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Reducing Climate Risks by Improving Food Production and Value Chains: A Case of Sandy Soils in Semi-arid Kenya

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Due to climate change and variability, extreme weather events are becoming more frequent worldwide, causing significant reductions in agricultural production and food security. The livelihoods of smallholder farmers, especially those eking out a living by farming on sandy soils, are particularly affected. We examined this issue using the case of Makueni County, a semi-arid area with sandy soils in south-eastern Kenya. Using survey data from 202 households, we examined extreme weather events affecting smallholder farmers and current management strategies used to mitigate the consequences. We then performed field experiments to assess potential gains of implementing sub-surface water retention technology (SWRT) in the region. Finally, we held group discussions with stakeholders in food value chains (FVC) to identify ways of managing climate risks to smallholder farmers. Analysis of the survey data showed that 199 of 202 farmers surveyed had experienced an extreme event associated with climate change and variability during the previous five years. Of these 199 farmers, 161 reported having changed their farming practices to adapt, especially to drought (70%) and increased temperature (22%). Common adaptation practices included early planting, reducing the area under cultivation, and water harvesting. In the field experiments, using SWRT resulted in a 50, 100, 150, and 170% increase in maize grain yield, cob numbers, cob weight, and maize stover biomass, respectively, compared with the control (without SWRT). Stakeholder group discussions along the FVC demonstrated a need for synergy among actors to mitigate climate risks caused by extreme weather events. These findings suggest that diversification of management strategies at farm level, combined with external inputs (new technologies, improved seeds, etc.) and services (credit access, learning from peers and professionals), will be instrumental in reducing future climate risks to smallholder farmers. Improving access to viable markets and fostering mutually beneficial linkages with post-harvest processors would add value to farm produce, thus further increasing income and the capacity of smallholder farmers to manage climate risks.

Keywords: climate risks, food value chains, sandy soil, semi-arid region, Makueni

INTRODUCTION

Globally, climate change and variability are increasing the frequency of extreme weather events and negatively impacting livelihoods in rural communities. The vulnerability of communities to extreme weather events depends on their socio-economic and environmental conditions. Climate change and variability are affecting entire global food value chains (FVC) (Havemann, 2016), with particular impacts and risks for smallholder farmers living in regions with limited capacity to adapt (Asfaw et al., 2018). The negative impacts of climate change on livelihoods are more severe in such regions because agricultural yields on smallholder farms are generally low and farmers have insufficient income to finance climate adaptation measures, such as diversification of production. Managing climate risks in agri-food systems requires the use of holistic strategies and tactics that can solve productivity, socio-economic, and environmental challenges, creating a need for multi-sector interventions (Negra et al., 2020). Strategies for climate risk reduction that can be implemented at farm level include crop diversification, labor diversification among household members or across seasons, and diversification of income sources. However, in regions where smallholder agriculture is the main activity, developing a sustainable FVC with diverse sources of income will require appropriate economic and policy support. Besides the need to promote products and diversified crop types and varieties, policymakers need to facilitate introduction of critical networking infrastructure, including physical, digital, and social platforms. Such measures to mitigate climate risks will require appropriate institutional, economic, and technical support.

In arid and semi-arid regions, drought and aridity are standard factors causing loss of crops, livestock, and vegetation cover, with severe consequences for humans and livestock (Cyrilo and Mung'ong'o, 2020). Communities in these areas are accustomed to frequent total crop failure, reduced yield, and diets of low diversity (i.e., a narrow range of available foods), which affect their well-being through food insecurity and health problems. The situation is further exacerbated by lack of financial capital to invest in better farming technologies (or inputs) and lack of adequate extension services (Jellason et al., 2021). To break the vicious cycle of low inputs, low productivity, and low quality of life, efforts are needed to promote climate-smart agricultural techniques that can increase agricultural productivity and incomes, despite recurrent extreme weather events caused by climate change and variability (Lipper et al., 2015, 2018). Cost-benefit analyses of climate-smart agriculture technologies that increase productivity show that most of these technologies can be scaled up (Ng'ang'a et al., 2021). However, scaling up will require creation of enabling environments, through (i) active engagement of value chain stakeholders, (ii) information and communication technologies and agro-advisory services, and (iii) policymaker engagement (Westermann et al., 2018). One of the technologies proposed for soil water and nutrient management in arid and semi-arid regions is sub-surface water retention technology (SWRT) (Nkurunziza et al., 2019). Enabling factors (or non-technical barriers to overcome) for successful diffusion of this technology include reducing and financing initial investment costs, creative public-private partnerships, etc.

Developing sustainable and inclusive FVC for agricultural commodities is crucial to managing and spreading climate risks for smallholder farming communities. In essence, inclusive value chains empower smallholder households to benefit from their produce by connecting them to viable markets and maximizing returns. However, attempts to achieve empowerment of smallholder households through improved market connections and value chain development have failed in many instances (Lamboll et al., 2015; Ros-Tonen et al., 2019; Doherty and Kittipanya-Ngam, 2021). The key factors in increasing sustainability in smallholder-based value chains include financial and policy support to incentivize critical investments and management actions among smallholder farmers with limited resources. Lack of such incentivizing mechanisms can lead to limited production, resulting in lack of end-products to meet consumer demands. Another issue is that the plans and processes of current food systems, from farm to fork, are based on normal climate conditions. However, with climate risks associated with extreme weather events, sustainable and inclusive value chains for common crops (e.g., maize) or high-value crops (e.g., vegetables) need to be rethought.

In this study, we selected Makueni County, a semi-arid area with sandy soils in Kenya, as a case in order to pursue three research objectives. First, using survey data from 202 households, we examined extreme weather events that affect smallholder farmers and the current management strategies used to mitigate the consequences. Second, we conducted field experiments to assess the potential gains of implementing SWRT in the region. Third, we held group discussions with stakeholders in FVC to identify ways and means of managing climate risks.

