Environmental Management
https://doi.org/10.1007/s00267-022-01592-0

The Influence of Soil Organic Carbon and Climate Variability on Crop Yields in Kongwa District, Tanzania

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Received: 13 May 2021 / Accepted: 1 January 2022

Abstract

This study assessed the influence of soil organic carbon (SOC) accumulation and climate variability on crop yields in Kongwa District, central Tanzania. In doing so, climate data and soil samples were collected from Mnyakongo and Ugogoni villages through soil sampling, interviews and surveys. Walkley–Black method, Mann–Kendall test, and MS Excel were used to analyze SOC, climate, crop yields respectively. The results exhibited that the accumulation of SOC was significantly greater in soils under organic fertilization (1.15 and 0.80 MgC ha^{-1} at soil 0–20 cm and 20–30 cm depth) than under no-fertilization (0.35 and 0.30 MgC ha^{-1} at 0–20 cm and 20–30 cm) and decreased with increasing soil depths. Under these two soil treatments, the average yields for maize, sorghum and millet were almost 1.8 tn ha^{-1} under organic fertilization and 0.6 tn ha^{-1} under no-fertilization. Specifically, maize yields ranged from 1.5 to 2.2 tn ha^{-1}, while both sorghum and millet had 1.1–1.7 tn ha^{-1}. Therefore, yields were significantly higher under organic fertilizations than under no-fertilizations. Besides, the mean annual rainfall or temperature (1980–2020) fluctuated at a decreasing ($R^2 = 0.21$) or an increasing trend ($R^2 = 0.30$). Comparatively, the yields for maize, sorghum or millet fluctuated at a decreasing trend at $R^2 = 0.07$, 0.05, or 0.85, respectively. Correspondingly, it was found that the temporal increase in rainfall and temperature had positive (R^2 ~0.5) and negative (R^2 ~0.3) correlations with crop yields, respectively. In contrast, the decline in rain's intensity and frequency had negative impacts on crop yields. Thus, both SOC and climate correlated with crop yields.

Keywords Agroecosystems · Climate · Fertilization · Semi-arid areas · SOC · Tanzania

Introduction

There is substantial evidence that the mean and extremes of climate variables have been changing in recent decades, and this trend can intensify in the coming decades (IPCC 2014). Most climate models project that most parts of Africa, and particularly East Africa will experience considerable climatic changes and this will be more pronounced in most subtropical regions, with slight increments in precipitation in the tropics (Paavola 2008; Ericksen et al. 2011; Rowhani et al. 2011; IPCC 2012, 2014; Mwongera et al. 2014).

This climate trend has brought significant impacts to agricultural production in most developing countries (IPCC 2012, 2014). These impacts are amplified by low fertility in the soil and poor agronomic practices. Crop yields in most semi-arid areas of Tanzania are significantly low due to the combination of these factors (Mkonda 2011; Mkonda and He 2018a). Under such a situation, most semi-arid zones experience frequent food insecurity and abject poverty. As a way of limiting this deficit, some extension and agricultural officers have examined the better way of improving the existing farming systems i.e., cropping, livestock keeping and agro-pastoralism though this has not yet been more fruitful.

Most smallholder farmers in most rural areas are subjected to lengthy environmental stresses that subsequently affect the livelihoods (Ahmed et al. 2011; Mkonda and He 2018b). Most of these stresses are results of climate change impacts. Under global climate change scenario, there has been an increased need to integrate numerous ecological

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aspects such as soil amendment, moisture conservation and proper agronomic practices, just to mention a few, to optimize nutrient cycling, and adapt climate change impacts (Rowhani et al. 2011). This aspect is the main component of soil organic matter and inorganic carbon. Soil organic matter is formed by elemental carbon such as coal, charcoal, and graphite while inorganic carbon is composed of carbonate minerals, such as calcite and dolomite. Its deposit exists in thousand of 1000 s Pg around the world. The accumulation understudy is mainly attributed by soil organic management i.e., organic fertilization (Batjes 1992; Sombroek et al. 1993). Lal (2008) clarified that despite climates and vegetation having a significant ($p < 0.05$) contribution to SOC accumulation at a global level, soil organic management is prominent in doing so at the farm level. Besides, soil depth has a significant influence on SOC accumulation in various agroecology (Wang et al. 2010). However, the results from quantum calculation of SOC may have spatial and temporal variation (Nelson and Sommers 1982; Johannes et al. 2017). Among other things, this variation is caused by land use change and other natural factors.

