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# Climate-smart agriculture options on coarse-textured soils for improved food security in semi-arid areas

## Climate change awareness and adaptation, sub-surface water retention, plant density and nutrient management

Sandra Makaita Madamombe

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## Abstract

Rainfed maize production by smallholder farmers is at risk due to climate change, exacerbated by low soil moisture and poor fertility in sandy soils under semi-arid conditions. This thesis assessed climate-smart agriculture (CSA) options to deal with the risks. A survey was conducted in Zimbabwe to assess farmers' awareness of extreme weather events, their adaptation strategies and associated maize yield. On-farm experiments evaluated CSA options for management of soil water, nutrients and crop density. All 245 farmers interviewed reported awareness and experience of extreme weather events such as drought, flooding and temperature changes. However, despite a range of reported adaptation strategies, reported maize yield averaged only 0.6 t $ha^{-1}$. Integrating sub-surface water retention technology (SWRT) with different maize densities or soil amendments improved maize productivity to different degrees in dry (305-352 mm) and wet (424-780 mm) seasons. Use of SWRT increased maize grain by 21-24% and total biomass yield by 13-22%, and showed potential to increase maize rainwater use efficiency (RWUE) over four years. Plant density increased from 37,000 to 43,000 plants $ha^{-1}$ gave optimal four-year average maize grain yield (2.7 t $ha^{-1}$), and RWUE (5.5 kg $ha^{-1}$ $mm^{-1}$). Combining organic and inorganic soil amendments gave 2.3-3.4 t $ha^{-1}$ grain yield as a three-year average. Average maize yield ranged between 0.3-1.4 t $ha^{-1}$ in dry seasons and 3-5.5 t $ha^{-1}$ in wet seasons. In conclusion, management of crop density, soil water and nutrients in smallholder farming increased maize productivity to varying degrees due to seasonal variations in rainfall patterns.



Keywords: Extreme weather, soil and water management, maize, plant density

# Dedication

To Kunashe, Watipaishe, Ayana and Ellton Elliot.

# Contents

# List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Madamombe, S.M., Ng'ang'a, S.K., Öborn, I., Nyamadzawo, G., Chirinda, N., Kihara, J. & Nkurunziza, L. (2024). Climate change awareness and adaptation strategies by smallholder farmers in semi-arid areas of Zimbabwe. *International Journal of Agricultural Sustainability* 22 (1), 2293588.

II. Madamombe, S.M., Nyamadzawo, G., Öborn, I., Smucker, A., Chirinda, N., Kihara, J. & Nkurunziza, L. Maize productivity under subsurface water retention technology and different plant densities in rainfed smallholder farming system (manuscript)

III. Madamombe, S.M., Nyamadzawo, G., Öborn, I., Smucker, A., Chirinda, N., Kihara, J. & Nkurunziza, L. Integrating sub-surface water retention technology (SWRT) and site-specific nutrient management in maize production on sandy soil in semi-arid areas. (manuscript)

The contribution of Sandra Makaita Madamombe to the papers included in this thesis was as follows:

I. Main author planned the study with co-authors. SMM participated in data collection supervised by SK and GN. SMM analysed the data, interpreted the results and wrote the manuscript, which was developed further from the contributions of other co-authors.

II. Main author. SMM, planned, supervised and conducted fieldwork. SMM analysed the data, interpreted the results and prepared manuscript. SMM consolidated co-authors´ contributions and reviews.

III. Main author. SMM designed the experiment together with co-authors. SMM, planned, supervised and conducted fieldwork. SMM analysed the data, interpreted the results and wrote the manuscript. All authors contributed to the preparation of the manuscript.

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# Abbreviations

| | |
|---|---|
| CSA | Climate smart agriculture |
| SWRT | Sub-surface water retention technology |
| IP | Infiltration pits |
| TC | Tied contours |
| SC | Standard contours |
| SOC | Soil organic carbon |
| RWH | Rain water harvesting |
| GHG | Greenhouse gas |
| SDG | Sustainable development goal |
| BAU | Business as usual |
| SPAD | Soil-plant analyser development |
| DAP | Days after planting |
| RWUE | Rain water use efficiency |

# 1. Introduction

Global crop production and food security are high-priority issues due to the constantly growing global population, which is projected to reach 9.7 billion by 2050 (United Nations, 2019). Over 50% of the global population, mainly in Asia and Africa, rely on rice as a staple crop (FAO 2014b). Maize is the most cultivated cereal crop in Africa making up 46% of the total cereal production (FAOSTAT 2021). Around 20% of global calorie intake comes from wheat, mainly in Europe, North America and parts of Asia (Shiferaw et al. 2013) and 10% comes from maize, a major food source particularly in Africa (Erenstein et al. 2022). Future production of these staple crops will be at risk because of climate change and related extreme weather events unless agricultural practices are adapted to the new conditions. Agriculture accounts for 70% of freshwater withdrawal and regions with arid or semi-arid conditions have higher depletion rates, exacerbated by extreme weather events (Yadav et al. 2022). Global surface temperature is projected to rise by 1.5 °C compared with pre-industrial levels in coming decades, to 2.0 °C by 2040, and will affect biogeochemical cycles, influencing crop production (Adak et al. 2023).

Maize production is important in sub-Saharan Africa, particularly the southern region, constituting around 30% of daily calorie intake of most households (Galani et al. 2022). The dependence on maize as a staple crop makes its production essential for food security and nutrition in the region (Mujeyi 2021). However, crop production by smallholder farmers in sub-Saharan Africa is declining due to adverse climate conditions, particularly for maize production (Mulungu & Ng'ombe, 2019; Stuch et al. 2021). Over the years, these smallholder farmers have experienced severe droughts, shortened growing season and erratic rainfall, affecting their livelihoods. The warming climate has considerably damaged agricultural activities in sub-

Saharan Africa, necessitating adaptive climate measures to avoid food scarcity or economic stagnation in agriculture-driven economies in African countries (Talib et al. 2021). Several models predict increasing vulnerability, intensity, magnitude and frequency of drought events in the region (Cairns et al. 2013; Pangapanga-Phiri & Mungatana, 2021). An average maize yield reduction of 7.4% is predicted for every 1 °C rise in global temperature (Zhao et al. 2017). Crop production is strongly affected by climate change, but at the same time, it contributes to climate change. The proportion of maize yield reduction attributable to climate change variability over the past decade is estimated to be 77% in Zimbabwe, 75% in Kenya, 66% in Malawi, 61% in Angola and 50% in South Africa, resulting in overall reductions in maize production in the region and globally (Ray et al. 2019).

Lack of pre-warning, disaster preparedness and poor planning for the season aggravate the impacts of climate change-related weather conditions on crop production. Moreover, current farming practices are damaging the environment and are a source of greenhouse gas (GHG) emissions (contributing around 19-29% of the total) (Campbell et al. 2014). Low soil water availability and poor soil fertility in sandy soils under semi-arid conditions also exacerbate the impacts of extreme weather conditions on crop productivity (Mak-Mensah et al. 2021).

Use of climate-smart agriculture (CSA) technologies can help to address the adverse impacts of climate change on crop production (FAO, 2014; Lipper et al. 2018). Climate-smart agriculture is an integrated approach to food production and land management that helps farmers and other producers to achieve sustainable development goals (SDGs) by addressing food security (SDG 2) and climate change related challenges (SDG 13) forming interlinkages with other various SDG targets. (FAO 2014a, 2019). The approach includes a broad range of practices, such as conservation agriculture, agroforestry, precision agriculture, water and nutrient cycling, and more(FAO 2014a; Zougmoré et al. 2021) . It also involves adoption of practical technologies, such as weather forecasting and early warning systems, to help manage the effects of climate change (Ogallo 2010). The goal of CSA is to increase the productivity of farms while maintaining the natural resources that are essential to the long-term success of the agriculture sector. A CSA technology therefore addresses at least one of the CSA principles, *i.e*. (i) increasing productivity and incomes, (ii) enhancing adaptation and resilience of livelihoods and ecosystems, and (iii) mitigating greenhouse gas emissions (FAO 2014a).

Adoption of CSA technologies among smallholder farmers is low, despite its potential economic and environmental benefits (Makate et al. 2019). The adoption rate is influenced by farmers' inclusion or exclusion of local knowledge, socio-economic status, heterogeneity of farming systems and government policy (Musafiri et al. 2020; Ogunyiola et al. 2022).

## Overall aim

The overall aim of the work presented in this thesis was to assess climate-smart agriculture options for food security on coarse-textured soils in semi-arid smallholder farms. Specific objectives were to:

- Assess smallholder farmers' awareness of extreme weather events, identify adaptation strategies and factors underlying these, and evaluate maize yield under different soil fertility and water management practices (Paper I).

- Evaluate the effect of sub-surface water retention technology (SWRT) on maize performance and rainwater use efficiency at different plant densities on sandy soils under rain-fed semi-arid farming conditions (Paper II).

- Determine the effect of integrating SWRT and different soil amendments (fertilisers) on rainfed maize production and soil nutrient status of sandy soils under semi-arid farming (Paper III).

# 2. Background

This chapter presents a general review of CSA options for semi-arid areas and of CSA technologies designed to help farmers increase resilience to climate variability and extreme weather events, make better use of available resources, and reduce the negative impacts of climate change on agriculture. There are various entry points to CSA; these include landscape, sustainable agriculture practices, innovative approaches depending on specific socioeconomic, environmental, and climate change factors (FAO 2014a). The landscape approach is where the management of production systems and natural resources covers enough land area to produce ecosystem services. This can be implemented through multiple stakeholders operating at different scales and can integrate different land uses for example, forestry, fisheries, water etc (Schwartz et al. 2021; Fenta et al. 2022). Sustainable agricultural practices approach include techniques such as mulching, intercropping, conservation agriculture, crop rotation, integrated crop-livestock management, agroforestry, improved grazing, and water management (Kumar & Singh 2024). Innovative approaches incorporates strategies such as climate services information systems, insurance and resilient crops (Tall et al. 2018).

The CSA technologies presented in this chapter overlap across approaches mentioned above and they include crop-diversification, improved crop varieties and crop management, sustainable soil moisture management and soil nutrient management. In Southern Africa, conservation agriculture (CA) is the most widely practised CSA (Marongwe et al. 2011; Simwaka et al. 2020; Nyagumbo et al. 2022; Thierfelder et al. 2024) and is promoted through provision of training and subsidisation of inputs by the government and research partners (CIAT; World Bank 2017).

## 2.1 Crop diversification

Crop diversification includes a range of cropping techniques, such as intercropping, crop rotation, multiple cropping and/or use of intermediate crops, cover crops and agroforestry (Zabala et al. 2023). Crop diversification enhances the sustainability and resilience of agriculture cropping systems (Mhlanga et al. 2021). It is often combined with other sets of crop production practices, such as intercropping, reduced tillage, integrated pest management, integrated soil fertility management *etc*. (Hufnagel et al. 2020). Choice of crop diversification strategy is guided by the purpose and intended goal of the practice (Njeru 2013). For example, crop diversification can be used for CSA, improving ecological services function, produce market value, climate change adaptation *etc*. However, farmers need to maximise productivity per crop (Makate et al. 2016) and some recommended diversification patterns may not bring net benefits to farmers (Bellon et al. 2020). Therefore, farm businesses end up opting for simpler or less diversified options in which maximum productivity of each crop in the system is guaranteed, such as rotations or sequential cropping (Van Zonneveld et al. 2020). Studies to date on crop diversification have focused on the biophysical benefits of minor crops included in diversification strategies. Little information is available on the interaction of value-chain actors, other stakeholders and crop diversification adoption by farmers.

Intercropping is considered an effective strategy in sustainable agricultural intensification, as it brings about greater crop diversification and improved food security (Rusinamhodzi et al. 2013; Setimela et al. 2022). Intercropping with legumes, particularly in low-input systems, can contribute significant amounts of nitrogen (N) through biological nitrogen fixation, and thus alleviate nitrogen deficiency in nitrogen-scarce environments, thereby providing multiple benefits to farmers. Some legumes can fix up to 30 kg N $ha^{-1}$ $year^{-1}$ or more depending on the type of legume and yield level (Peoples et al. 2021).

## 2.2 Improved crop varieties and crop management

Use of improved germplasm is one of the ways in which smallholder farmers can adapt to climate change. The genetics of drought tolerance in maize in sub-Saharan Africa have been extensively investigated over the past three decades (Prasanna et al. 2021), breeding for drought tolerance has advanced, and improved varieties suitable for every agroecological zone are available on the market (Setimela & B Mwangi 2009; Edge et al. 2018). For example, recently developed drought-tolerant and low-input maize seeds have proven to be a game-changer for crop production by smallholder farmers in semi-arid areas (Cairns et al. 2013). Drought-tolerant legumes have been explored as potential climate-smart crops to provide adequate food and nutrition security (Jiri et al. 2017b). In the study by Jiri et al. (2017a), tapery bean, cowpea and common beans were shown to be suitable for drought-prone areas and were recommended for integration with other drought-tolerant cereals crops. However, utilisation of indigenous legumes, such as Bambara nut and African yam bean, in breeding and research for CSA has been limited, despite these species being better adapted to abiotic stresses (Paliwal et al. 2020). Research on integration of these legumes and drought-tolerant cereals into a suitable cropping pattern for smallholder farmers in semi-arid areas is also limited.