MATERIALS AND METHODS

Study Area

This study was conducted in Mukange, Kambu, Kiteng'ei, and Kathekani wards in Makueni County (1°35′-3°00′S; 37°10′-38°30′E) in south-eastern Kenya (**Figure 1**). The average population density in Makueni County is 125 people per km^2. However, the population density varies, depending on the agricultural potential of the local land, from 63 people per km^2 in the infertile lowland areas in Kibwezi to 284 people

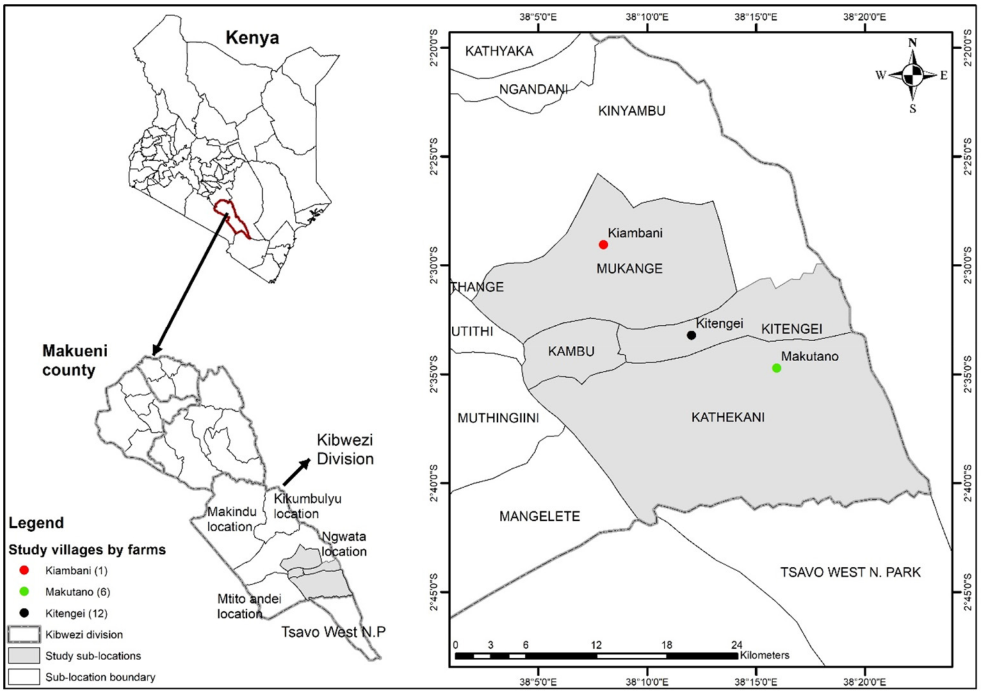

FIGURE 1 | Maps of Makueni County, south-eastern Kenya, showing the location of **(left)** study sub-locations in the county (shaded area) and **(right)** on-farm experiments (colored dots) in Kiambani, Kitengei, and Makutano.

TABLE 1 | Long-term average rainfall (1961–2012) and short-term (2015–2019) average annual rainfall and temperature in the two main growing seasons in Makueni: March, April, and May (MAM) and October, November, and December (OND).

Growing season	**Rainfall (mm)**						**Temperature (°C)**				
Season	**1961–2012**	**2015**	**2016**	**2017**	**2018**	**2019**	**2015**	**2016**	**2017**	**2018**	**2019**
MAM	280	318	247	155	560	139	26.4	27.1	26.7	24.7	27.3
OND	294	414	261	213	364	695	26.3	26.7	26.0	25.6	24.9

per km^2 in the fertile hilly areas in Kilungu (Makueni County Integrated Development Plan, 2018). The elevation varies from 600 m above sea level (asl) in low-lying areas (e.g., Tsavo) to 1,900 m asl in hilly areas. Soils in Makueni County are predominantly sandy to sandy loam, classified as Arenosols and Haplic Acrisols.

The rainfall pattern in Makueni is bimodal; a long rainy season runs through March, April, and May (MAM), while short rains occur in October, November, and December (OND). The onset of cropping in both seasons varies significantly because of erratic and unreliable rainfall. Rain events in the short rainy season are more reliable than those in the long rainy season, when the rains are unpredictable and often fail to occur, making the region a one-season cropping area. Low-lying parts of Makueni County receive mean annual rainfall of between 250 and 400 mm, while hilly parts receive between 800 and 900 mm (Makueni County Integrated Development Plan, 2018). Mean monthly temperature varies from 20 to 26°C in hilly areas and can be as high as 35.8°C in low-lying areas.

Regarding rainfall patterns and temperature, crop-growing seasons where rainfall amount exceeds half the potential evapotranspiration are few and many seasons receive below 250 mm of rainfall, making them unsuitable for maize production (Recha et al., 2016). Long-term data from Makindu meteorological station in Makueni indicate average rainfall of 280 mm and 294 mm for MAM and OND, respectively (Recha et al., 2016), values used as reference in the survey. The average rainfall and temperature values for the recent period 2015–2019 (Huntington et al., 2017) are shown in **Table 1**.

Livelihoods in Makueni County are directly linked to agriculture through farming, herding, beekeeping, small-scale processing, artisanal production, charcoal production, small-scale trading, etc. Agricultural production is mainly rainfed-subsistence, although a small proportion (∼100 ha; 900 households) of the cultivable area in Makueni is under irrigation (Makueni County Integrated Development Plan, 2018). Marginal mixed farming (crop and livestock combined) is the main production form, with maize (*Zea mays*) and sorghum [*Sorghum*

TABLE 2 | Number of farmers selected per village.

Village name	Village size (sampling frame)	Sampling interval	Desired sample size
Changamwe	200	10	20
Kiteng'ei A	300	12	25
Kiteng'ei B	406	14	29
Yikivumbu	206	8	25
Viktoria	200	10	20
Kiambani	240	12	20
Mulilunі	256	11	23
Mwamba	202	10	20
Yumbuni	224	10	20
Total sample size			202

bicolor (L.) Moench] as the main cereals and cowpea [*Vigna unguiculata* (L.) Walp.], common bean (*Phaseolus vulgaris* L.), pigeon pea [*Cajanus cajan* (L.) Millsp.], and mung bean [green gram; *Vigna radiata* (L.) R. Wilczek] as priority legumes. Mango (*Mangifera indica* L.), bananas (*Musa* spp.), and oranges (*Citrus* spp.) occur in the landscape, and high-value crops such as kale/collard greens (*Brassica* spp.) and tomatoes (*Solanum lycopersicum* L.) are found in some areas.

Survey Sample Selection, Data Processing, and Analysis

In February 2020, a survey was conducted to collect baseline data on smallholder farms in the study area before testing the potential of SWRT on sandy soils. Nine villages with predominantly sandy soil were purposively selected from three sub-locations (**Figure 1**, left), with the help of key resource individuals with knowledge of soil texture in the area. Details of the selected villages within the three sub-locations are presented in **Appendix 1**. Village selection was followed by systematic random selection of farmers for the baseline household survey. A list of all farmers in the nine villages, created with the help of local chiefs, was used as the sampling frame. Farmers were selected by randomly selecting a starting name from the list for a particular village and then selecting additional names by skipping a given number of farmers (also known as fixed interval selection or sampling interval). The sampling interval was arrived at by dividing the population per village by the desired sample size (**Table 2**). This process continued until the required number of farmers in each village was obtained. The fixed interval varied with the sampling frame used in each village (selecting farmer number two, three, four, or five as the starting point). The number of farmers selected per village was non-uniform because village size varied (cf. **Table 2**), as did the sampling frame (Etikan and Bala, 2017).