Besides, Ahmed et al. (2011) found that rainfall has significantly decreased in Tanzania especially in recent years and is further expected to decrease by the mid of this century. In addition, Challinor et al. (2007), cautioned that; the increasing trend of climate mate will exacerbate the vulnerability of the rain-fed agriculture. As a response, Lobell and Burke (2008) and Mkonda and He (2018c) realized the importance of studying and proposing ways of reducing the vulnerability among the rural communities in most developing countries, because their livelihoods depend on rain-fed agriculture. Similarly, this vulnerability has implications for agricultural production and the ecosystem services in the area as farmers may continue degrading the environmental resources as a way of coping with, and adaptation to associated challenge (Mkonda et al. 2018).

Moreover, there is considerable literature which examine the effects of climate change on agriculture and environment in most developing countries. In Tanzania for instance, the National Adaptation Plan of Action and Tanzanians National Strategy for Growth and Reduction of Poverty; recognized droughts and floods as amongst the primary threats to agricultural productivity and vulnerability

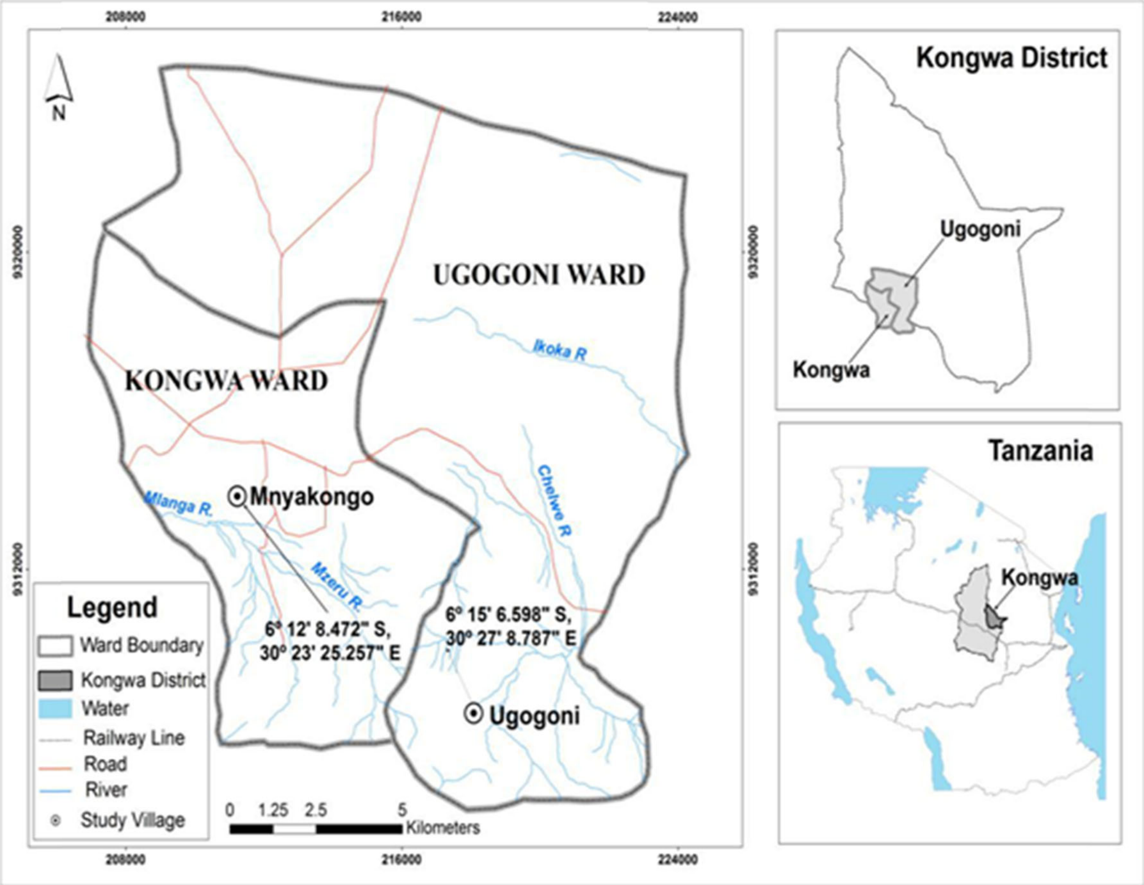

Fig. 1 A study area

intensification in the country (URT 2007). Correspondingly, Paavola (2008), Rowhani et al. (2011) and Mkonda and He (2017a) confirmed on the decreasing rainfall and insisted that this scenario has significant implications for crop yields.

While the science of identifying changes in yields, SOC and climate change impacts is progressing fast, there are still a variety of knowledge gaps. Most studies have established the mentioned aspects independently, and not collectively. Principally, this paper aims at assessing the accumulation of SOC and its correlation with crops yields, as well as establishing the trends of climate variability and that of crop yields in the semi-arid agroecological zone of Tanzania. Further, it aims to intensify the adaptation measures that would increase crop yields in the area. This is going to strengthen the knowledge posed by different scientist (Rossi 2009; Usuga et al. 2010; Batjes 2011; Araujo et al. 2017).

Materials and Methods

This study was carried out in the Kongwa District, the semi-arid zone of Central Tanzania between June and September, 2020 (Fig. 1). The elevation of the District ranges 900–1000 m above sea level and it is located on the leeward side of Ukaguru Mountains. It is located between latitude 5° 30’ to 6°0′S and longitude 36° 15′ to 36°E, with an area of about 4041 km^2. The vegetation type of Central Tanzania is of bush or thicket. Total annual