Managing plant densities can assist smallholder farmers to practice good crop management and adapt to climate change (Sinapidou et al. 2020). Plant densities can be adjusted at different environmental contexts for example between 33,000 and 44,000 plants $ha^{-1}$ applies for maize in dry-land farming under semi-arid conditions (Nyamuzenda 2000). Under irrigation and high rainfall, high plant densities of maize between 55,000 to 80,000 plants $ha^{-1}$ have been achieved (Moswetsi et al. 2017). Thus, adjustment of plant densities may be necessary if soil moisture conditions are improved.

## 2.3 Sustainable soil moisture management

Extreme weather events related to climate change affect every level of the water cycle, as well as nutrient cycling (Codjoe & Atiglo 2020). Water storage in the soil depends on the intensity of rainfall, soil depth, soil structure, soil temperature, and soil organic carbon content and type (Blanco & Lal 2023). Stable forms of organic carbon, such as humus, hold more water than other organic carbon forms (Bot & Benites 2005). Sandy soils are highly permeable, have low capacity to retain water and offer limited capacity to protect soil organic matter compared with clay soils, which can effectively retain water and nutrients (Yost & Hartemink 2019; Diop et al. 2022).

Appropriate soil management can improve soil water content by increasing infiltration or allowing steady infiltration, strengthening the capacity of the soil to store water and reducing soil water evaporation during extreme weather events (Ward 2016; Oduor et al. 2021). Ground cover management measures such as mulching have significant effects on soil organic matter content, structure, porosity, aeration and bulk density (Were et al. 2016).

Previous studies conducted under semi-arid conditions have demonstrated soil moisture management through installation of contour-based or *in situ* rainwater harvesting structures (RWH) such as tied contours (TC) infiltration pits (IP), tied ridges and planting basins (Nyakudya & Stroosnijder 2011; Nyagumbo et al. 2019; Kugedera et al. 2020; Kubiku et al. 2022) (Figure 1). These RWH improvements affect infiltration rates (Nyamadzawo et al. 2013), water storage and availability of water to plants (Turmel et al. 2015). Innovative techniques for soil moisture management such as subsurface water retention technology (SWRT) have been designed to mitigate the effects of short- and long-term droughts on field crops and horticultural crops grown on sandy soils (Guber et al. 2015a; Lahbouki et al. 2022).

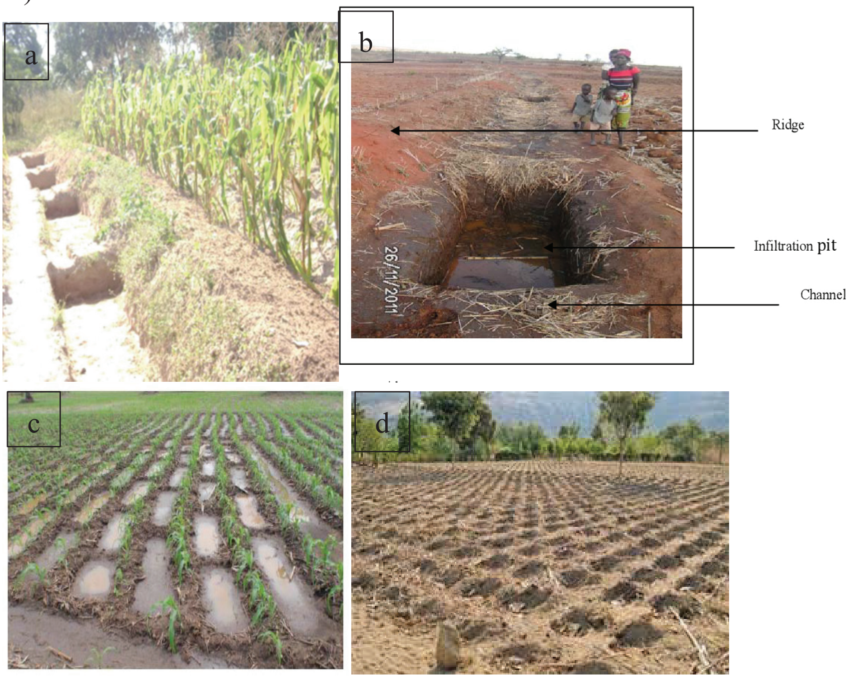



Figure 1. Photos showing (a) Tied contours photo by George Nyamadzawo adopted from Wuta et al. (2018), (b) Infiltration pits adopted from Nyakudya et al. (2012), (c) Tied ridges adopted from Nyirenda et al. (2021) and (d) planting basins.

The technology involves installation of polyethylene membranes below the root growth zone to minimise water losses, improve retention of plant nutrients and support improved crop production (Smucker 2013; Guber et al. 2015b). Previous studies in other regions have shown that SWRT significantly improves vegetable and cereal production (Churchman & Landa 2014; Almasraf & Salim 2018; Smucker et al. 2018; Aoda et al. 2021). Field research with SWRT conducted on smallholder farms under rainfed and semi-arid conditions is limited.

Managing soil compaction increases the effectiveness of rainfall, enhances crop productivity and lowers the risk of waterlogging (Ahmed et al. 2019). Integrated management of soil-crop-water relations improves soil nutrient and water retention capacity and enhances soil biodiversity, while simultaneously increasing the resilience of crop production systems to climate change (Leippert et al. 2020).

## 2.4 Soil nutrient management

Soils are an integral part of nutrient cycling, carbon sequestration, filtration and storage of water and in providing habitats for biological activity. Soils also play a critical role in farming activities and crop production. Farming practices affect soil health and functions, which in turn influence carbon sequestration and greenhouse gas emissions. Climate change alters the soil net carbon balance and the net flux of greenhouse gas emissions from the soil. High soil surface temperatures increase the rate of mineralisation of soil organic matter and impair the capacity of soil to sequester carbon and retain water, which ultimately limits plant growth. Thus, careful management of soils provides an opportunity for climate change adaptation and mitigation. According to FAO (2015), sustainable soil management refers to maintenance of the supporting, provisioning, regulating and cultural services provided by soil without significantly impairing the soil functions or biodiversity that enable those services. Sustainable soil management CSA practices include soil nutrient management, managing soil physical properties, soil water management, pest and disease management, cover crops and crop rotations (Ramborun et al. 2020).

Soil nutrients required for plant growth and their availability for plant uptake depend on the timing of fertilisation, the method and the quantity of different nutrients applied to the soil. Correct plant nutrition management interacts with many factors. For example, increasing fertiliser use efficiency involves reducing losses of plant nutrients from soil due to leaching, denitrification, evaporation and surface flow (Chikowo et al. 2014; Masvaya et al. 2017). Therefore, precision application of nitrogen has been recommended for good fertiliser management (Kihara et al. 2022). High nitrogen losses lead to environmental problems such as groundwater contamination and contribute to greenhouse gas emissions (Peng et al. 2022). Nutrients such as phosphorus (P) and potassium (K) can be transformed into non-volatile forms in the soil (Kihara & Njoroge 2013). Proper management of the soil helps to improve the availability of phosphorus (Bekunda et al. 2022). Thus, practicing integrated soil fertility management increases soil nutrient retention capacity and availability of nutrients to plants (Kihara et al. 2022).

Tillage methods such as conventional tillage (with ploughing) and minimum tillage, soil disturbance, cover crops and crop diversification influence soil quality (Busari et al. 2015), soil organic matter (Breil et al. 2023) and nutrient availability (Kafesu et al. 2018). Factors such as soil water retention, soil water movement, soil compaction and soil temperature are also affected by tillage methods and by general management of agricultural soils, and thereby affect mineralisation of fertilisers (Plaza-Bonilla et al. 2015). Soil quality indicators such as total organic carbon (SOC), soil moisture content, soil acidity (pH), electrical conductivity (EC), soil microbial meso- and macrofaunal biomass, soil aggregate stability *etc.* can be used to assess how CSA practices affect the resilience, adaptation or mitigation aspects of agricultural systems.

Various studies in sub-Saharan Africa on integrated soil fertility management have been conducted at different levels and scales (Chikowo et al. 2014; Masvaya et al. 2017; Kafesu et al. 2018; Kihara et al. 2020; Shumba et al. 2020; Nyamasoka-Magonziwa 2021). These studies can be used to extract learning points for implementation of CSA practices. Fertiliser management includes maximising the use efficiency of chemical fertilisers and organic fertilisers, taking into consideration plant nutrient requirements, soil nutrient status and fertiliser type, dose, application time and method (Vanlauwe et al. 2011). Mechanical incorporation of fertilisers through ploughing and disturbing the soil disrupts the formation of new soil aggregates (Lal 2010; Sithole et al. 2019) and speeds up microbial activity, leading to rapid mineralisation of organic nitrogen fertilisers (Singh & Ryan

2015). Tillage to loosen soil and control weeds is a business as usual (BAU) practice that exposes the loose soil to raindrop impact, wind and heat, thereby aiding soil erosion and soil carbon losses (Bationo et al. 2015; Sithole et al. 2019). Business as usual soil fertility management practices that are not climate-smart include inappropriate type, timing and application method of fertilisers, which results in reduced efficiency and losses of nutrients through leaching or greenhouse gases (Anuga et al. 2020).

Therefore, soil nutrient management for CSA can include practices such as application of organic fertilisers, residue retention, cover crops, legume intercropping patterns, minimum tillage and precise application of fertilisers.

# 3. Materials and methods

## 3.1 Study overview

The work reported in Papers I-III in this thesis comprised a questionnaire-based survey and two on-farm field experiments in Zimbabwe.

### 3.1.1 Study area description

The survey and on-farm research were conducted in seven different wards in the Marange area, Mutare district, Manicaland province, Zimbabwe (18°59′-19°25′S; 32°1′-32°37′E) (Figure 2). The field experiment sites were within one of the wards included in the survey (Ward 2, Mutanda), in smallholder farmer fields at Mt. Zonwe (Figure 2). The study location in Paper II (site A; 19°11′30″S, 32°3′28″E) was at 833 m above sea level and that in Paper III (site B; 19°11′54″S, 32°3′34″E) was at 835 m above sea level (Figure 3). Coarse-textured sandy soils are dominant in the area. The choice of the Marange area was guided by the extensive area of sandy soils, which can gain great potential benefits from adopting soil and water management practices to improve crop production under recurrent seasonal droughts (Kubiku et al. 2022). The area is located in Agro-ecological Region IV, characterised by annual rainfall of <650 mm and mean maximum air temperature of 28 °C (Manatsa et al. 2020). The rainfall pattern is unimodal and the duration of the cropping season is from October to March. The crop growing season has average long-term rainfall of around 380 mm (Chiturike et al. 2024). Mid-season dry spells and periods of heavy rainfall are common during the crop growing period. The vegetation in the area is typically semi-arid savannah, comprising deciduous trees and shrubs interspaced with overgrazed grass. The landscape is relatively flat, with scattered rocky outcrops. The area is suitable for drought-tolerant crops such as cowpeas (*Vigna unguiculata* L.), maize varieties requiring 105-120 days to maturity, extensive cattle ranching, rearing small livestock such as goats, and wildlife (Manatsa et al. 2020). Farmers in the area grow crops such as maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), pearl millet (*Pennisetum glaucum* (L.) R. Br.), finger millet/rapoko (*Eleusine coracana* L.) and groundnuts (*Arachis hypogea* L.) (Chiturike et al. 2022). Mixed farming, including livestock rearing, field crops and horticultural seasonal crops, is common in the area.