We relied on a strong network of farmers to identify the homesteads of selected farmers. Smallholder farmers available and willing to participate in the survey were interviewed, while unwilling farmers were replaced with the next farmer in the sampling frame. Therefore, the interviews were conducted gradually, with the interviewed farmers providing directions to the interviewer about how to get to the next selected farmer, until all 202 selected farmers (determined using Eqs 1, 2) were interviewed. To ensure good representation and variability in the data, the number of farmers interviewed per village varied between 20 and 29.

$$n_0 = \frac{Z^2\,(pq)}{e^2} \tag{1}$$

$$n_0 = \frac{1.96^2(0.5^*0.5)}{0.069^2} = 201.73 \approx 202 \tag{2}$$

where n_0 is the sample size, Z^2 is the standard deviation at the identified confidence level (in most cases, 1.96 is commonly used for the 95% confidence interval), p is expected to be present in the population, q is (1-p), and e is the required level of precision.

The interviews were conducted using computer-assisted personal interviews (CAPI) with the help of six trained local enumerators. The data were entered into the software SurveyCTO and then checked for completeness and quality. Questionable values were flagged for follow-up. Checks and quality control coding in SurveyCTO also helped to ensure that illogical answers were excluded (for an example of criteria, see **Appendix 2**). All data were then uploaded to the cloud, from where the whole database was downloaded for further processing, data cleaning, and analysis using Stata version 14 software (StataCorp, 2015). Data were anonymized before analysis and all linked or relational datasets that might disclose personal identities were anonymized and kept confidential.

To collect information on farmers' knowledge and perceptions of climate change and variability and how they have adapted, participating farmers were asked whether they had observed any extreme weather events during the past five years. Specifically, the respondents were asked whether they had observed extreme weather events such as high temperature, precipitation, or frequent and intense droughts over the past five years (for the full survey section, see **Appendix 3**). They were also asked to state the measures they had implemented to adapt to the changes. To ascertain whether these adaptation measures had had a positive impact on livelihoods, the respondents were also asked whether they would continue paying the costs of adaptation practices or not. Willingness to pay was taken to indicate confidence in the effectiveness of a measure.

On-Farm Experiments

From July to October 2020, we manually installed SWRT membranes on 11 selected smallholder farms in the areas where the survey was conducted six months earlier (Mtito Andei) (**Figure 1**, right). These farms were in two sets located in two different villages within the study area, for ease of management. The key criterion for selecting farms was that they should have at least 1 m depth of sandy soil. To confirm soil texture and depth on the selected farms, we used an auger to sample the soil at 15-cm intervals to 135 cm depth, and determined soil texture at each interval using a quick field test outlined by Jaja (2016). This involved rubbing a moist soil sample between the forefinger and thumb and firmly squeezing it in the hand. Samples were considered sandy if the soil felt gritty and fell apart when the hand was opened. Farms where any sample from 0–100 cm depth

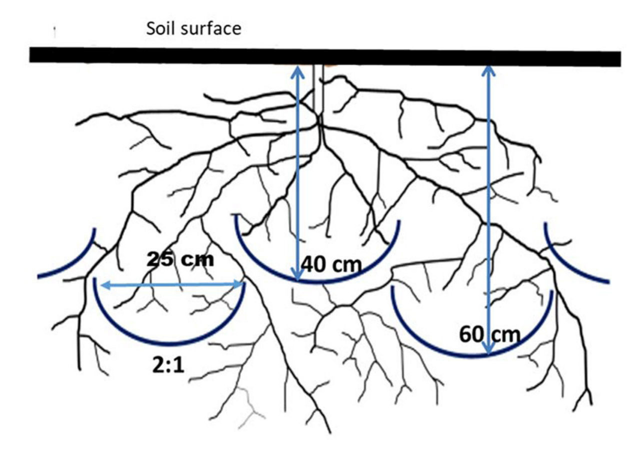

FIGURE 2 | Location and aspect ratio of U-shaped sub-surface water retention technology (SWRT) membranes (25 cm wide) installed in the root zone of on-farm SWRT plots.

felt smooth, sticky, or slippery and still held its shape after the test were excluded. In each on-farm experiment, three 12 × 20 m plots were prepared and SWRT was installed in two of these plots, while the third plot, without SWRT, was used as a control. The capillary rise method described by Goebel et al. (2004) was used to determine membrane installation depth.

The membrane used was a linear low-density polyethylene film that has been shown to improve water and nutrient retention in the plant rooting zone (Kavdir et al., 2014; Guber et al., 2015). In the two 200 m^2 SWRT plots in each on-farm experiment, three U-shaped lengths of membrane (25 cm width) were installed, at 60, 40, and 60 cm depth (see **Figure 2**). These alternating depths were designed to enable up to 95% interception of vertical soil water flow while still allowing the soil to drain, to avoid waterlogging during excessive rainfall (Guber et al., 2015).

In early November 2020, maize was planted on five of the 11 selected farms and cowpea was planted on the remaining six. The plant spacing of maize was 75 × 20 cm, while that of cowpea was 65 × 15 cm, with one seed per 5 cm deep hole. Crop and surface soil management of the SWRT plots and control plots was similar for farms with maize and cowpeas. All plots received 150 kg ha^{-1} of di-ammonium phosphate (DAP) fertilizer (27 kg N ha^{-1}, 69 kg P ha^{-1}) and 4 t ha^{-1} of farmyard manure during the planting period. In addition, maize was top-dressed at six weeks after emergence with 90 kg ha^{-1} granulated calcium ammonium nitrate (CAN, 24.3 kg N ha^{-1}). All plots were kept weed-free by hand weeding twice during the season. Maize stemborer was controlled by standard applications of the pesticides Dudurthrin and Lotus. Aphids in cowpea crops were controlled by dual sprayings of the pesticide GOLAN 20 SP (acetamiprid 200 g L^{-1}).