precipitation in the area is 400–600 mm with a maximum of rain between December and April and mean annual temperature is 26 °C. According to World Reference Base for Soil Resources, the soils are classified as Chromic Luvisols (FAO 1988), with a sandy loam texture. The silt contents of the soils at the different farms were not significantly different ($p > 0.05$) and ranged between 170 and 255 g kg^{-1} soil with a bulk density between 1.25 and 1.65 Mg m^{-3}. The soils are neutral to alkaline pH values, medium levels of organic C, N, P, K and trace soil elements. It has moderately high cation exchange capacity and high base saturation.

In this study, different research methods were employed to collect both quantitative and qualitative data from primary and secondary sources. Both purposive and random sampling techniques were employed to select samples and locations (Cramb et al. 2004). The research employed numerous approaches to collect the required data. It involved field soil sampling, household surveys, interviews, discussion, physical observations, solicitation of secondary data from the Ministry of Agriculture, Livestock and Fisheries, and Tanzania Meteorological Agency. For more details, see Table 1.

Table 1 Summary of questionnaires administration and PRAs tools in the selected villages

	Mnyakongo Total HH (2050)	Ugogoni Total HH (2080)
Questionnaires ($n = 400$)		
Number of households interviewed	200	200
Crop farmers (%)	70	80
Livestock farmers (%)	10	10
Both crop and livestock farmers (%)	20	10
Focus group discussion ($n = 30$)		
Number of people participating in group		
Discussion	15	15
Crop farmers	12	10
Livestock farmers	0	2
Both crop and livestock farmers	3	3
Interview ($n = 20$)		
Number of people participating in		
Informative interviews	10	10
Crop farmers	8	9
Livestock farmers	0	0
Both crop and livestock farmers	2	1

Source: Field Data Survey

PRA participatory rural appraisal, *HH* household heads, *n* sample

Soil samples were collected in July 2020 from the established pits in Mnyakongo and Ugogoni villages. Soil was sampled according to standard guidelines for soil description. In each village (site) we established two treatments (i.e., farm under organic fertilization, and with no-fertilization) each with two soil depths/profiles (0–20 and 20–40 cm), whereas for each profile the field to establish four soil ditches was randomly selected ($W \times L \times D = 40 \times 50 \times 40$ cm). Then, using a 150 ml volumetric soil sampler (6 cm diameter and 5.3 cm height) four soil cores in each established ditch as seen in Table 2 was sampled. In this respect, volume-specific samples at 5-cm-increments were collected in each soil profile without mixing horizons.