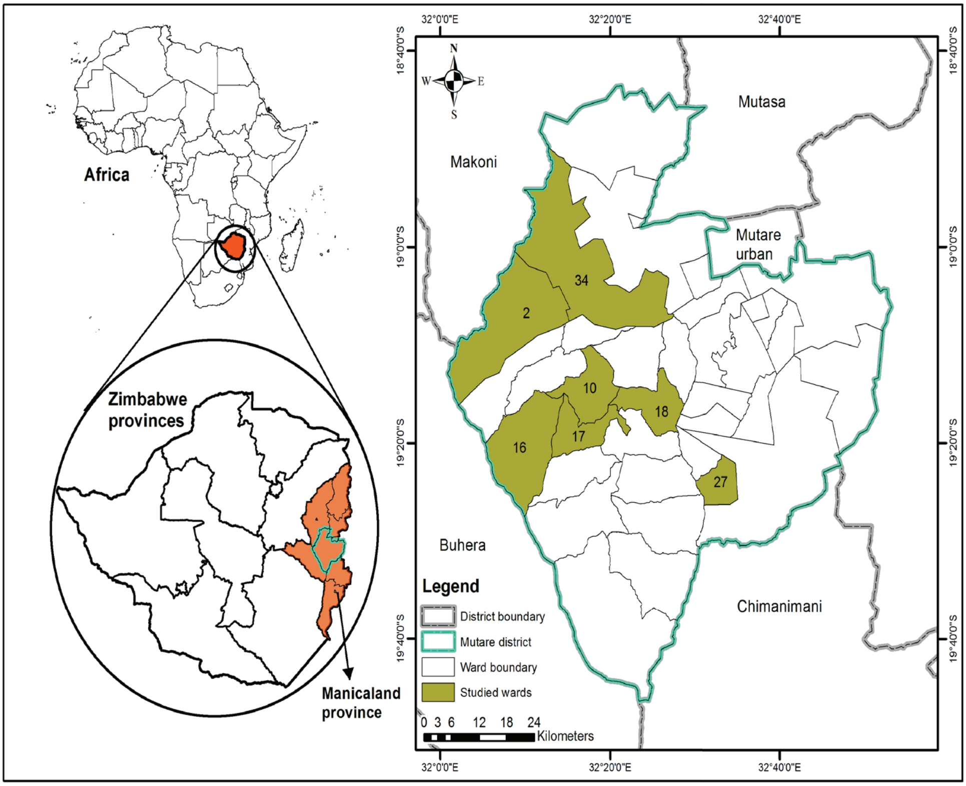



*Figure 2.* Maps showing (left) the location of Manicaland province in Zimbabwe, southern Africa, and (right) the study areas in Marange, Mutare district (Wards 2 (Mutanda), 34 (Nyagundi), 16 (Mafararikwa), 10 (Nyachityu), 17 (Takarwa), 18 (Mudzimundiringe) and 27 (Munyoro)).

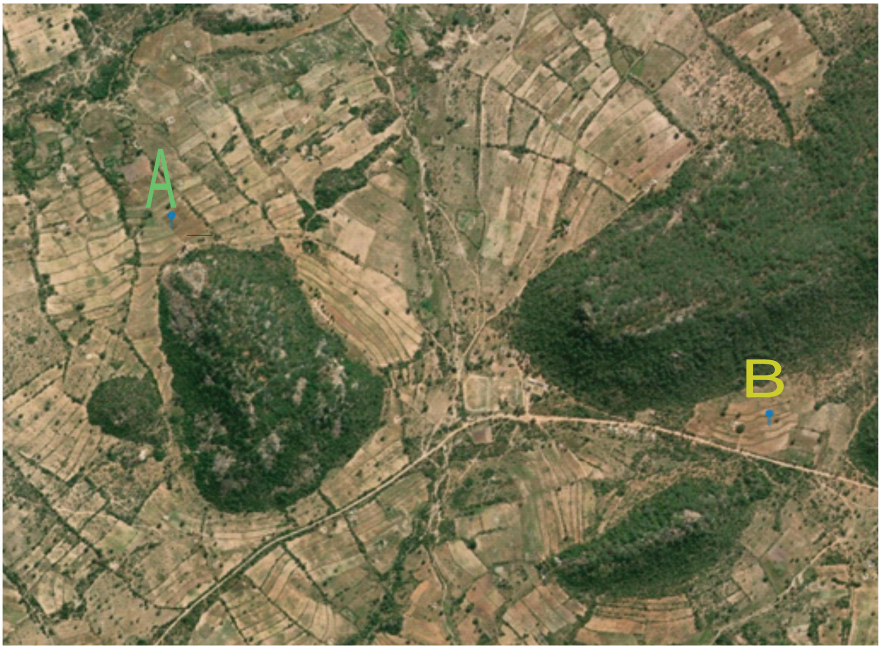



*Figure 3*. Location of study site A (91°11′33″S, 32°3′29″E) in Paper II and site B (19°11′54″S, 32°4′34″E) in Paper III, both in Mt. Zonwe, Ward 2 (Mutanda), Marange, Mutare district. Image modified from Google earth version 10.55.0.1. Map data: Google /Maxar Technologies/Airbus Landsat (accessed 13 April 2024).

Soil characterisation in terms of soil organic carbon (SOC), pH, exchangeable base cations, mineral nitrogen and available phosphorus was conducted at both field experiment sites (A and B). Soil samples were taken from five different soil layers (0-10 cm, 10-20 cm, 20-40 cm, 40-60 cm, 60-80 cm) prior to setting up the experiments. Five sub-samples collected from each experimental block/ row and layer were pooled to a composite sample. The composite soil samples were air-dried, sieved (<0.002 m) and analysed at the laboratory of the Chemistry and Soil Research Institute (Department of Research and Specialist Services in Zimbabwe).

Soil pH was measured using 0.01M $CaCl_2$ (Anderson & Ingram, 1993), and readings were taken using a standard pH meter (Hanna, H18424). Exchangeable bases were extracted using 1 M ammonium acetate (Anderson & Ingram, 1993). Soil organic carbon was measured using a modified Walkley-Black method (Okalebo et al. 2002). Mineral nitrogen was measured as ammonium-nitrogen ($NH_4^+$-N) and nitrate-nitrogen ($NO_3^-$-N), using 0.5 M $H_2SO_4$ for extraction, followed by colorimetric methods

(Okalebo et al. 2002). Available phosphorus was extracted using 0.5 M $NaHCO_3$ and measured using inductively coupled plasma optical omission spectrometry (Agilent 5100 ICP-OES) (Okalebo et al. 2002).

The results revealed that the experimental field at site A was low in SOC (range 0.55-0.72%) and had moderately acidic pH (5.7) in the plough layer (Table 1). The concentrations of mineral nitrogen, available phosphorus, SOC and soil pH decreased with depth in the soil (Table 1). The field at site B had pH (0.01 M $CaCl_2$) of 5.1 within the topsoil layer (0-10 cm depth) and became strongly acidic with depth. The concentrations of mineral nitrogen and available phosphorus decreased with depth. The SOC concentration was low (~0.63%) in the 0-10 cm layer and decreased with depth (Table 1).

Table 1. *Characteristics of the soil profile at experimental sites A and B, based on analysis of composite samples from n=3 blocks (site A) and n= 3 rows (Site B). Mean and standard error for soil pH ($CaCl_2$), mineral nitrogen ($NH_4^+$-N + $NO_3^-$-N), available phosphorus (resin extract), soil organic carbon (SOC) and exchangeable cations*

| Site A | | | | | Exchangeable cations, me $(100g)^{-1}$ | | | |
|---|---|---|---|---|---|---|---|---|
| Soil layer (cm) | Soil pH ($CaCl_2$) | Mineral N, mg $kg^{-1}$ | Available P, mg $kg^{-1}$ | SOC, % | $K^+$ | $Ca^{2+}$ | $Mg^{2+}$ | $Na^+$ |
| 0-10 | 5.7 ± 0.2 | 76.5 ± 4.5 | 10.2 ± 1.5 | 0.72 ± 0.04 | 0.22 ± 0.09 | 2.34 ± 0.02 | 0.83 ± 0.03 | 0.58 ± 0.02 |
| 10-20 | 5.7 ± 0.03 | 30.0 ± 5.5 | 5.2 ± 0.4 | 0.55 ± 0.07 | 0.26 ± 0.01 | 2.35 ± 0.09 | 0.89 ± 0.15 | 0.62 ± 0.02 |
| 20-40 | 5.1 ± 0.2 | 29.3 ± 3.8 | 2.7 ± 1.2 | 0.63 ± 0.16 | 0.24 ± 0.02 | 2.15 ± 0.12 | 0.82 ± 0.05 | 0.61 ± 0.03 |
| 40-60 | 5.0 ± 0.3 | 36.7 ± 6.2 | 2.2 ± 0.9 | 0.41 ± 0.40 | 0.24 ± 0.03 | 1.98 ± 0.14 | 0.78 ± 0.34 | 0.59 ± 0.03 |
| 60-80 | 5.2 ± 0.6 | 44.0 ± 3.6 | 5.9 ± 3.8 | 0.41 ± 0.09 | 0.23 ± 0.02 | 2.08 ± 0.18 | 0.75 ± 0.04 | 0.59 ± 0.05 |
| Site B | | | | | | | | |
| 0-10 | 5.1 ± 0.07 | 48 ± 5.5 | 8.7 ± 1.5 | 0.63 ± 0.10 | 0.2 0± 0.02 | 1.79 ± 0.06 | 0.68 ± 0.02 | 0.53 ± 0.01 |
| 10-20 | 4.6 ± 0.06 | 41.± 4.7 | 6.7 ± 1.6 | 0.53 ± 0.08 | 0.15 ± 0.02 | 1.76 ± 0.10 | 0.68 ± 0.02 | 0.53 ± 0.03 |
| 20-40 | 4.6 ± 0.09 | 56.± 8.6 | 3.3 ± 1.3 | 0.44 ± 0.07 | 0.13 ± 0.02 | 1.85 ± 0.07 | 0.76 ± 0.03 | 0.49 ± 0.02 |
| 40-60 | 4.9 ± 0.1 | 62 ± 5.4 | 1.2 ± 0.2 | 0.40 ± 0.08 | 0.12 ± 0.01 | 2.00 ± 0.06 | 0.83 ± 0.03 | 0.54 ± 0.02 |
| 60-80 | 5.0 ± 0.1 | 58 ± 7.7 | 2.7 ± 1.5 | 0.42 ± 0.06 | 0.11 ± 0.02 | 2.12 ± 0.13 | 0.85 ± 0.06 | 0.55 ± 0.03 |

## 3.2 Study design and data collection

### 3.2.1 Household questionnaire survey (Paper I)

A structured household questionnaire-based survey was conducted in September 2019. The questionnaire included modules on socio-economic data, land management and agricultural inputs, crop information, livestock, poultry and their products, labour source, gender-related aspects, access to capital, credit, extension services and external resources, climate and soil, food security and wealth status (Paper I).

The sample for the population-based household survey was selected with the help of extension officers, using a non-probability-based snowballing sampling approach (Naderifar et al. 2017) to provide a statistically representative sample of the project implementation wards in Marange, Mutare district (Figure 2). Seven wards within the Marange area were selected to capture the range of variation in awareness of climate change and adaptation strategies. Person-to-person interviews were held with 245 smallholder farmers within the seven wards in the study area and their responses were recorded on printed questionnaires by trained local enumerators. To evaluate climate awareness and adaptation strategies, a range of relevant variables were selected. The most relevant indicators to the objectives of the survey were farmer awareness of extreme weather events, types of events, adaptation strategies, barriers to adaptation and maize yield per hectare (Paper I).

### 3.2.2 Soil water management and plant density experiment (Paper II)

The on-farm experiment at field site A was established in the 2019/20 summer cropping season (November 2019). The experiment lasted for four years, until the 2022/23 summer cropping season. A split-plot design was used, with sub-surface water retention technology (SWRT; Figure 4) and control (no-SWRT) in main plots and different maize planting densities in sub-plots in three replicate blocks (Figure 5). The main plots measured 40 m ×15 m (Figure 5). SWRT membranes were installed at 40 cm and 60 cm depth within the soil profile (Figure 4) and 40 m along the full plot length. Three plant densities were assigned to subplots: high, medium and low, with 111,111 plants ha$^{-1}$ (spacing 60 cm × 15 cm), 74,000 plants ha$^{-1}$ (spacing 90 cm × 15 cm) and 37,000 plants ha$^{-1}$ (spacing 90 cm × 30 cm), respectively. Farmers in the study area usually aim for 37,000 plants ha$^{-1}$ (spacing 90 cm × 30 cm). The plot length was reduced from 40 m to 20 m from the second season (2020/21) to accommodate another experiment.

Medium-maturity commercial maize hybrid PHB 30G19 was planted manually at the beginning of each season in November/December. Basal NPK fertiliser (7% N, 14% $P_2O_5$, 7% $K_2O$) in an amount of 6 g per planting station was applied at planting, and about 5 g of ammonium nitrate topdressing was applied between 36 and 44 days after planting (DAP) and 54 and 67 DAP, depending on soil moisture availability (Table 2).

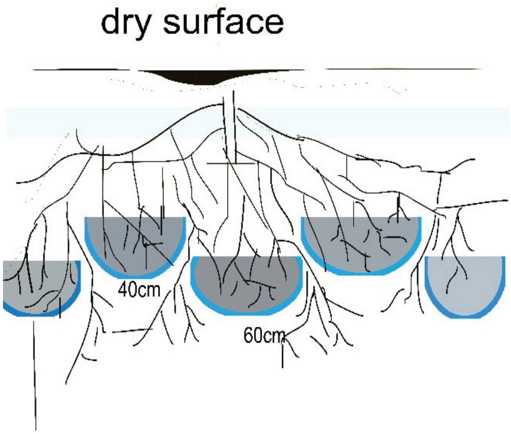



*Figure 4.* Sub-surface water retention technology (SWRT) used in the experiment in Paper II and III. A U-shaped polyethylene membrane was installed at two depths (40 cm and 60 cm) below the root growth zone to create an artificial watertable, with the aim of increasing water and nutrient availability and reducing leaching losses.