Both crops were harvested at maturity. Maize was harvested in each plot by separating cobs from stover and cutting the stover at 5 cm above ground level. Fresh weight yield of stover and cobs was determined on-site, using a spring balance. Cowpea was harvested by separating grain and husks from haulm (crop residues of the whole aboveground plant after grain harvesting) and fresh weight yield of grain, husks, and haulm was determined on-site. Random subsamples of maize stover and cowpea haulm were chopped and mixed, their fresh weight was determined to the nearest 0.1 g, and they were oven-dried at 65°C to constant weight. Biomass of stover and haulm was determined by multiplying total fresh weight per plot by the dry matter content (dry weight/fresh weight ratio). Data from two farms with cowpea were excluded from the analysis because the farmers harvested some cowpea leaves for other purposes during the season, and thus only data from the remaining four farms were available for cowpea. Maize cob samples were air-dried and threshed, and the weight of grain and shelled cobs was determined.

Analysis of variance (ANOVA) was used to test for differences between SWRT and control plots in terms of total biomass (both maize and cowpea), stover biomass (maize), cobs yield (maize), haulm (cowpea), husk (cowpea), and grain (maize and cowpea). All statistical analyses were performed using R software (R Core Team, 2020).

Mapping Climate Risks Beyond Production Systems and Risk Mitigation

To identify ways of managing climate risks apart from changing production form, stakeholders in functioning FVC were identified (**Figure 3**) and used to develop a conceptual model for multi-actor FVC following adoption of SWRT. According to this model, successful production resulting from improved harnessing of water and nutrients through SWRT or other soil and water management strategies would improve the overall FVC, creating opportunities along the value chain for different actors. Since identifying climate risks at different levels of contributing FVC segments in a given region is vital for decision-makers seeking to implement climate risk mitigation measures, bottlenecks to achieving the goals of each stakeholder group in Makueni County were assessed.

Stakeholder discussions were held with a total of 51 agricultural actors (belonging to the groups in **Figure 3**) during a workshop held in Kiambu on 29 April 2021. The participating stakeholders included two farmer representatives, two suppliers of seed, one membrane supplier, and two technology suppliers (irrigation, mechanization), seven county and national government representatives, two agricultural extension officers, two representatives from bank and insurance institutions, nine researchers, two NGO representatives, and two communication and dissemination officers. Discussions in groups of five to six people were held to better understand: (i) the extent to which drought frequency and duration affect stakeholder businesses, (ii) stakeholder perceptions and the food distribution system in the region, (iii) forms of support needed to manage the current climate risks and related problems, (iv) enabling conditions required when augmented crop production is achieved by e.g., introduction of improved soil and water management technologies, and (v) possible additional measures to deal with climate change risks in the region. The workshop method is effective for producing a shared picture of research

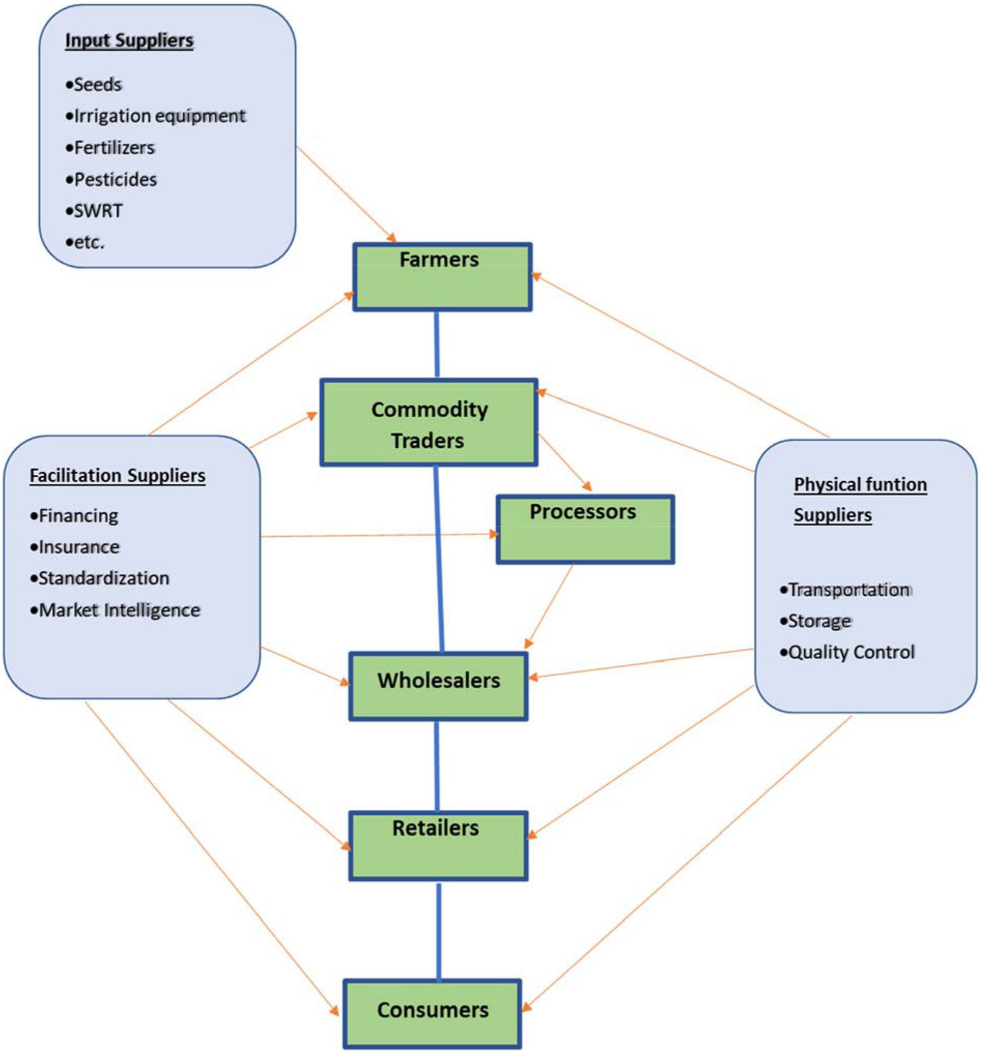

FIGURE 3 | Conceptual model of the food value chain in the study region following increased food crop production due to successful implementation of sub-surface water retention technology (SWRT) on smallholder farms.

needs and reaching an understanding of the views of multiple actors (Hauggaard-Nielsen et al., 2021).

RESULTS

Survey Insights on Farming, Extreme Weather Events, and Current Management Strategies to Mitigate Risks

Demographic Information, Farm Characteristics, and Decision Making

Of the 202 farmers interviewed, 136, 42, and 17 were household heads, spouses, and offspring (above 18 years), respectively. The interviewees ranged in age from 35 to 74 years, and household size ranged between 1 and 14 people (with a mean of five people per household). Around 90% ($n = 184$) of the households owned a mobile phone. Of the interviewed farmers, 80% worked only on their farms, while the other 20% worked away from home for more than three months every year. The level of education of the household head ranged from primary school only (55%) to secondary school (24%), adult education (9%), tertiary education (6%), and vocational training (2%).