Soil analyses were done at the Department of Soil Sciences and Geological Studies at Sokoine University of Agriculture. The Walkley–Black method was used for SOC analyses. Statistically, the data were presented as the arithmetic means of two replicates plus standard deviations. The variables were tested for homogeneity of variance and normality, and where necessary, the data were transformed prior to analysis.

Yields data from the Ministry of Agriculture and those collected in the study area (i.e., from respondents) were parameterized, compared and averaged to acquire a reliable and representative data package. Quantitative data for rainfall and temperature were analyzed using Mann–Kendall test (at 95% level of confidence), while the yields for maize, sorghum and millet were analyzed through MS Excel. Subsequently, the Pearson's moment correlation coefficient two-tailed test and regression analyses were used to compare the trends of rainfall and temperature variability versus crop yields, and extrapolation of the future correlations. p values <0.05 were supposed to be statistically significant ($p < 0.05$). Qualitative data were analyzed through theme content analysis.

Results

SOC Accumulation and Crop Yields

The results of the present study showed that SOC accumulation was more significant in soils under organic fertilization (1.15 and 0.80 MgC ha^{-1} at both depths soil 0–20 cm and 20–30 cm) than the areas under no-fertilization or soil amendments (0.35 and 0.30 MgC ha^{-1} at 0–20 cm and 20–30 cm). In addition, the SOC accumulation decreased with increasing soil depths as seen in Table 3.

Similarly, there were significant differences ($p < 0.05$) in yields among these diverse soil treatments. Generally, the normal yields for maize, sorghum and millet were about 1.8 tn ha^{-1} under organic fertilization and 0.6 tn ha^{-1} under no-fertilization. Explicitly, yields for maize fluctuated from 1.5 to 2.2 tn ha^{-1} while that of sorghum and millet were around 1.1–1.7 tn ha^{-1}. Overall, the areas with organic fertilization had more yields than those under no-fertilizations as seen in Table 4, and the different was significant.

Table 2 Soil sampling per villages (sites)

Treatment	Depth (cm)	No. of samples (Ug)	No. of samples (Mn)
Organic fertilization	0–20	16	16
	20–40	16	16
No fertilization	0–20	16	16
	20–40	16	16
Total	64	64	Grand total = 128

Source: Field Soil Sampling (2020)

Ug Ugogoni, *Mn* Mnyakongo

Observed Temperature and Rainfall, and Crops Yields

The results in Fig. 2 exhibit that there has been a temporal slight decrease in rains (A) while experiencing an increase in temperature on time basis (B). These aspects explore the overall information on the ground about climate and later, pose significant effect to crop production in the area as seen in Figs. 3 and 4, respectively.

As well, the mean annual rainfall or temperature (1980–2020) varied at a decreasing ($R^2 = 0.21$) or an increasing trend ($R^2 = 0.30$) as seen in Fig. 2. This trend was supported by the findings from the farmers in the study area as seen in Table 5.

Relatively, the yields for these crops (maize, sorghum, or millet) varied at a decreasing trend at $R^2 = 0.07$, 0.05, or 0.85, respectively. Consistently, it was also found that the temporal increase in rainfall and temperature experienced positive ($R^2 \sim 0.5$) and negative ($R^2 \sim 0.3$) correlations with crop yields, respectively (as seen in Figs. 3 and 4). In contrast, the decline in rains intensity and frequency had negative impacts on crop yields. Eventually, the yield decline had negative impacts on food security in the study region and the country (Tanzania) at large.