Table 2. *Dose of basal compound fertiliser (7% N, 14% $P_2O_5$, 7% $K_2O$) and ammonium nitrate topdressing (34.5% N) applied at low (37,000 plants ha$^{-1}$, spacing 90 cm × 30 cm), medium (74,000 plants ha$^{-1}$; spacing 90 cm × 15 cm) and high (111,111 plants ha$^{-1}$; spacing 60 cm × 15 cm) plant density*

| | Basal fertiliser | | | Ammonium nitrate |
|---|---|---|---|---|
| Plant density | N kg ha$^{-1}$ | P kg ha$^{-1}$ | K kg ha$^{-1}$ | N kg ha$^{-1}$ |
| Low | 16 | 14 | 13 | 128 |
| Medium | 31 | 27 | 26 | 255 |
| High | 47 | 41 | 39 | 383 |

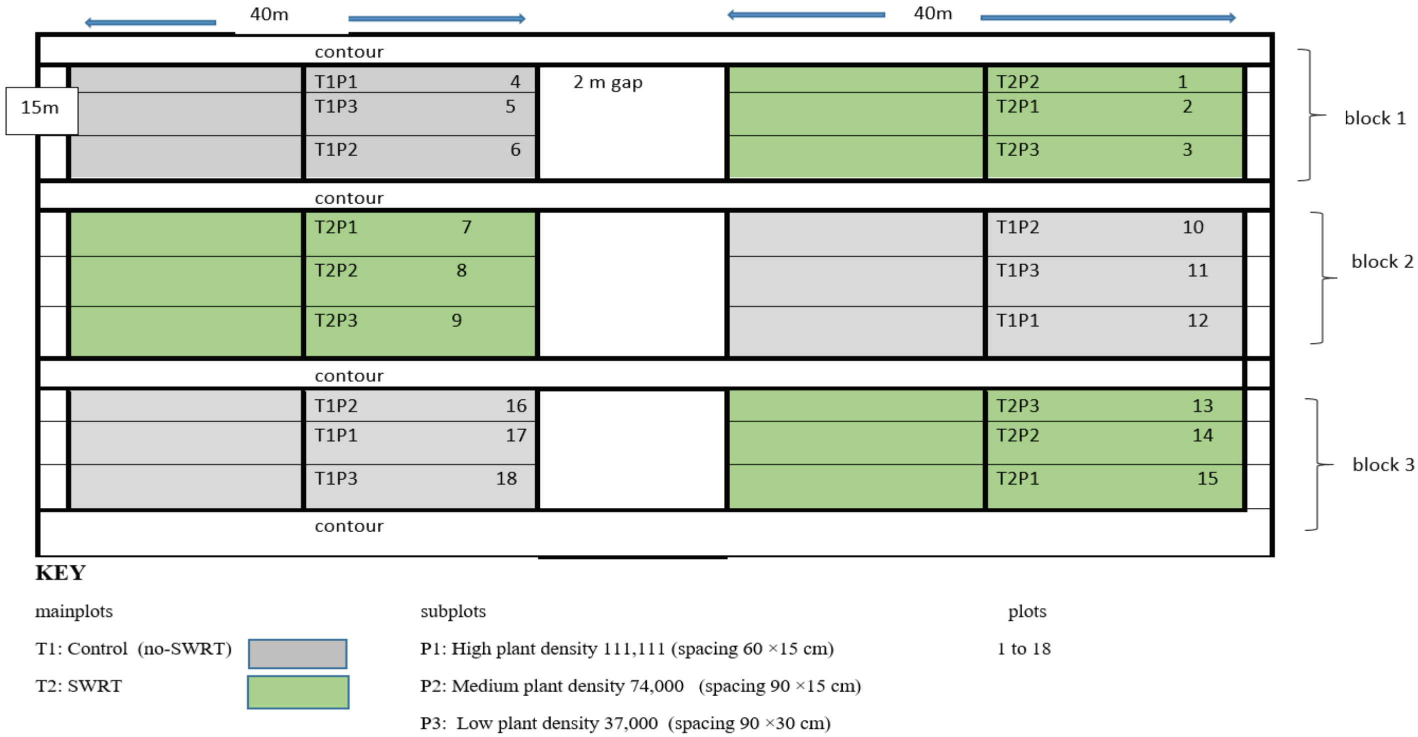



*Figure 5.* Experimental layout of main plots and sub-plots at site A. Full 40 m length was used in year 1, 20 m in years 2-4. SWRT, sub-surface water retention technology.

### 3.2.3 Soil water and nutrient management experiment (Paper III)

The on-farm experiment at field site B was conducted over three cropping seasons (2019/20 to 2021/22). The experiment was set up in a split-plot design replicated six times in three rows (Figure 6). The main plots (10 m × 9.8 m) included SWRT and the control, while the sub-plots (5 m × 4.5 m) had different soil amendments. In addition to the farmers' business as usual, the soil amendments consisted of different combinations of manure, basal fertiliser and topdressing, as described in Table 3. Manure containing 1.1% N, 0.3% P and 0.7% K was applied at a rate of 3 t ha$^{-1}$ to the plots at planting. Basal compound fertiliser (7% N, 14% $P_2O_5$, 7% $K_2O$) was also applied at planting to plots receiving basal fertiliser as a soil amendment. Topdressing with ammonium nitrate (34.5% N) was split into two doses, applied between 36 and 44 DAP and 54 and 67 DAP depending on soil moisture status. The selected soil amendments were applied each season. A medium maturing maize variety (PHB30G19) was sown manually at the beginning of each season, at a spacing of 90 cm inter-row and 15 cm in-row, giving an average of 74,000 plants ha$^{-1}$. Weed control was performed by hand hoeing when necessary.

Table 3. *Amounts of nitrogen (N), phosphorus (P) and potassium (K) (kg ha$^{-1}$) applied in treatments T1-T4 in Paper III, in combination with soil moisture management with sub-surface water retention technology (SWRT). The treatments comprised application of manure and topdressing in T1, basal fertiliser and topdressing in T2, manure, basal fertiliser and topdressing in T3 and business as usual (BAU) for farmers (control) in T4*

| | Manure kg ha$^{-1}$ | | | Basal fertiliser kg ha$^{-1}$ | | | Topdressing kg ha$^{-1}$ | Total kg ha$^{-1}$ | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Treatment | N | P | K | N | P | K | N | N | P | K |
| T1 | 33 | 9 | 21 | | | | 255 | 288 | 9 | 21 |
| T2 | | | | 31 | 27 | 26 | 255 | 286 | 27 | 26 |
| T3 | 33 | 9 | 21 | 31 | 27 | 26 | 255 | 319 | 36 | 47 |
| T4 (control) | | | | | | | 52 | 52 | | |

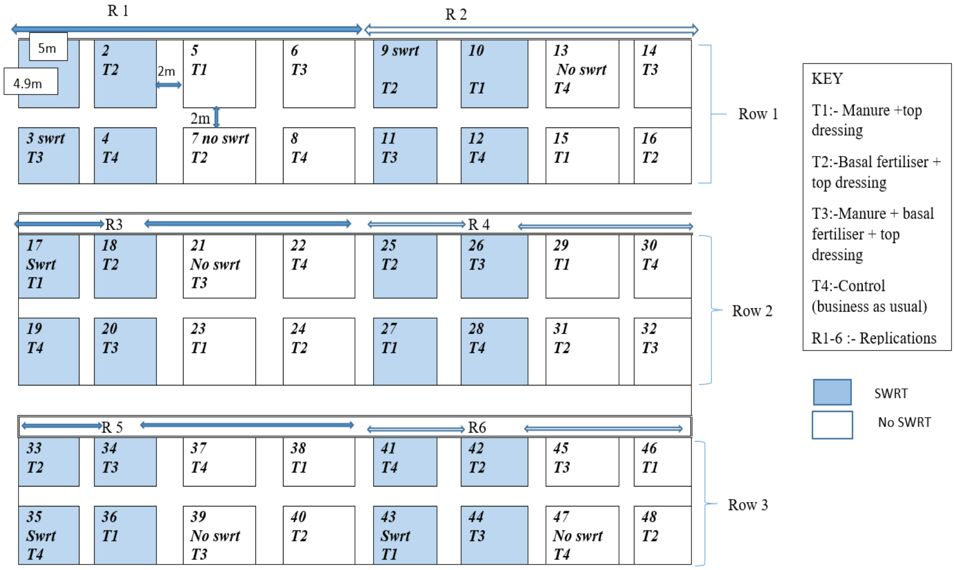



*Figure 6*. Experimental layout of main plots with sub-surface water retention technology (SWRT) and sub-plots with soil amendment treatments T1 to T4, following rows/contours in the field.

### 3.2.4 Field measurements, sampling and calculations

Leaf chlorophyll content and plant height were monitored during the season. Leaf chlorophyll was measured using a Soil-Plant Analyser Development (SPAD-502) meter (Minolta, Japan), to follow nitrogen uptake by the crop. In Paper II, six, three, two and six chlorophyll measurements were conducted in the 2019/2020, 2020/2021, 2021/2022 and 2022/2023 season, respectively. In Paper III, SPAD readings were made during the three seasons of the study (2019/20 to 2021/22) and leaf chlorophyll content before the second fertiliser application was considered for further analysis. Plant height was measured on the same occasions as chlorophyll in all seasons except 2019/2020, when the SPAD-meter was only available after the first four height measurements (Paper II). Plant height measured at harvest was considered in Paper III. All height measurements determined the height from the ground to the apex of the uppermost leaf.

To measure maize biomass and grain yield in the first year in Paper II, a net plot of 8 m (within the row) × 3 rows in each plot was harvested. From 2020-21 to 2022-23, three plots measuring 2.7 m long × 3 rows wide (8 m linear length harvested per plot) were randomly selected for harvesting in each treatment plot (Paper II). The width of the harvested rows was measured three times along the harvested plot, to obtain the average width of the three rows at different densities. In Paper III, maize biomass and grain yield were harvested from 5.4 $m^2$ plots of each treatment yearly. Aboveground biomass, including cobs and stover, from each plot was sampled and weighed using a digital balance, after counting the number of plants and cobs. The number of plants in the harvested plots was used to estimate the final population standing at harvest per hectare. Harvested cobs and approximately 500 g of biomass were taken from each harvested plot for further analysis. Maize cobs and biomass sub-samples were air-dried and re-weighed, and grain moisture content was measured after two to three weeks using a mini-GAC® moisture tester (DICKEY-John, USA). The maize cobs were shelled and grain yield was converted to t $ha^{-1}$ at 12.5% standard moisture content. Final plant population at harvest and maize grain yield in kg $ha^{-1}$ were used to determine maize grain yield per plant, by dividing maize grain yield $ha^{-1}$ by final plant population. Harvest index was calculated as the ratio of maize grain yield to total above-ground biomass.

In paper II, 48 composite soil samples representing every treatment were collected at harvest in the third season (April 2022) and sent for analysis of available P, SOC, pH and exchangeable bases (K+, Ca 2+, Mg2+).

Rainfall (mm) was recorded by the farmers using a rain gauge installed at the experimental sites. Rainwater use efficiency (RWUE) was calculated based on total rainfall received between sowing and harvesting of maize and grain yield at 12.5% grain moisture content recorded for each plant density (Paper II) with and without SWRT (Mupangwa et al. 2016), using the equation:

$$RWUE\ (kg\ ha^{-1}mm^{-1}) = \frac{Grain\ yield\ (kg\ ha^{-1})}{Total\ rainfall\ (mm)} \qquad i$$

## 3.3 Statistical analyses

To assess farmers' awareness of extreme weather events, data analysis including descriptive statistics on the percentage of farmers who had experienced extreme weather events was conducted, using the IBM SPSS statistical package. To identify adaptation strategies implemented, cross-tabulations were made for adaptation options linked to the weather events experienced. Factors underlying the implemented adaptation strategies were assessed using generalised linear regression model (glm) with a logit link in R version 4.2.1 (R Core Team 2022). Definitions of variables used (response and explanatory) and the glm equation can be found in Paper I (Equation (ii) in Paper I). To evaluate maize yield under different soil fertility and water management practices and for different varieties, the data were first split into categories of farmers applying different types of fertiliser (four levels), water management practices (seven levels) and crop varieties (two levels) (see 'Data management' section in Paper I). Taking maize yield as a response variable, the linear model function in R statistical software Version 4.2.1 (R Core Team, 2022) was then used to analyse variations in the management categories employed by farmers to improve yield (Equation (i) in Paper I). Where there were no interactions between management categories, the Kruskal-Wallis test was used to test for differences within categories, which was followed by a post-hoc pairwise multiple comparison to separate the different groups, using Wilxocon Mann-Whitney test for significant categories (Paper I).