Ninety-six per cent of the farmers interviewed owned their land, while 2% farmed on rented land. The average area of owned land was about 2.3 ha, while the area of rented land was about 0.9 ha. Only 27% of the farmers interviewed had title deeds to their land. Decision making on cropping was mainly done (64%) by the household head (primarily men) and their spouse. About 98% of the labor utilized in crop and livestock production was provided by household members, with labor from extended family and hired labor only constituting 2% of the total labor inputs. In terms of topography, 60, 37, and 2% of farms were on flat, slightly sloping, and steep terrain, respectively.

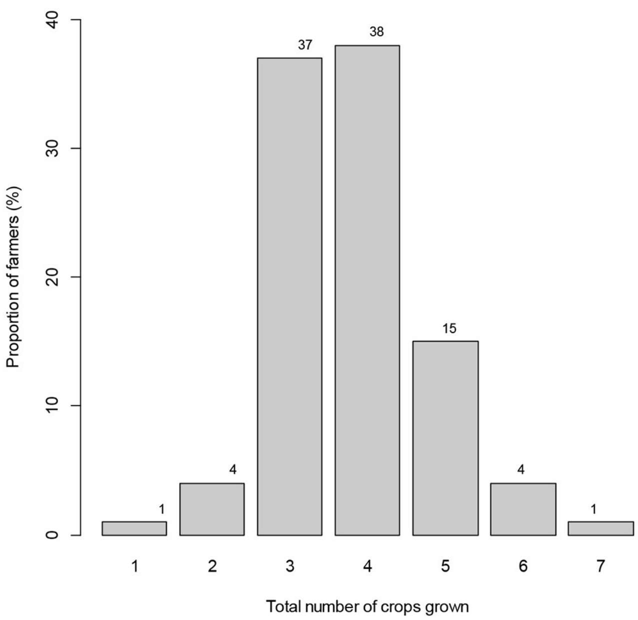

FIGURE 4 | Proportion of farmers interviewed ($n = 202$) in Makueni County growing different numbers of crop species annually on their farm.

Diversification of Crops and Management

The number of crops grown per year varied between farmers. During the previous 12 months, 38, 37, and 15% of the farmers had cultivated three, two, and four crop species, respectively (**Figure 4**). The main crops, in descending order of reported frequency were maize (37%), cowpeas (33%), green gram (19%), pigeon pea (6%), sorghum (4%), and cotton and beans (2%). Three types of manure were used but, based on reported frequency of application, farmyard manure was by far the most common (74%), followed by compost (23%), while green manure was used by only 3% of respondents. Only 46% of the farmers reported using improved seeds during the previous 12 months. Three types of irrigation, i.e., pouring water by hand (using a container), drip irrigation, and a manual pump (i.e., moneymaker), were reported, by 12, 5, and one farmer, respectively. The three primary irrigation water sources were borehole, well, and water pan, depending on the available water source. All interviewed farmers reported that they had practiced agroforestry during the last 12 months. Some farmers integrated crops with trees for income generation (about 82%), while others adopted agroforestry to improve soil quality (about 18%). Livestock rearing (i.e., cattle, sheep, goats, donkeys, and rabbits) was reported by 83% of the farmers. Cattle, goats, and sheep were owned by 42, 50, and 7% of the interviewed farmers, respectively. Donkeys and rabbits were owned by one farmer each.

Extreme Weather Events and On-Farm Measures for Mitigating Climate Risk

Based on the interview responses, 199 of the 202 farmers had experienced extreme weather events since 2015. As a result, 161 farmers had changed their farming practices by adopting some adaptation measures. Around 70% of farmers reported adapting to drought, while 22% reported adapting to increased temperature and 8% to rainfall variability. The adaptation practices adopted to deal with extreme climate events varied widely (see **Table 3**). The three most common practices for all the three climate risks were increased early planting while the total crop area remained the same, reducing the area under cultivation, and water harvesting to manage soil moisture. Farmers also responded to increased temperatures by early planting (**Table 3**).

When asked whether they would be willing to pay to install technology that could enhance crop yield, only eight of the 199 farmers who had experienced an extreme weather event expressed willingness to pay for such technology. The main reasons given for low willingness to pay were lack of money, poor access to credit, lack of inputs, shortage of labor, and lack

TABLE 3 | Extreme events associated with climate change and variability, and related adaptation strategies adopted by the 202 farmers surveyed.

Extreme weather event	Adaptation strategies to reduce negative impacts	No. of farmers
Drought	Increased area under crop production	1
	Reduced area under cultivation	20
	Irrigation	1
	Water harvesting	11
	Use of improved seeds	4
	Early planting	69
	Mulching for soil moisture management	5
	Crop-livestock integration	1
	Surface mulching to prevent damage to vegetables	1
	Timely planting	2
	Use of drought-tolerant crops	1
Increased temperature	Increased area under crop production	1
	Early planting	13
	Mulching for soil moisture management	21
Rainfall variability	Increased area under crop production	3
	Water harvesting	1
	Early planting	4
	Late planting	2

Number of farmers is shown for each strategy.

TABLE 4 | Analysis of variance (ANOVA) results [degrees of freedom (df), F-value, *P*-value] for differences between sub-surface water retention technology (SWRT) plots and control plots in performance indicators of cowpea and maize at crop maturity.

	Cowpea				Maize		
	Df	***F*-value**	***P*-Value**		**Df**	***F*-value**	***P*-Value**
Biomass	1	1.3	0.27^{NS}	Biomass	1	19.0	0.0005^{***}
Haulm	1	0.3	0.62^{NS}	Stover	1	22.3	0.0002^{***}
Husk	1	5.1	0.04^{*}	Cobs	1	12.0	0.003^{**}
Grain	1	10.7	0.008^{**}	Grain	1	11.8	0.003^{**}

$^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$; and NS, $P > 0.05$.

of information on climate change, reasons cited by 23, 2, 2, 8, and 51 farmers, respectively.

Risk Mitigation Case: Soil Water Management by SWRT

During the growing season November 2020–March 2021, there were notable differences in crop growth between the SWRT and control plots in the cowpea and maize plots. **Table 4** shows summary statistics for differences in cowpea and maize crop performance indicators at maturity.

In the SWRT plots, aboveground biomass and haulm weight for cowpeas were not significantly different from those in the control plots (**Figure 5**). However, the cowpea plants in the SWRT plots remained green and healthy throughout the growing season (field observations). Cowpea grain yield in the SWRT plots ranged between 0.43 and 1.22 t ha^{-1}, with a mean value of 0.90 ± 0.20 t ha^{-1}, while that in the control plots ranged between 0.43 and 0.57 t ha^{-1}, with a mean value of 0.50 ± 0.08 t ha^{-1} (**Figure 5**). On average, cowpea grain yield was significantly higher (about 50%) in SWRT plots compared with the control.