Discussion

This study has demonstrated how SOC is accumulated under different soil managements. It has revealed how organic fertilizations had a significant contribution to SOC accumulation ($p < 0.05$). In this regards, the accumulation of SOC was higher at 0–20 cm in both soils under organic and no-fertilizations (Lal 2008). Apparently, SOC were higher under organic fertilizations than under no-fertilizations. This implies that soil organic amendments optimize crop yields and thus, it can be recommended for use especially under climate change scenarios and in arid and semi-arid conditions of Tanzania.

Table 3 Analyses result of soil samples from the study area

Field ref.	Depth (cm)	No. Samp	TN-Kjeld (%)	OC-BlkW (%)	Ext.P (mg/kg) PBry-1	CEC (cmolKg) CEC
Org. Fertil.	0–20	32	0.40	1.15	2.40	36
Org. Fertil.	20–40	32	0.16	0.81	2.10	28
No. Fertil.	0–20	32	0.05	0.35	0.14	34
No. Fertil.	20–40	32	0.03	0.30	0.07	24

Source: Lab soil = analyses at Sokoine University of Agriculture (2020)

Samp. sampling, *Org. Fertil.* organic fertilization, *No. Fertil.* no fertilization

Table 4 Correlation (r) between average crop yields (tn ha^{-1}) and soil treatments in the sampled villages

Year	Organic fertilization					No-fertilization		
	Maize	Sorghum	Millet	r^2	Maize	Sorghum	Millet	r^2
2014	1.5	1.1	1.1	0.35	0.4	0.6	0.5	0.27
2015	1.6	1.2	1.1	0.37	0.4	0.6	0.5	0.27
2016	1.7	1.5	1.4	0.42	0.8	0.5	0.5	0.29
2017	1.6	1.4	1.6	0.51	0.5	0.5	0.5	0.18
2018	2.2	1.7	1.6	0.56	0.6	0.6	0.6	0.23
2019	2.1	1.6	1.6	0.58	0.6	0.5	0.5	0.25
2020	2.2	1.7	1.6	0.63	0.6	0.7	0.7	0.27

Source: Field Data Analysis (2020)

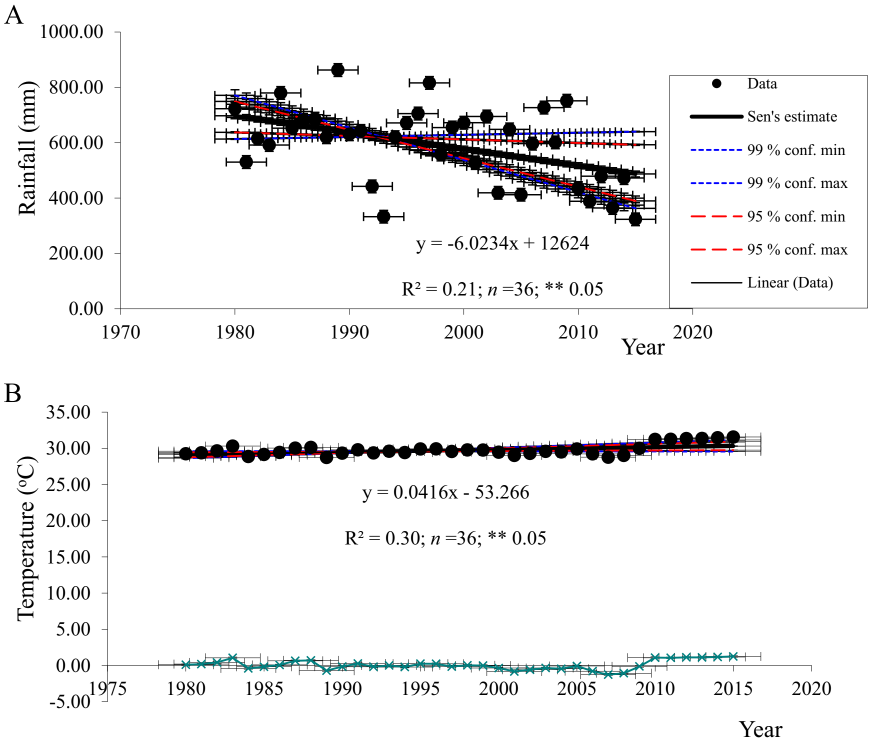

Fig. 2 Trend of total annual rainfall (**A**) and mean annual temperature (**B**) in the study area. Source: Field Survey Data (2020)