To evaluate the effect of SWRT on maize performance and RWUE at different plant populations across seasons in Paper II, the four seasons of data (2019/20-2022/23) on maize grain yield, total biomass, individual plant yield, final plant population at harvest, harvest index and RWUE were combined and assessed for normality. Where data lacked homogeneity of variance, log transformation was performed, *i.e.* on maize grain yield (Paper II). Maize grain yield, total biomass, individual plant yield, final plant population percentage at harvest, harvest index and RWUE were expressed as a function of season (year), SWRT and plant density in a linear mixed-effects model using the lmer function from the statistical package *lmerTest* (Kuznetsova *et al.* 2017) in R statistical software Version 4.3.0 (R Core Team, 2023). The fitted model in Paper II comprised fixed effects of season (year), SWRT, plant density, interaction effects, and random effects of blocks within season and SWRT treatment. Data on leaf chlorophyll (SPAD readings) and plant height at each selected DAP were analysed for each season in linear mixed-effects models (Paper II). The fitted model for growth parameters comprised SWRT, plant density, interactions and random effects of blocks.

In Paper III, maize grain and total biomass yield for the three seasons (2019/20 to 2021/22) were expressed as a function of SWRT, soil amendments and season in linear mixed effects models, to determine the effect of SWRT and soil amendments on maize yield. The model comprised fixed effects of SWRT, soil amendment, season and their interactions and random effects of replication within season. Chlorophyll levels recorded before application of the second topdressing dose and maize height at harvest were analysed for each season and for all three seasons combined (Paper III). The fitted model for chlorophyll and that for maize height parameters included fixed effects of SWRT treatments, soil amendments, their interaction and random effects replications. When all three years of the study were combined, additional fixed factors of season, all interactions associated with season and random effect of season were added to the model.

To determine the effect of SWRT and soil amendments on soil nutrient status in Paper III, soil chemical analysis data were subjected to linear mixed-fixed effect models. The model included fixed effects of SWRT, soil amendment, sampling depth, all interactions and random effects of depth within replications.

To compute statistical *p*-values for the treatment and interaction effects in Paper II and Paper III, all the fitted linear mixed-effects models were subjected to analysis of variance (ANOVA) of type III with Kenward-Roger degrees of freedom. Computation of estimated marginal means (emmeans) to determine the averages of yield parameters, RWUE, plant height, chlorophyll and soil nutrient status for each treatment, and their interactions in the fitted models, was done using the *emmeans* package (Lenth, 2022). Where ANOVA of the fitted model showed significant ($p<0.05$), treatment and treatment interaction effects, emmeans separation was performed using Tukey's HSD test at alpha = 0.05.

# 4. Results

## 4.1 Farmer characteristics, awareness of extreme weather and adaptation measures used

Smallholder farmers in the study area owned between 2.8 and 3.8 ha of land per farm (Paper I). Around 90% of the respondents out of the total of 245 surveyed owned land. Maize was the main cereal crop, grown by 69% of farmers in the study area. Other cereal crops included pearl millet, sorghum and finger millet/rapoko, grown by 42%, 26% and 9% of farmers, respectively. Grain legumes, were also frequently grown by the farmers; of whom 35% grew groundnuts, 20% grew Bambara nuts (*Vigna subterranea*) and 8% grew cowpea.

Of the 245 farmers included in the study, 50-55% reported having suffered from food insecurity from December to January. About 25% and 14% of the farmers reported experiencing food insecurity in February and March, respectively. Only 2% of the farmers experienced food insecurity from April to July. In August, September, October and November, 10%, 30%, 42% and 48% of farmers, respectively, had experienced food insecurity (Table 3 in Paper I).

### 4.1.1 Farmers' awareness of extreme weather events (Paper I)

All 245 smallholder farmers interviewed confirmed that they had experienced extreme weather events in the past five years. Drought was the most commonly experienced extreme weather event, reported by 46% of farmers. Other extreme weather events reported were above-average temperatures, strong winds and floods, which were reported by 26%, 12% and 10% of farmers, respectively. Below-average winter temperatures were reported by 5% of the farmers. A few farmers (<5%) had also experienced erratic rainfall patterns, short crop growing season and cyclones.

### 4.1.2 Adaptation strategies implemented and underlying factors (Paper I)

Of the eight types of extreme weather events reported, farmers had employed adaptation strategies for five: drought, floods, strong winds, increased temperatures and reduced temperatures (Figure 7). Nine adaptation strategies were reported against drought, while three to five were reported for other types of extreme weather events. Common adaptation strategies against drought were water harvesting, changing planting dates, soil moisture management, alternative crops and use of improved seeds (Figure 7).

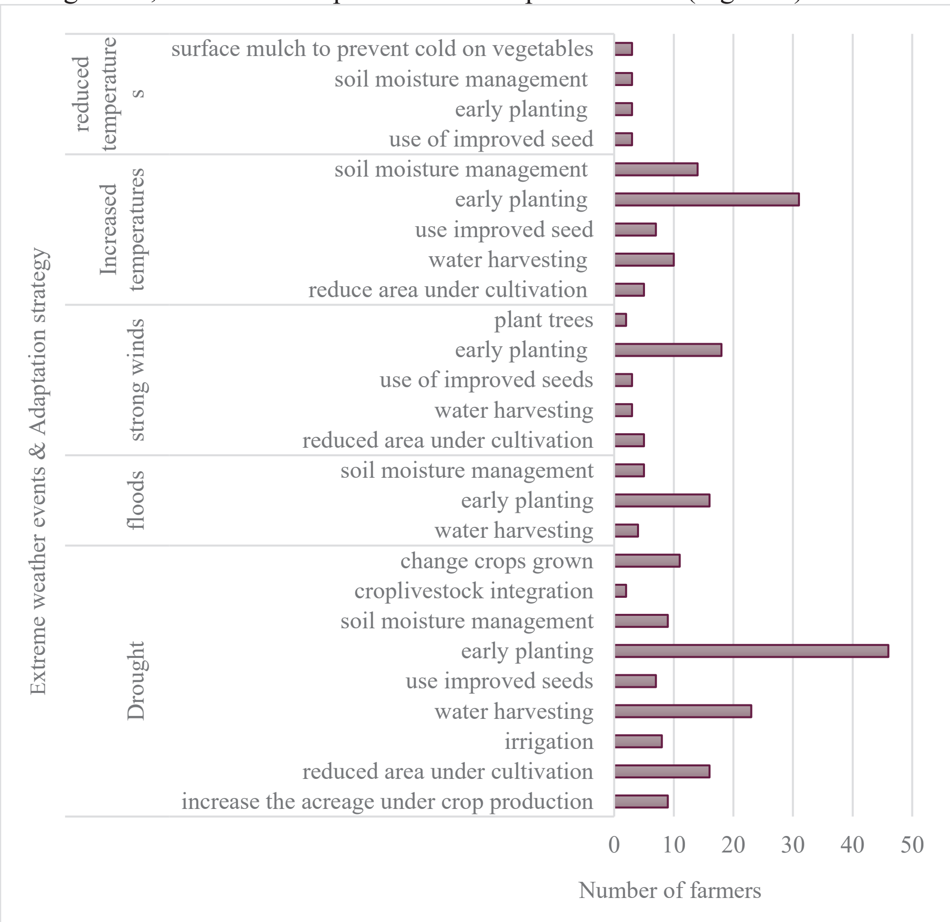



*Figure 7.* Adaptation strategies to extreme weather events reported by surveyed farmers (n=245) in Marange, Mutare district, Zimbabwe (Paper I).

Farmers in the study area highlighted barriers to adaptation to extreme weather events, such as lack of resources (*i.e.* agricultural inputs and financial credit facilities), shortage of information on climate and adaptation practices and labour availability challenges (see Figure 2 in Paper I). Results from the generalised linear regression model indicated that farmer access to extension services positively impacted adoption of soil water management strategies, whereas it negatively influenced planting of trees and use of irrigation. Farmer education level (either primary or secondary school) positively influenced adoption of irrigation. Whereas gender, age and secondary education level were positively correlated with adoption of crop diversification. Household size was positively correlated with farmer adoption of irrigation and crop-livestock integration (Table 4 in Paper I).

### 4.1.3 Maize yield under different soil fertility and water management practices and with improved varieties (Paper I)

The ANOVA results showed no significant interactive effect of different management practices (soil fertilisation, maize variety and water management strategies) on the maize yield reported by farmers. Around 10% of the farmers surveyed applied manure, 32% applied mineral fertilisers and 38% applied a combination of manure and mineral fertilisers. The remaining 20% did not apply any fertiliser (Table 1 in Paper I).

Farmers who reported applying mineral fertiliser obtained average maize yield of 0.61 t $ha^{-1}$, whereas those who applied only manure reported yield of on average 0.62 t $ha^{-1}$ (Figure 8). The farmers who used both organic and inorganic fertilisers obtained average maize yield of 0.33 t $ha^{-1}$, while the farmers who reported that they applied neither inorganic nor organic fertiliser obtained 0.20 t $ha^{-1}$ (Figure 8). The Kruskal-Wallis *p*-values for the soil fertility categories indicated significant differences in the reported maize yields ($p$=0.03), while pairwise comparisons using the Wilcoxon Mann-Whitney test identified some significant differences between the soil fertility management categories (Figure 8). Reported maize yield of farmers who stated that they applied no fertilisers differed significantly from that of farmers who applied manure only, fertiliser only or a combination of both manure and fertiliser (Figure 8).

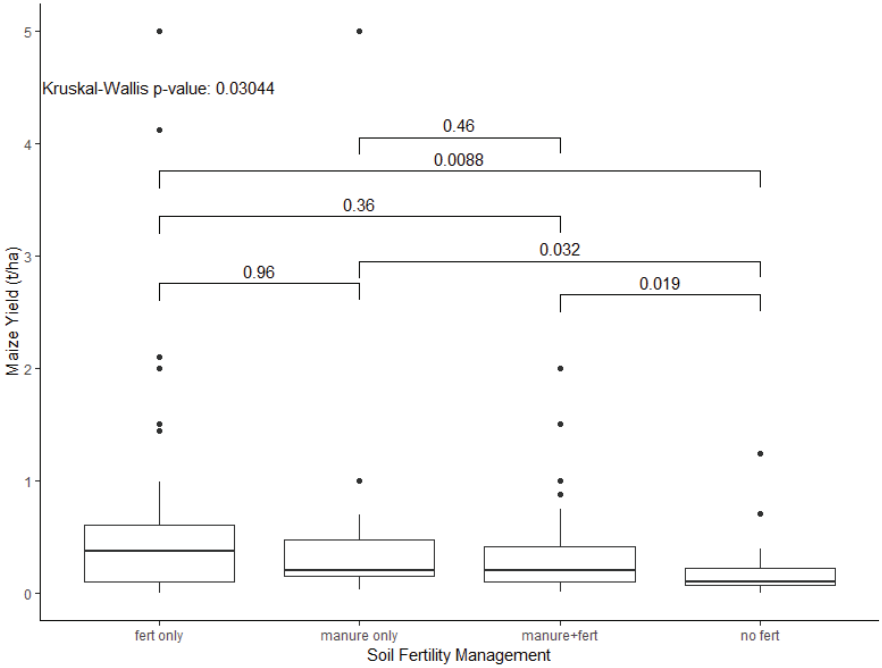



*Figure 8.* Average maize yield response to soil fertility management reported by smallholder farmers (n=245) in Marange, Mutare district, Zimbabwe. The bars connect groups of soil fertility management approaches and the numbers above each bar are Wilcoxon *p*-values. Fert, fertiliser (Paper I).

Smallholder farmers in Marange reported using different soil water management strategies on field crops, such as irrigation and in-field and out-field water management technologies (Table 1 in Paper I). Around 6% of respondents used in-field measures (*e.g*. mulching, potholing, basins, ridges, autumn ploughing), 34% used irrigation (low technology), 37% used a combination of irrigation and in-field measures, 2% used a combination of irrigation and in-field and out-field measures (*e.g*. standard contours, tied contours, infiltration pits, terracing), 6% used a combination of irrigation and out-field measures, 5% used out-field water management only and 10% of the farmers did not employ any soil water management strategy (Table 1 in Paper I).