For maize, all crop performance indicators measured (total biomass, stover, cobs, grain yield) were significantly higher in the SWRT plots than in the control plots (**Figure 6**). Grain yield in the SWRT plots ranged between 1.36 and 3.48 t ha^{-1}, with a mean of 2.00 ± 0.62 t ha^{-1}. In control plots, maize yield ranged between 0.18 and 2.17 t ha^{-1}, with a mean of 0.77 ± 0.81 t ha^{-1}.

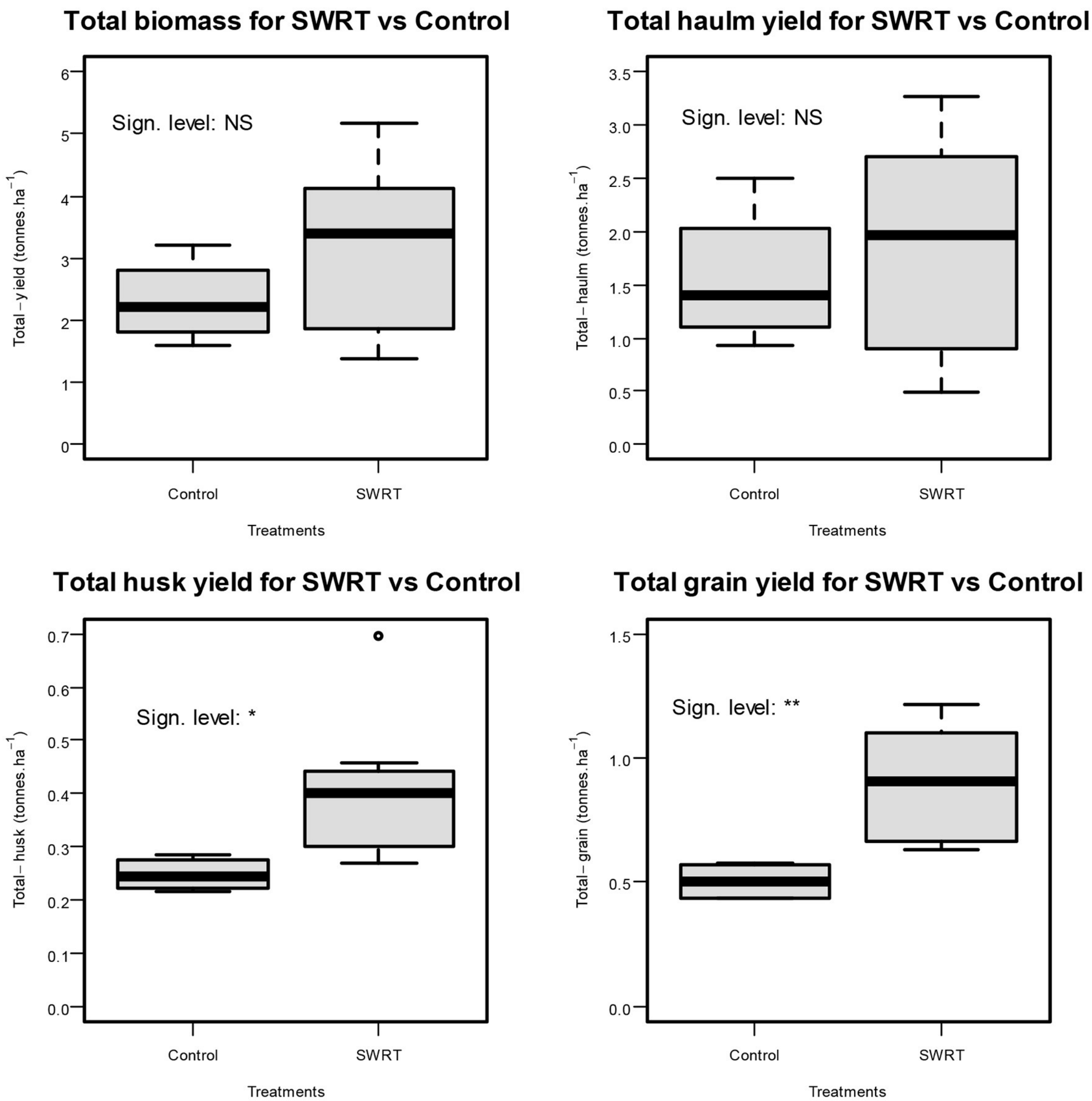

FIGURE 5 | Yield at harvest in sub-surface water retention technology (SWRT) plots and control plots of whole cowpea biomass (sum of haulm, husk, and grain) and of cowpea haulm, husk, and grain. "Sign. level" in each panel denotes the level of significance of differences between SWRT and control plots (**$p < 0.01$, *$p < 0.05$, NS $p > 0.05$).