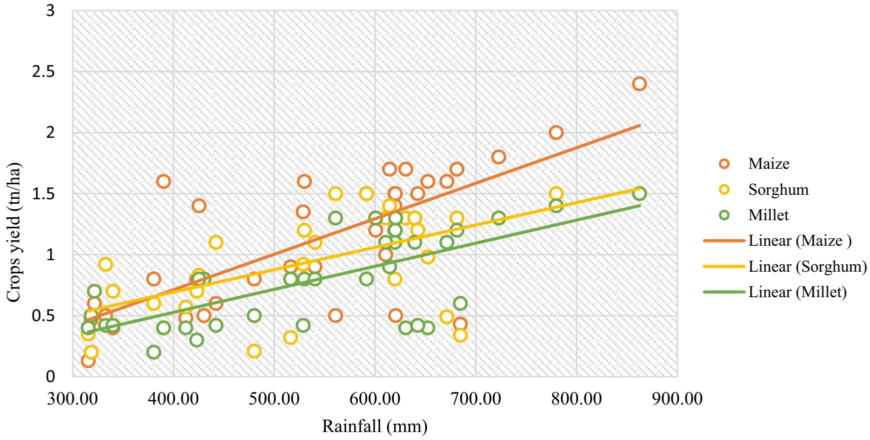

Fig. 3 Correlation between rainfall and crop yields in the study area. Source: Field Survey Data (2020)

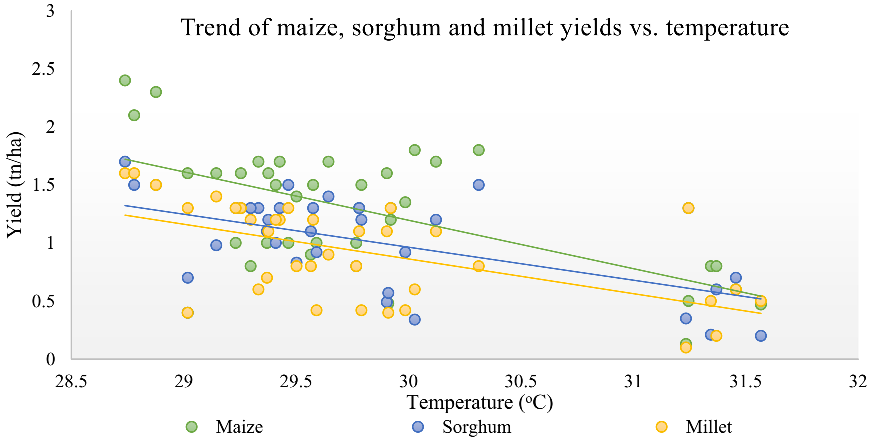

Fig. 4 Correlation between temperature and crop yields in the study area. Source: Field Survey Data (2020)

Table 5 Impacts of climate change (in percent) to a specific crop yields

Crop	Mnyakongo ($n = 200$)	Ugogoni ($n = 200$)
Maize	90 (very severe)	85 (Very severe)
Millet	60 (Severe)	65 (Severe)
Sorghum	50 (Moderate)	40 (Slight)

Source: Field Data Survey (2020)

These findings advance knowledge on that of other studies conducted in different agroecological zones such as plateau, arid and alluvial just to mention a few (Bationo et al. 2006; Batjes 2011). In addition, Baker et al. (2007) and Baldock (2007) found that the accumulation of organic matter in the soil has significant contribution to yields optimization. Other studies conducted in similar agroecological zones with the present study had more less similar findings. For instance, the study by Ngwira et al. (2014) revealed that; conservation agriculture practices among smallholder farmers in Malawi was predominantly adopted for yield optimization and biodiversity conservation in various agroecological zones.