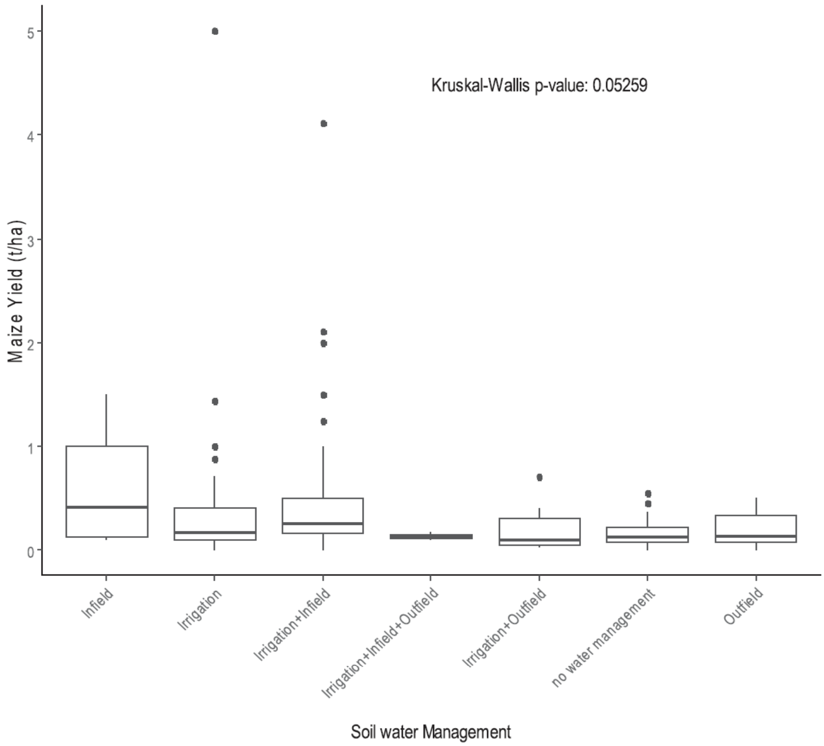



*Figure 9.* Average maize yield response to soil water management use by smallholder farmers (n=245) in Marange, Mutare district, Zimbabwe (Paper I).

The maize yields reported by farmers who applied soil water management strategies did not differ significantly from the yields reported by farmers who did not use any water management strategy ($p>0.05$) (Figure 9).

Most of the smallholder farmers surveyed used improved maize varieties, with 63% using certified maize hybrid seed and 37% using seed retained from the previous season (Table 1 in Paper I). Farmers who used an improved seed variety reported significantly higher ($p<0.001$) maize yields than those farmers who stated that they used non-improved seeds (Figure 4 in Paper I).

## 4.2 Seasonal rainfall variations (Papers II and III)

Total seasonal rainfall varied over the seasons at study sites A and B (Figure 10). The first cropping season (2019/20) received 313 mm of rainfall, primarily within six rainfall events of at least 20 mm $day^{-1}$. The study area had three short dry spells, lasting 11 to 15 days, in that season, in December-January, January-February and March-April. The most prolonged dry spell lasted 31 days during the February-March period. During the 2020/21 cropping season, total rainfall received was 780 mm, with 17 rainfall events of more than 20 mm $day^{-1}$, and there were a few short dry periods lasting 10 days at most. The third cropping season (2021/22) received total cumulative rainfall of 305 mm, with seven rainfall events of over 20 mm $day^{-1}$, and had the most prolonged dry spell (56 days) from the end of January to the end of March. Maize growing in that season suffered induced senescence due to the dry period, which affected crop growth, mainly grain filling and setting of maize cobs. During the fourth cropping season (2022/23, Paper II only), about 424 mm of cumulative rainfall was received from planting to harvesting, and the rainfall was evenly distributed. The dry spells experienced during the fourth cropping season did not exceed 10 days (Figure 10).

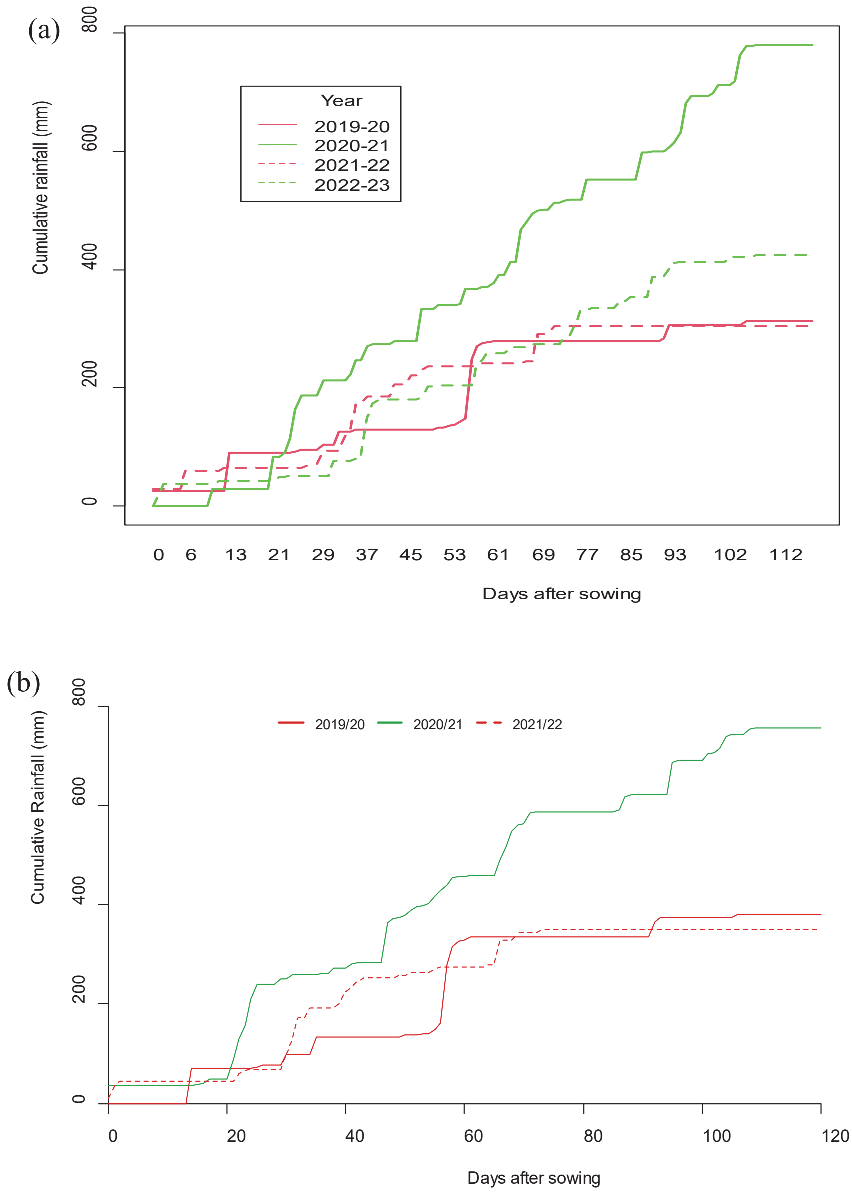



*Figure 10.* Cumulative seasonal rainfall distribution at (a) site A and (b) site B after planting. Planting date at site A was 15 December, 12 November, 21 November and 27 November in 2019-20, 2020-21, 2021-22 and 2022-23 season, respectively. Planting date at site B was 15 December, 13 November and 21 November in 2019/20, 2020/21 and 2021/22 respectively.

Study site B received 381, 757 and 352 mm of rainfall during the 2019/20, 2020/21 and 2021/22 cropping season, with similar periods of drought as at site A.

## 4.3 Effect of SWRT on maize performance and rainwater use efficiency at different plant densities (Paper II)

### 4.3.1 Maize crop growth

Maize height reached at least 200 cm by harvest in all seasons covered in Paper II. Maize chlorophyll content (SPAD reading) was commonly between 50 and 60 after applying topdressing. During the first cropping season at site A (2019/20), plant density significantly affected height ($p$=0.003) from 51 DAP onwards, with low plant density giving greater height than the other densities tested (high, medium). There were significant interactive effects of SWRT and plant density on maize height at 51, 59 and 79 DAP (Figure 5 in Paper II). The SPAD values decreased towards physiological maturity for both SWRT and control plants at different plant densities (Figure 5 in Paper II). Significant differences in SPAD values were observed between the different plant densities only at 74 DAP ($p$=0.035), with the highest SPAD values observed at high plant density.

During the second cropping season (2020/21), SWRT had no significant effect on maize height. Leaf chlorophyll SPAD values increased with maize growth and decreased towards physiological maturity. The SPAD values increased from low to high plant density at 74 DAP and onwards (Figure 5 in Paper II).

In the third cropping season (2021/22), significant effects of SWRT, plant density and their interaction on maize height were observed at 33 DAP. Maize height increased with SWRT use and plant density, following the order low < high < medium. Chlorophyll measurements were generally below 50 SPAD units in all treatments at 33 DAP, with some further decrease towards 60 DAP (Figure 5 in Paper II). No SPAD values were recorded for later stages in the third season, due to wilting and crop failure. In the fourth cropping season (2022/23), maize height was similar across plant densities, regardless of SWRT. Average SPAD values decreased with crop growth, but increased post-topdressing, decreasing again towards physiological maturity.

### 4.3.2 Effect of SWRT and plant density on maize yield (Paper II)

Maize yield at site A varied between seasons, with higher yields observed in the two wet seasons (2020/21 and 2022/23) than in the dry seasons (2019/20 and 2021/22). Plant density was the main source of grain yield variation during the second and fourth seasons and total biomass yield in the second and third seasons. Use of SWRT showed some tendency to improve yield within each season, with no significant interactive effect with plant density (Figure 11).

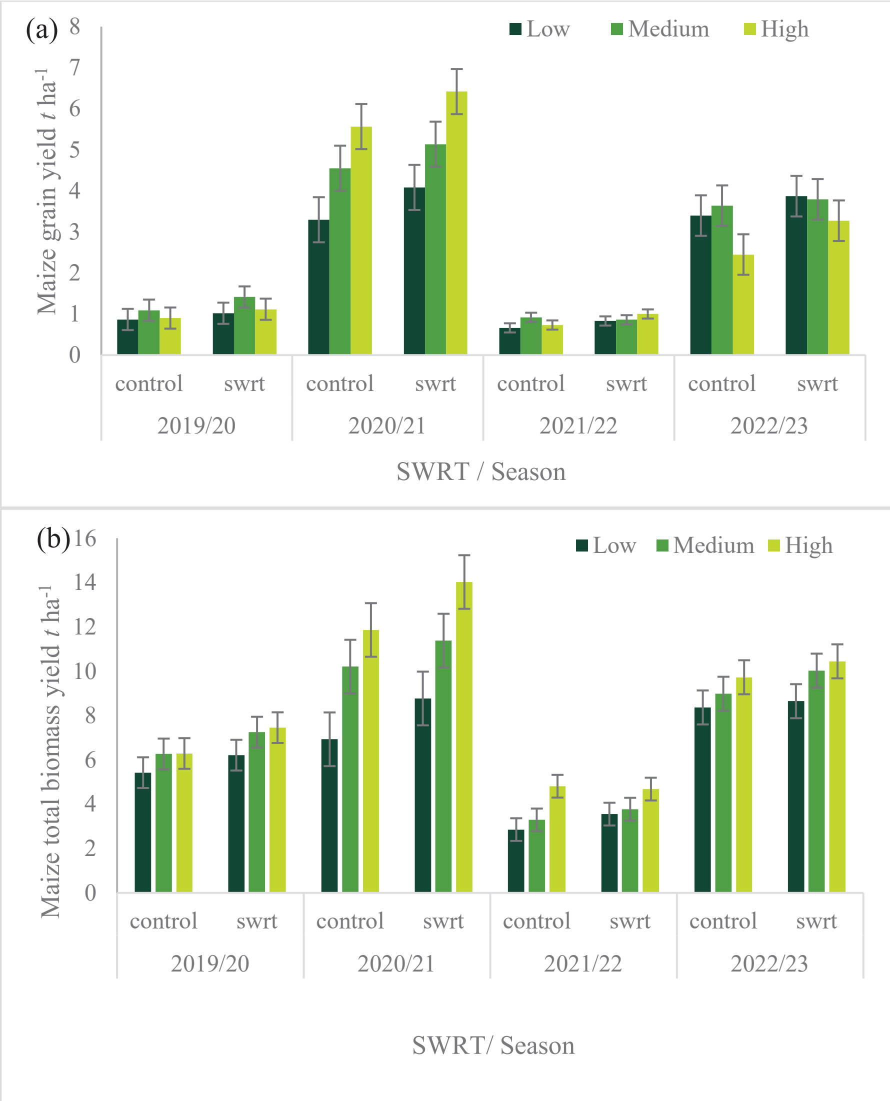



*Figure 11*. (a) Grain yield and (b) total biomass yield of maize under soil water management (control, SWRT) and at different plant densities (low (37,000 plants $ha^{-1}$; spacing 90 cm × 30 cm); medium (74,000 plants $ha^{-1}$; spacing 90 cm × 15 cm); high (111,111 plants $ha^{-1}$; spacing 60 cm × 15 cm)) at site A in the four seasons studied (2019/20 -2022/23).