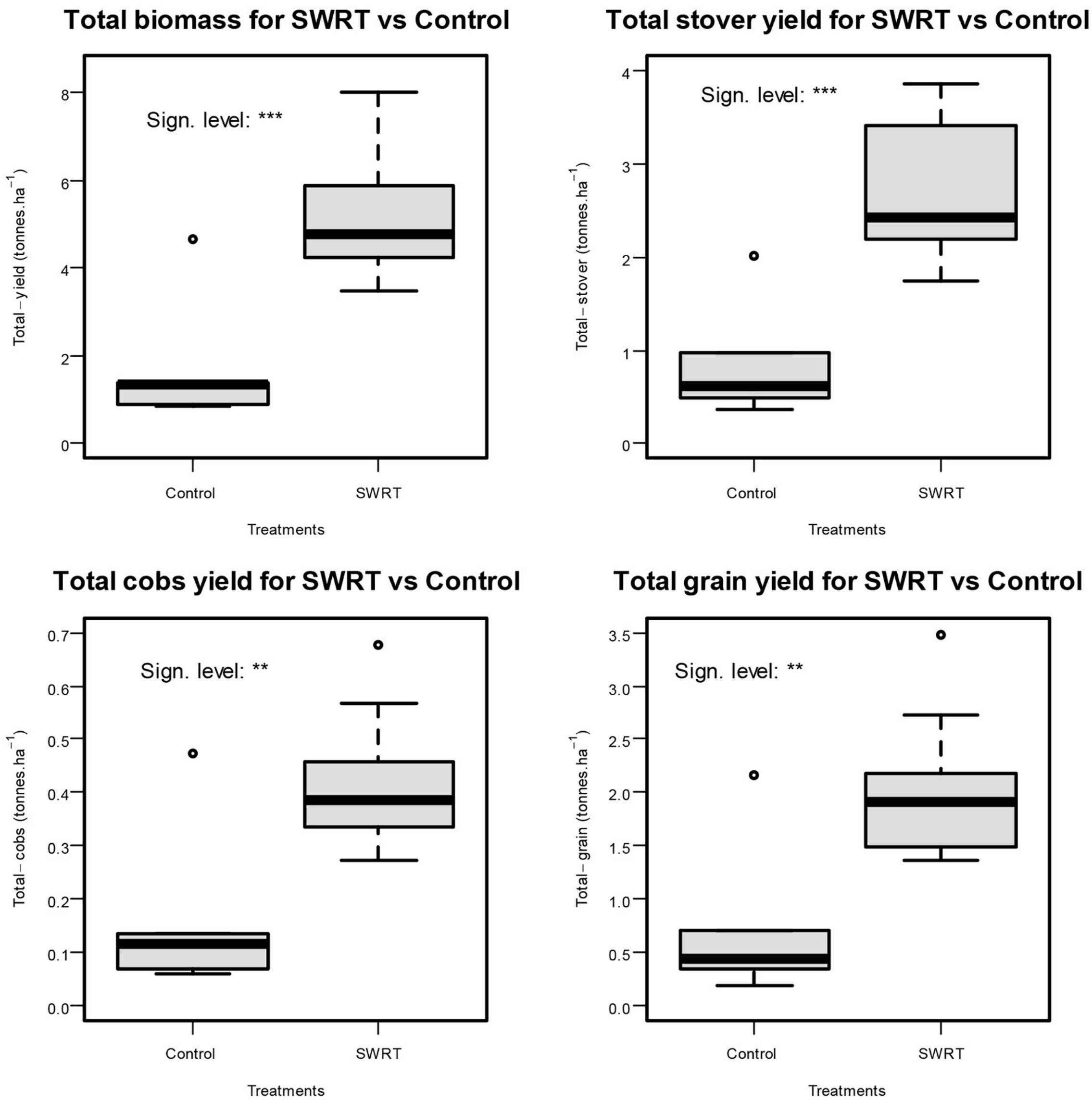

FIGURE 6 | Yield at harvest in sub-surface water retention technology (SWRT) plots and control plots of total maize biomass (sum of stover, cobs, and grain) and of maize stover, cobs, and grain. "Sign. level" in each panel denotes the significance level of differences between SWRT and control plots (***$p < 0.001$, **$p < 0.01$).

On average, an increase of around 158% in grain yield was found for SWRT maize plots compared with control plots.

Climate Risk Management Along the Food Value Chain

The stakeholder group discussions showed that drought spells have severe negative impacts on all FVC segments in the region. Besides the impact of low rainfall and high temperatures on producers, the businesses of upstream and downstream actors were also reported to be negatively affected (**Table 5**). Upstream of farms, demand for inputs (and associated income for suppliers) decreased when farmers faced crop failure in previous seasons, while downstream actors experienced decreased supply of agro-produce.

Downstream stakeholders reported delivery difficulties and failure to meet contractual obligations. Among the forms of support needed to manage the current climate risks, financial support was mentioned by all three main stakeholder groups. This financial support can take the form of loans and credits for inputs and investments (e.g., irrigation systems) or insurance schemes to ensure resilience after extreme weather events. Once producers can adapt to climate variability and maintain good food production levels, actors in the upstream and downstream FVC segments must create a viable market for the resulting farm produce.

TABLE 5 | Major climate-related risk factors in food value chain (FVC) segments: producers/farmers, upstream actors (suppliers and service providers), and downstream actors (brokers, intermediaries, stockists, processors, and exporters), current food distribution challenges, and suggested ways to improve the FVC.

Upstream actors	Producers	Downstream actors
1. Identified climate-related risk factors in the region		
Decreased demand for inputs Inability to plan accordingly Reduced and/or loss of income Increased costs of doing business Loans not reimbursed Generating lower profit Content of extension message affected by adverse weather Low technology adoption	Total crop failure or yield losses Loss of livestock due to lack of pasture/feed Human-wildlife conflict Loss of income (leading to conflicts) Soil degradation and low soil fertility Disruption in market access Internal displacement of people Increased incidence of diseases and pests	Disruptions to procurement and deliveries Compromised ability to plan accordingly Increased costs of doing business Failure to meet contractual obligations and agreements
2. Current challenges in food distribution in the region		
	The food distribution system exploits farmers with low prices. Different types of food are available in the region: cereals, e.g., maize, millet and sorghum; legumes, e.g., mung bean, cowpea; vegetables, e.g., cowpea leaves, kale, spinach	Stockists play a crucial role in food distribution Stockists serve as aggregators; groups also do so Spirit of cooperatives embraced in the county; programs like NARIGP* have such systems The county government has set up four cooperatives for four key value chains, an apex organization has also been formed to perform regulation. A warehouse receipt system has been tried, but was not successful A contract farming system is applied by the four cooperatives, but is being refined Local arrangement for paying school-fees in-kind (beans, maize) Need to streamline and improve marketing system
3. Adaptive measures to reduce climate vulnerability or increase resilience		
Financial support to scale up technologies Innovative crop insurance Government support for farmers to build farm ponds, water tanks for irrigation Extension services dedicated to climate-smart agriculture	Adopt resilient farming practices such as Zai pits, conservation agriculture Use of high-quality seeds Install SWRT Get crop insurance	Facilitative policies at county and national level Enhanced financial support for farmers in aggregation centers
4. Improvements needed to maintain crop production after introducing soil and water management technologies		
Strengthen farmer aggregation centers Encourage strong private sector in the marketing chain Provide multiple demonstration plots Increase the number of qualified extension officers Provision of financial support to scale up	Use improved seed varieties Increase adoption of suitable technologies	Facilitate market linkages Good prices for farmers Improve post-harvest handling (storage, drying, transformation)
5. Additional measures to deal with climate change risks in the region		
Rehabilitation and reclamation of degraded land Strengthening of early warning systems Teach climate management risk in schools	Establishment of tree nurseries, agroforestry Control soil erosion Practice zero-grazing	Act in groups when handling post-harvested food (storage, transport, transformation, etc.)