However, these studies focused much on the amendments and utilization of the top soils, while the present study went further by assessing nutrient availability in various soil profiles from the top to beneath layers (i.e., 20 cm, 40 cm, etc.) as a results of soil organic amendments. The findings of the present study were also supported by the District Agricultural and Livestock Officer of Kongwa who asserted that "In our district we practically advice farmers to till the soil at least to 30 cm deep and add some organic manure for soil fertility optimization and biological conservation".

Besides, this study found that climate change has been widely depicted on the ground. For instance, from 1980 to 2020 temperature has been fluctuating at an increasing trend contrary to rainfall which has been fluctuating at a decreasing trend (Rowhani et al. 2011; Mkonda and He 2018b). These findings are in line with those of global perspectives and local conditions in various areas of Tanzania (Ahmed et al. 2011; Rowhani et al. 2011; Mtengeti et al. 2015). Unfortunately, the change in weather patterns and climate especially rainfall and temperature has mainly brought negative impacts to agricultural production and biodiversity conservation.

On the other hand, the study revealed that the trends of maize, sorghum and millet yield have been behaving like that of rainfall (Fig. 3). This indicates that there has been significant correlations between these variables (Ahmed et al. 2011; Rowhani et al. 2011). The influence of climate in SOC accumulation was also revealed as high rainfall and moderate temperature influenced the production of biomass, organic matter and SOC. Generally, climate has influence on crop yields and SOC and vice versa. This finding was also supported by the Kongwa District Agricultural and Livestock Officer who asserted that: "Agricultural ecosystems of our district is seriously affected by prolonged droughts and soil exhaustion".

Besides, there were significant variations in crop yields among maize, sorghum and millet in the study area ($p < 0.05$). Maize had high yields (in ton per hectare) compared to sorghum and millet (Fig. 5), but in all crops, there were significant yields fluctuation. Here, about all the crops experienced optimal yields from 1980 to 2020, while meager yields were observed from 1997 to 2000 and 2011 to 2018 (Table 4). The yields trend of these crops are affected by climate change impacts and other agroecological factors as seen in Figs. 3 and 4.

These results add significant knowledge to those established by Challinor et al. (2014), Hertel et al. (2010) and Rao et al. (2011) which established the correlations of yields and climate using a single crop. Besides, the results of the present study are in line with those by Speranza et al. (2009) which also established these kind of correlations in semi-arid agroecological zone.

To increase the yields of maize, sorghum and millet, we need to enable smallholder farmers to adopt compelling

Fig. 5 Crop yields in ton per hectare in study area from 1980 to 2020. Source: Field Survey Data (2020)

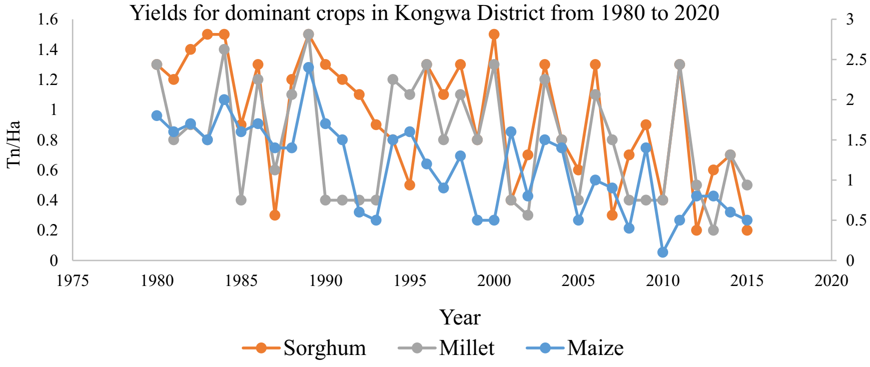

Table 6 The existing adaptation and mitigation measures in the study area (in percentage)