The results of all four years combined showed that grain yields in plots with SWRT were significantly higher by 21% than in control plots without SWRT (Table 4). The medium plant density gave significantly higher grain yield than the low plant density (Table 4). Cropping season had significant effects on maize grain yield, with lower yields in the drier first and third cropping seasons than in the wetter second and fourth seasons (Table 4). Maize grain yield differences were also explained by the interactive effect of season and plant density (Table 4). Maize grain yield increased from low to medium density, then decreased at high plant density during the first, third and fourth cropping season (Table 5). Significantly high grain yields were recorded in the second season (2020/21) than in other seasons, and yield increases followed the order low < medium < high plant density. Grain yield of around 5.9 t $ha^{-1}$ was recorded in the second season under high plant density, whereas in first and third seasons yields of only around 0.8 and 0.9 t $ha^{-1}$ were obtained in that treatment (Table 5).

Total maize biomass yield increased with increasing plant density within seasons and varied across seasons. Total biomass yields recorded at the medium and high plant densities were higher in the (wetter) second and fourth seasons than in the first and third seasons. Low plant density gave lower biomass yields in all seasons, and biomass yield varied with season (Table 5). Treatments with SWRT had significantly higher biomass yield (13%) compared with the control (Table 4).

Final plant density and harvest index (HI) were used to further assess how manipulation of plant density affected maize yield. The results showed that low plant densities gave the highest plant density in the stand at harvest. The high and medium plant density treatments had significantly lower final plant density relative to the initial density (58-59% of the initial value) (Table 4). Plant density at harvest also varied with season, with the dry seasons giving less dense stands than the wet seasons. On average over the four years, HI was below 0.5 for all plant densities, although low plant density gave significantly higher HI than high plant density (Table 4).

Table 4. *Effects of sub-surface water retention technology (SWRT), plant density (37,000 plants ha$^{-1}$, spacing 90 cm × 30 cm; 74,000 plants ha$^{-1}$, 90 cm × 15 cm; 111,111 plants ha$^{-1}$, 60 cm × 15 cm) and season on four-year average maize grain yield, total biomass, final plant density stand at harvest and harvest index (HI)*

| Treatment | Grain yield (t ha$^{-1}$) | Total biomass yield (t ha$^{-1}$) | Grain yield, kg plant$^{-1}$ | Final plant density stands at harvest (%) | HI |
|---|---|---|---|---|---|
| *SWRT* | | | | | |
| SWRT | 2.06 (7.63*)$^{b}$ | 8.01$^{b}$ | 0.049 (-3.01)$^{b}$ | 67$^{a}$ | 0.31$^{a}$ |
| CONTROL | 1.70 (7.44)$^{a}$ | 7.10$^{a}$ | 0.041 (-3.19)$^{a}$ | 67$^{a}$ | 0.30$^{a}$ |
| *Plant density* | | | | | |
| 37 000 plants ha$^{-1}$ (90 × 30) cm | 1.72 (7.45)$^{a}$ | 6.34$^{a}$ | 0.056 (-2.88)$^{b}$ | 84$^{b}$ | 0.32$^{b}$ |
| 74 000 plants ha$^{-1}$ (90 × 15) cm | 2.04 (7.62)$^{b}$ | 7.65$^{b}$ | 0.049 (-3.01)$^{b}$ | 58$^{a}$ | 0.32$^{b}$ |
| 111,111 plants ha$^{-1}$ (60 × 15) cm | 1.86 (7.53)$^{ab}$ | 8.66$^{c}$ | 0,033 (-3.41)$^{a}$ | 59$^{a}$ | 0.27$^{a}$ |
| *Season* | | | | | |
| 1 (2019/20) | 0.98 (6.89)$^{a}$ | 6.48$^{a}$ | 0.029 (-3.53)$^{a}$ | 55$^{a}$ | 0.16$^{a}$ |
| 2 (2020/21) | 4.68 (8.45)$^{b}$ | 10.53$^{b}$ | 0.102 (-2.28)$^{b}$ | 87$^{b}$ | 0.46$^{c}$ |
| 3 (2021/22) | 0.81 (6.70)$^{a}$ | 3.83$^{a}$ | 0.024 (-3.73)$^{a}$ | 53$^{a}$ | 0.22$^{a}$ |
| 4 (2022/23) | 3.29 (8.10)$^{b}$ | 9.37$^{b}$ | 0.070 (-2.66)$^{b}$ | 74$^{b}$ | 0.37$^{b}$ |
| *p-value* | | | | | |
| Season | (<0.001) | <0.001 | 0.005 | <0.001 | <0.001 |
| SWRT membrane | (0.026) | 0.026 | 0.024 | 0.945 | 0.557 |
| Plant density | (0.022) | <0.001 | <0.001 | <0.001 | <0.001 |
| *Interactions* | | | | | |
| Season × SWRT | (0.920) | 0.560 | 0.875 | 0.865 | 0.892 |
| SWRT membrane × Plant density | (0.496) | 0.992 | 0.446 | 0.980 | 0.333 |
| Season × Plant density | (0.004) | 0.002 | 0.034 | <0.001 | 0.004 |
| Season × SWRT membrane × Plant density | (0.829) | 0.957 | 0.201 | 0.019 | 0.365 |

*Numbers in brackets denote log(x) transformed emmeans of grain yield as log(x). Means within columns followed by different letters are significantly different at $p<0.05$.

Table 5. *Maize yield (kg ha$^{-1}$) at low (37,000 plants ha$^{-1}$, spacing 90 cm × 30 cm), medium (74,000 plants ha$^{-1}$, 90 cm × 15 cm) and high (111,111 plants ha$^{-1}$, 60 cm × 15 cm) plant density in the four study seasons at site A (2019/20 to 2022/23)*

| | Plant density | | |
|---|---|---|---|
| | Low | Medium | High |
| Season | Grain yield, t ha$^{-1}$ | | |
| 2019/20 | 0.93 (6.83)*$^{a}$ | 1.15 (7.05)$^{ab}$ | 0.88 (6.78)$^{a}$ |
| 2020/21 | 3.64 (8.20)$^{cd}$ | 4.77 (8.47)$^{cd}$ | 5.88 (8.68)$^{d}$ |
| 2021/22 | 0.73 (6.59)$^{a}$ | 0.87 (6.77)$^{a}$ | 0.84 (6.73)$^{a}$ |
| 2022/23 | 3.57 (8.18)$^{c}$ | 3.68 (8.21)$^{cd}$ | 2.72 (7.91)$^{bcd}$ |
| | Total biomass yield, kg ha$^{-1}$ | | |
| 2019/20 | 5.82$^{abc}$ | 6.76$^{abcd}$ | 6.87$^{abcd}$ |
| 2020/21 | 7.85$^{bcd}$ | 10.79$^{ef}$ | 12.94$^{f}$ |
| 2021/22 | 3.21$^{a}$ | 3.53$^{a}$ | 4.75$^{ab}$ |
| 2022/23 | 8.51$^{cde}$ | 9.50$^{cdef}$ | 10.09$^{def}$ |

*Numbers in brackets denote *log(x)* transformed emmeans of grain yield as *log(x)*. Means within columns followed by different letters are significantly different at $p<0.05$.

### 4.3.3 Rainwater use efficiency of maize under SWRT and different plant densities (Paper II)

Rainwater use efficiency of maize at site A followed the same pattern as maize yield in all cropping seasons, *i.e*. it was significantly higher in the wetter second and fourth cropping seasons than in the dry first and third cropping seasons (Table 6). The SWRT treatment showed a tendency to increase RWUE by 17% compared with the control. The RWUE of maize was significantly higher at medium plant density (5.48 kg $ha^{-1}$ $mm^{-1}$) compared with low density (on average 4.69 kg $ha^{-1}$ $mm^{-1}$) (Table 6). Season and density had an interactive effect on the RWUE of maize (Figure 6 in Paper II).

Table 6. *Four-year average rainwater use efficiency (RWUE) of maize, per hectare and per plant, with and without sub-surface water retention technology (SWRT) at low (37,000 plants $ha^{-1}$, spacing 90 cm × 30 cm), medium (74,000 plants $ha^{-1}$, 90 cm × 15 cm) and high (111,111 plants $ha^{-1}$, 60 cm × 15 cm) plant density*

| Treatment | RWUE kg $ha^{-1}mm^{-1}$ | RWUE kg $plant^{-1}mm^{-1}$ |
|---|---|---|
| *SWRT* | | |
| SWRT | $5.5 \pm 0.35^{a}$ | $0.011 \pm 0.0002^{a}$ |
| Control | $4.7 \pm 0.35^{a}$ | $0.011 \pm 0.0002^{a}$ |
| *Plant density* | | |
| Low | $4.69 \pm 0.32^{a}$ | $0.014 \pm 0.0003^{c}$ |
| Medium | $5.48 \pm 0.32^{b}$ | $0.010 \pm 0.0003^{b}$ |
| High | $5.13 \pm 0.32^{ab}$ | $0.008 \pm 0.0003^{a}$ |
| *Season* | | |
| 2019-20 | $3.42 \pm 0.57^{a}$ | $0.01 \pm 0.0004^{a}$ |
| 2020-21 | $6.21 \pm 0.57^{b}$ | $0.02 \pm 0.0004^{b}$ |
| 2021-22 | $2.74 \pm 0.57^{a}$ | $0.01 \pm 0.0004^{a}$ |
| 2022-23 | $8.03 \pm 0.57^{b}$ | $0.01 \pm 0.0004^{a}$ |
| *p-value* | | |
| Season | 0.002 | 0.0001 |
| SWRT | 0.084 | 0.951 |
| Plant density | 0.017 | <2.2e-16 |
| *Interactions* | | |
| SWRT × Season | 0.930 | 0.982 |
| SWRT × Plant density | 0.447 | 0.990 |
| Plant density × Season | 3.105e-05 | 3.484e-10 |
| SWRT × Plant density × Season | 0.892 | 0.014 |

Means ± SE within columns followed by different letters are significantly different at $p<0.05$.

## 4.4 Maize production and soil nutrient status under integrated SWRT and soil amendment (Paper III)

### 4.4.1 Effect of SWRT and soil amendments on maize productivity

Maize yield varied significantly across seasons at site B, with higher yields observed in the second season than in the first and third season in all soil water and amendment treatments (Figure 12).

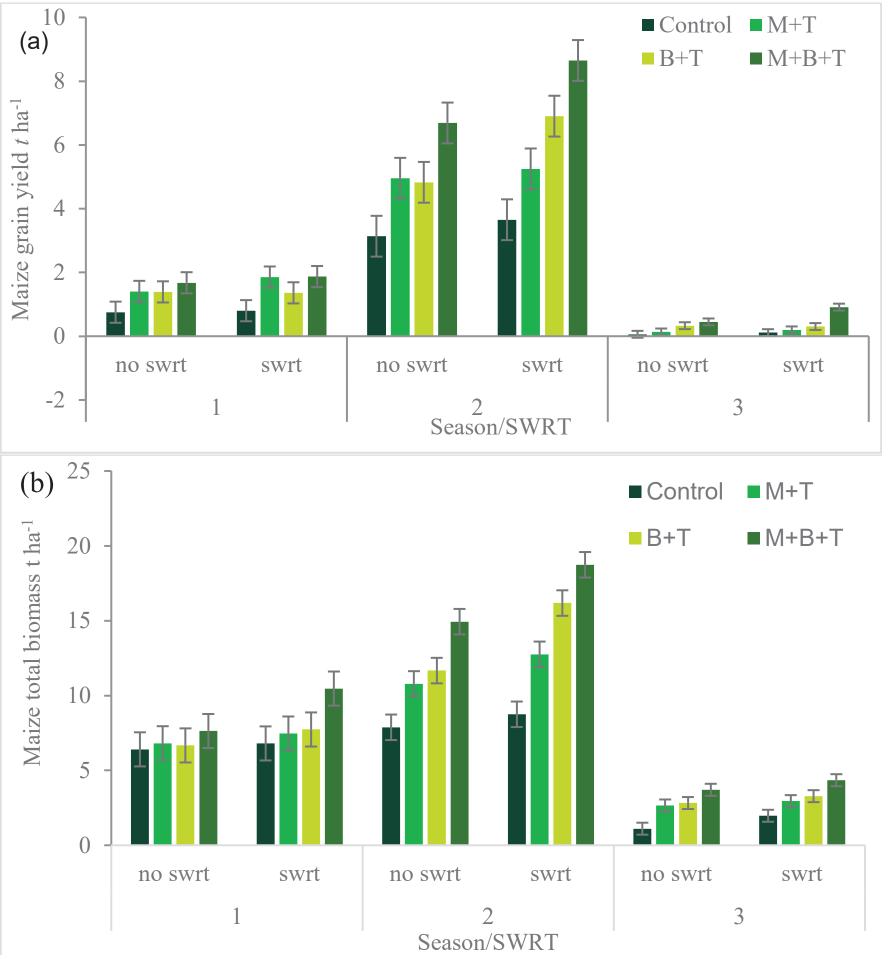



*Figure 12.* (a) Grain yield and (b) total biomass yield of maize at site B under sub-surface water retention technology (SWRT) or no-SWRT and soil amendment treatment T1 (manure (M) + topdressing (T)), T2 (basal fertiliser (B) + T), T3 (M + B + T) and T4 (control, business as usual) in seasons 1 (2019/20), 2 (2020/21) and 3 (2021/22).

