QUEFTS soil-fertility model was insufficient to explain farmers' actual yields, and that other factors not accounted for in the model could have played a role. Thus, soil fertility was not the only limiting factor for crop production in the study area. The QUEFTS model did not account for a number of factors, including soil moisture and rainfall, which are as important as soil nutrients in semi-arid areas. A crop-growth model that takes other major factors influencing crop production into account would thus be more appropriate for simulating yields in the study area and for enhancing understanding of spatial and temporal variability of crop yields.

Evidence from this study has shown that particular aspects of rainfall are more important than mean annual rainfall levels in determining crop yields in such semi-arid areas. Mean rainfall was a determinant of maize yields in only one out of the five 5-year periods of analysis, clearly indicating that other factors not identified in the study were important. Aspects of rainfall found to be important in determining crop yields were its seasonality and distribution. For example, the amount of rainfall received during the short rains was a better determinant of cowpea and bean yields than that received during the long rains.

Spatial and temporal variability and unreliability were the most important features of rainfall behaviour in the period 1980–2004, partly explaining the poor and fluctuating crop yields and the threat to agricultural sustainability. However, the fact that the relationship between rainfall and crop production was not clear from this 25-year analysis suggests that factors other than rainfall and soil fertility play a substantial part in determining crop yield, and that such factors need to be examined in future studies, using long-term data. High rainfall variability also presents other constraints and concerns that need to be addressed by the agricultural research and policy-making community. Prominent among these concerns are increased income risks, which may make new technologies less attractive to farmers and hence slow the pace of progress towards agricultural growth and sustainability.

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