Adaptation activities	Mnyakongo ($n = 200$)	Ugogoni ($n = 200$)	Average ($n = 400$)
Early planting	72	54	63.0
Adopting resistant crop cultivars	55	50	52.5
Mulching	35	43	39.0
Agroforestry	23	25	24.0
Crop rotation	35	30	32.5
Small scale irrigation	10	8	9.0
Fallowing	42	48	45.0
Afforestation	20	15	17.5
Transformative adaptation	21	23	22.0
Conservation of water sources	25	20	22.5

Source: Field Data Survey (2020)

adaptation measures that will even enhance their resilience to climate change impacts (Challinor et al. 2014; Mkonda and He 2017b). Table 6 indicates the general adaptation measures in the study area. These findings are in line with those by Agrawala et al. (2003) and Adger (2006) who revealed that most parts of Tanzania are vulnerable to climate change and thus, suggested various adaptation and mitigation measures to be in place.

Increased irrigation, adoption of drought resistant crop varieties and soil fertilizations (organic and inorganic) are among the reliable adaptation measures to limit the impacts of climate change (Speranza et al. 2009; Challinor et al. 2014). These would increase crop yields, increase food security and alleviate poverty (Paavola 2008; Ericksen et al. 2011). The use of improved seed like TMV-1, Stuka M1, Staha, TAN 250 and Kilima (for Maize) should be applied. Similarly, Macia for sorghum and Bulrush for millet are the resilient cultivars that should be equally adopted. These findings are in line with those by Lobell et al. (2008) and Luo (2011) who revealed more less similar findings.

Furthermore, seeds genoplasms should be well-engineered to get the most tolerant seeds that can withstand the increasing climatic stresses. Despite the significant influence of rainfall and temperature on maize, sorghum and millet yields; the influence of non-climatic factors such as soil management, agronomic practices, labor and capital, just to mention a few, could not be underrated (Lal 2008; Mwongera et al. 2014; Johannes et al. 2017; Mkonda and He 2018a). Among these, soil fertility was degraded by continuous cultivation without fertilization. This situation affected other biological functions of the soils.

Thus, poor soil fertility brought about poor yields and environmental services (Challinor et al. 2007; Mkonda and He 2018b). Given the community vulnerability due to climate change impacts, this study calls for more proactive action interventions to curb the problem (Kalhapure et al. 2013; Mkonda and He 2018c). For instance, agroforestry (afforestation) that is tenable for yields optimization and acts as Clean Development Mechanism to attempt an important goal of the Kyoto Protocol of 1997.

Thus, among other things, the present study serves as a baseline for future studies. It has revealed that there were significant correlations between the accumulation of SOC and soil managements, and climate with crop yields. To support this assertion, Kalhapure et al. (2013) and Nyadzi et al. (2006) confirmed that soil organic management increases the amount of soil mineralization more especially soil C, and therefore, increasing soil fertility and C sequestration.

Therefore, based on the findings of this study, it is worthwhile to advise farmers to adopt organic fertilization in their farming because of the attached potentials more especially increasing yields to curb frequent food shortages in most semi-arid of sub-Sahara Africa. This is more sensible under the auspices of climate change scenarios.

Conclusions

SOC and climate form better agroecology that can influence crop production in various agro-ecolocal zones of Tanzania and other countries. These aspects need to be plenty in the area in order to support agriculture sector in a particular country. Based on this study, the area with plenty SOC, and favorable rains and temperature had better yields than the areas without them. Therefore, it is envisaged that; building and enhancing the resilience of the vulnerable communities in most agroecological zones is inevitable when reducing, and adapting to climate change impacts. Since adaptation measures should base on the local context, there is a need to pilot and upscale the most suitable adaptation measures in a wider perspective. Specifically, there is a need to harness the irrigation potentials in the area, improve organic fertilization, and adoption of drought resistant seeds. This would significantly increase crop yields among the farmers. Lastly, the findings of this study open prospects for further researches to be conducted on the adaptations to climate change impacts in other agroecological zones, and countries.

Acknowledgements This work was supported by the College of Resources and Environment, Southwest University, China through the Ph.D. Research Grant funded by China Scholar Council International Ph.D. Program.

Compliance with Ethical Standards

Conflict of Interest The authors declare no competing interests.

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