**NARIP: National Agricultural and Rural Inclusive Project.*

DISCUSSION

Climate Risk Management at Farm Level in Makueni County

The case study in Makueni County clearly illustrates the climate risks faced by smallholder farmers in arid and semi-arid areas. Small farm size (<2.3 ha per household), sandy soils, and frequent droughts were the leading sources of production and profit risks in the study region. The interviewed farmers reported having experienced extreme weather events during recent years. Droughts were the most common climate event reported for the period 2015–2019, as reflected in the rainfall variability during that period (**Table 1**). Four out of 10 seasons in the period received <250 mm of rainfall per season, which is below the acceptable threshold for maize production (Recha et al., 2016), and five seasons received rainfall amounts below the long-term average for Makueni County. Farmers in the study region reported taking several actions to manage risks, but their crop yields were still low. Common drought management strategies included crop diversification, application of farmyard manure, use of improved seeds, and early planting, which were reported by 95, 74, 46, and 69 % of respondents, respectively. All strategies and actions reported by the smallholder farmers interviewed in this study are well-known in other regions facing similar vulnerability to drought conditions and locked in vicious poverty cycles as a result of droughts (Acevedo et al., 2020). However, while drought causes water shortages, few farmers in Makueni County use irrigation (∼9% of respondents) or attempt to conserve soil moisture for sustainable crop production.

According to the survey results, most farmers (∼99%) were unwilling to pay for promising technologies, with most citing lack of finance for investment in new technologies as the reason. Limited financing is one of the major barriers to adopting innovative agronomic practices for sustainable intensification in Sub-Sahara Africa (Kuyah et al., 2021), making it imperative to create viable credit facilities to support initial investments (Mutenje et al., 2019). Appropriately targeted investments could increase crop yields, which would allow repayment of the loan (Ng'ang'a et al., 2021). Along with investment costs, the labor costs of establishing some innovative technologies (e.g., agroforestry, plant basins) have also been found to limit their implementation (Kuyah et al., 2021). For example, 600 h per hectare are required to create plant basins for soil water and conservation (Kaboré and Reij, 2004). In the present case, with manual installation of SWRT, the estimated labor demand was even higher (>1,000 h per hectare), but could be reduced if smallholder farmers had access to tractor-mounted membrane installers. A return on initial investment costs within a short period (2–3 years) could be achieved if e.g., high-value crops such as vegetables were grown (Smucker et al., 2018) and if smallholder farmers were directly connected to a market. It is important to note that, to improve efficient use of investment funding, additional extension services might be required to guide smallholder farmers in adoption of appropriate management practices and technologies (Makate et al., 2019).

In the present study, on-farm experiments examining use of SWRT on sandy soils demonstrated a significant increase in marketable products (50 and 158% for cowpea and maize grain yield, respectively) and also an increase in maize biomass, which in the long term can improve soil health through carbon sequestration and soil moisture. The increase in grain yield was comparable to that reported in previous studies on water and nutrient conservation (see Magaia et al., 2016). The increased performance of SWRT maize plots resulted primarily from a higher germination rate and denser plant population than in control plots. Overall, results from the first growing season showed higher yield increases for maize than cowpea in response to SWRT membrane installation. It is also important to note that the experiments were conducted using local cultivars, which might be relatively well-adapted to water scarcity, and future testing using other commercial cultivars could reveal even greater advantages of SWRT.

Role of Food Value Chain Actors in Climate Risk Management

Stakeholder discussions showed that when extreme weather events affect primary food production, the negative impact spreads to other actors in the FVC (**Table 3**). The stakeholder discussions revealed a range of actions that can be taken to reduce the impact of extreme weather events on upstream, production, and downstream actors in the FVC. The importance of access to finance at all levels of the FVC was highlighted, which is in agreement with previous findings on the value of financing and investment (Havemann, 2016; Havemann et al., 2020; Negra et al., 2020). Previous studies describe many approaches used by FVC actors to reduce the economic risks under normal environmental conditions, but such conventional models can fail to perform following social and environmental disruptions, so new models such as blended financing are required (Havemann et al., 2020). The blended financing approach calls for more accountability in all segments of the FVC to ensure the sustainability of businesses.

In semi-arid regions, soil and water management is critical to mitigating the climate risks. However, smallholder farmers require support to adopt technologies such as SWRT and irrigation. While the increase in maize and cowpea yields in on-farm plots in this study was significant (>50%), the interviewed farmers viewed the high costs of purchasing SWRT membrane and hiring labor for membrane installation as prohibitive. Necessary preconditions for improving adoption of soil-enhancing practices must thus be created beyond the farm level, including FVC development, policy, and finance (Klauser and Negra, 2020), with social and institutional interventions needed to support structural/physical interventions (Havemann, 2016). In addition, it is essential to remember that SWRT only retains existing water and nutrients and, in the absence of rain or irrigation water, this technology may not produce the desired results. However, combining SWRT with irrigation could increase water and nutrient use efficiency, and thus help achieve yield stability in semi-arid regions such as Makueni County, even during periods characterized by low rainfall.

Overcoming barriers to scaling up water-related technologies (e.g., SWRT) may require support from downstream value chain actors (i.e., the private sector) to reduce installation costs and improve agro-advisory services for farmers (Westermann et al., 2018). Building on existing finance mechanisms in Makueni County can improve access to loans and insurance facilities. Some stakeholders at the workshop, representing e.g., One Acre Fund and Agriculture and Climate Risk Enterprise (ACRE Africa), reported that they already have financial services targeted at smallholder farmers. Therefore, apart from improving access for farmers to low-interest credit facilities, there is also a need to encourage cooperation among value chain actors to support adoption by farmers of management practices and technologies that enhance resilience to recurrent droughts (Nzeyimana et al., 2021). Our findings suggest that managing drought risks and sustainably transforming food systems will require appropriate, practical, and harmonized actions at individual farm, value chain and political level.

CONCLUSIONS

This study showed good potential to mitigate climate risks to smallholder farmers, even in a semi-arid area with drought spells and sandy soils, provided that other societal actors support good soil and water management practices. Installation of SWRT membranes resulted in a significant increase in marketable crop yield and could contribute to soil carbon sequestration if the increased amounts of crop residues are well-managed. Achieving positive effects of SWRT at greater scales will require combined efforts by value chain actors, including input/service providers, producers, and post-harvest actors. To effectively manage climate risks to smallholders in the region, existing and new financing modes (e.g., loans and insurances) need to be developed. There is also a need for continuous learning by all actors in the FVC to build a win-win food system.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

LN led the writing of the paper, with contributions of SKN for the survey study. SN and SM for the experimental part. SK and WK for the involvement of FVC actors. NC, IÖ, and AS contributed valuable comments during the study design and manuscript preparation. All co-authors participated in the whole process of writing.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2021.766583/full#supplementary-material

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