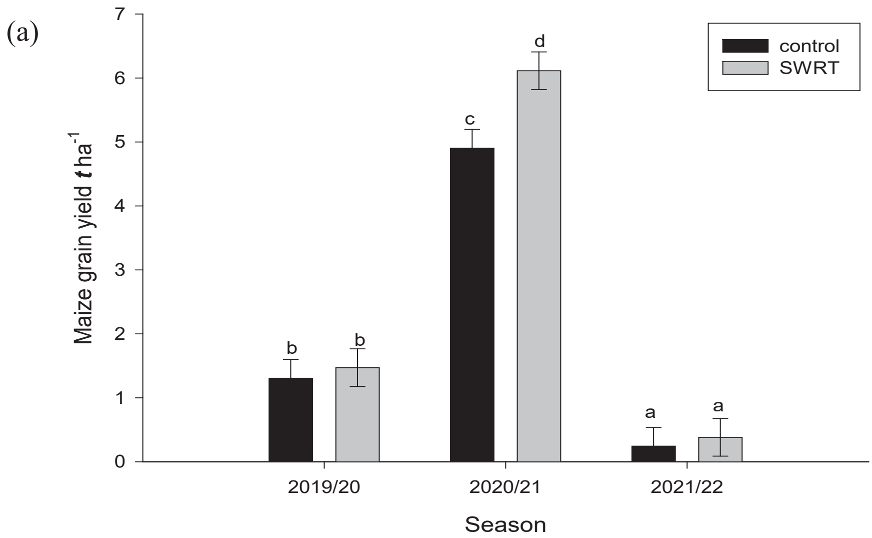
There were significant ($p<0.05$) main effects of SWRT, soil amendment and season on maize grain yield at site B. Main effect of SWRT gave higher grain yield (~2.7 t $ha^{-1}$) than the control without SWRT (~2.2 t $ha^{-1}$), a yield increase of 24%.

Among the soil amendment treatments, the control (T4, BAU) gave significantly lower grain yield than T2-T4. Overall, the highest (3.4 t $ha^{-1}$) grain yield response was observed in treatment T3 (manure + basal fertiliser + topdressing) (Table 7).

Table 7. *Main effect of sub-surface water retention technology (SWRT) and soil amendments on maize grain and biomass yield over the three experimental years at site B. *Means followed by different letters (a-c) are significantly different at* p<0.05*. SE, standard error*

| | Grain yield, t $ha^{-1}$ | Total biomass yield, t $ha^{-1}$ |
|---|---|---|
| *SWRT* | | |
| Control (no-SWRT) | 2.15[a]* | 6.92[a] |
| SWRT | 2.66[b] | 8.45[b] |
| *P-value* | *<0.001* | *<0.001* |
| *SE** | *0.242* | *0.264* |
| *Soil amendments* | | |
| T4, Control (BAU) | 1.42[a] | 5.49[a] |
| T1, Manure + topdressing fertiliser | 2.29[b] | 7.24[b] |
| T2, Basal + topdressing fertiliser | 2.52[b] | 8.06[b] |
| T3, Manure + basal + topdressing fertiliser | 3.37[c] | 9.97[c] |
| *P-value* | *< 0.001* | *<0.001* |
| *SE* | *0.259* | *0.357* |
| **Season** | | |
| 2019/20 | 1.39[b] | 7.49[b] |
| 2020/21 | 5.51[c] | 1.27[c] |
| 2021/22 | 0.31[a] | 2.86[a] |
| *P-value* | *<0.001* | *<0.001* |
| SE | *0.272* | *0.350* |

The results for the seasons averaged over SWRT and soil amendments showed that grain yield in the third season (0.3 t $ha^{-1}$) was significantly lower than that in the first and second season (1.4 and 5.5 t $ha^{-1}$, respectively).



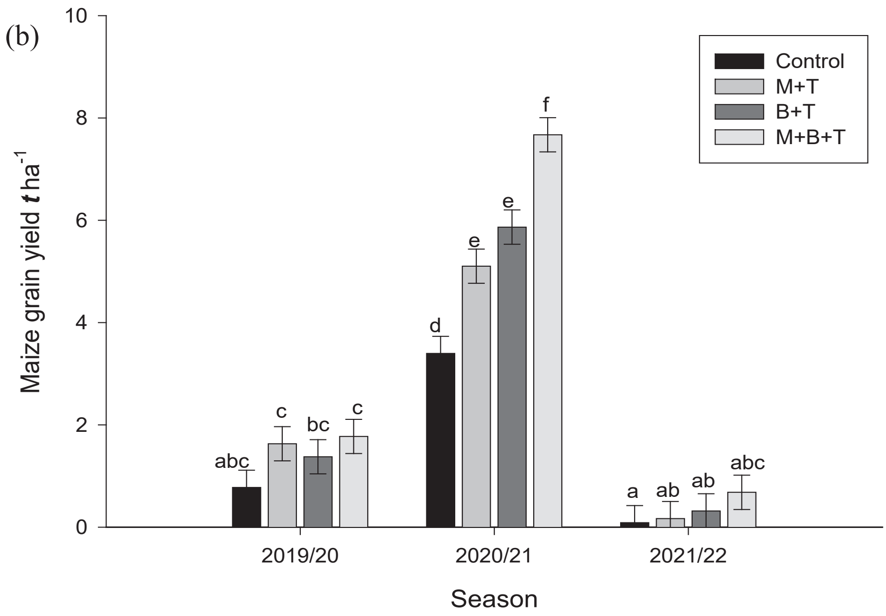




*Figure 13*. Effects of (a) sub-surface water retention technology (SWRT) × season and (b) soil amendment × season on maize grain yield. Soil amendments: T1 manure (M) + topdressing (T); T2 basal fertiliser (B) + T; T3 M + B + T; T4 control (business as usual).

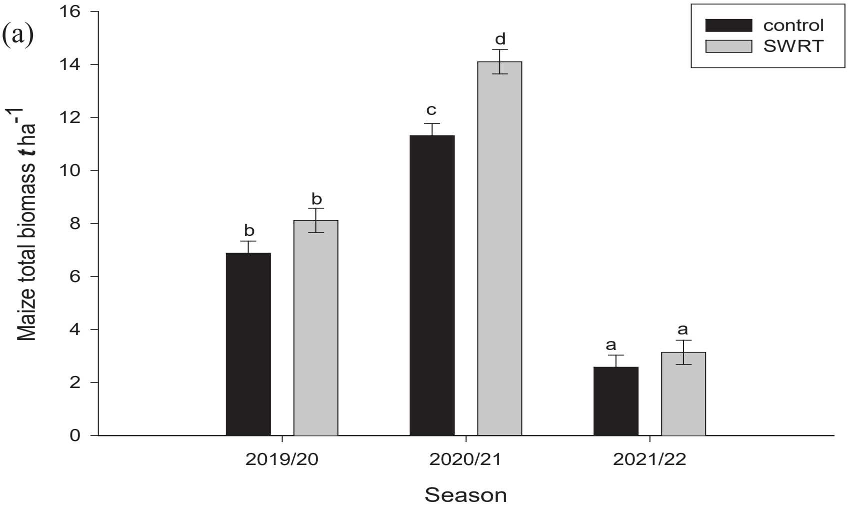
The differences in grain yield were explained by the interaction of SWRT × season, and soil amendment × season (Figure 13). The effect of SWRT on grain yield was dependent on season, with a significant increase in grain yield in the second season but no significant differences from the control (no-SWRT) in the first and third seasons. The third season had low grain yield for SWRT (~0.3 t $ha^{-1}$) compared with the first (1.5 t $ha^{-1}$) and second (6 t $ha^{-1}$) season. In addition, the control (no-SWRT) had significantly lower grain yield (0.2 t $ha^{-1}$) in the third season compared with the first and second season (1.3 and 4.9 t $ha^{-1}$, respectively) (Figure 13).

Use of a soil amendment showed a tendency to increase grain yield in the first and third seasons, with no clear differences between the treatments. Treatment T3 (manure + basal fertiliser + topdressing) resulted in significantly higher grain yield (7.7 t $ha^{-1}$) than other treatments during the second season. The control (BAU) had the lowest grain yield in all three seasons.

There were significant ($p<0.05$) main effects of SWRT, soil amendment, and season on total maize biomass yield (Table 7). Total biomass yield was higher by 22% with SWRT than the control. Regarding the main effect of soil amendment treatments, T1 (manure + top dressing), T2 and T3 gave significantly higher total biomass yield than T4 (BAU) (Table 7), with the highest total biomass yield (3.4 t $ha^{-1}$) observed in T3 (Table 7). The third season had lower total biomass yield than the other seasons.

In terms of interactions, the differences in total biomass yield of maize were explained by the interactive effect of SWRT × season and soil amendment × season. The effect of SWRT on total biomass yield was dependent on season, with a significant increase in total biomass yield observed in the second season. For SWRT, total biomass yield of about 8, 14 and 3 t $ha^{-1}$ was obtained in the first, second and third season at site B, respectively (Figure 14).

(a)




(b)

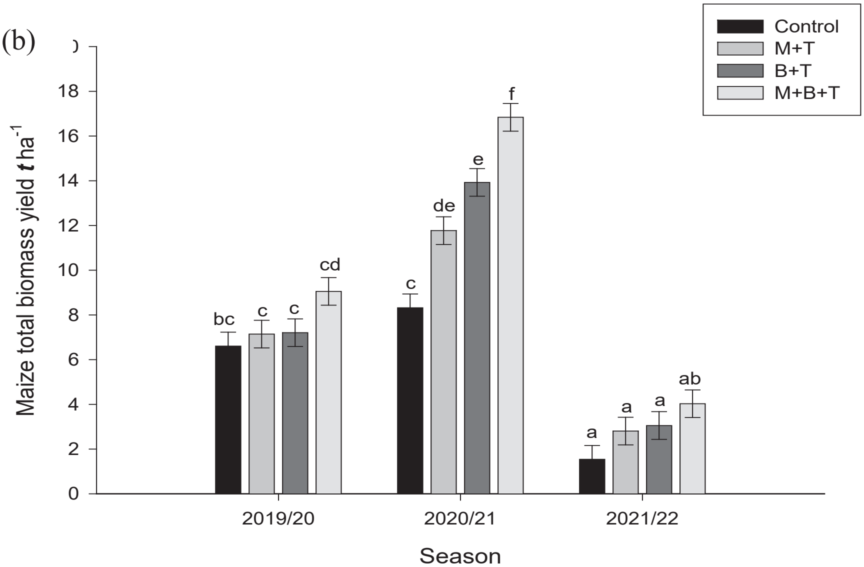



*Figure 14.* Effect of (a) sub-surface water retention technology (SWRT or no SWRT (control) × season and (b) soil amendment treatment × season on maize total biomass yield. Soil amendments: T1 manure (M) + topdressing (T); T2 basal fertiliser (B) + T; T3 M + B + T; T4 control (business as usual).

In the control treatment without SWRT, total biomass yield at site B was 6.9, 11 and 2.6 t ha$^{-1}$ in the three seasons, respectively (Figure 14). The effect of soil amendment treatments on total biomass yield varied with season (Figure

14). Soil amendment treatment T3 gave significantly higher total biomass yield (17 t $ha^{-1}$) than the other amendments during the second season. Only in the second season did BAU result in significantly lower total biomass yield compared with the other soil amendments. For all soil amendments, total biomass increased in the second season and decreased in the third season compared with the first season (Figure 14).

### 4.4.2 Effect of SWRT and soil amendments on chlorophyll content and height of maize

Chlorophyll content (SPAD reading) of maize measured before the second application of topdressing was significantly influenced by SWRT, soil amendment and season. Use of SWRT had a significant positive effect on maize SPAD values in the second and third season. The highest SPAD readings were observed in the T3 treatment and the second season, while the lowest values were recorded in the T4 treatment and the third season. There was a significant interactive effect of soil amendment × season on SPAD readings, which increased as an effect of soil amendment throughout the seasons. In the first season, T1 gave significantly lower SPAD readings than T4, T2 and T3, in that order. In the second season, the T4 treatment had the lowest SPAD readings. In the third year, higher SPAD values were recorded in the T2 and T3 soil amendments than in T1 and T4 (Figure 15).

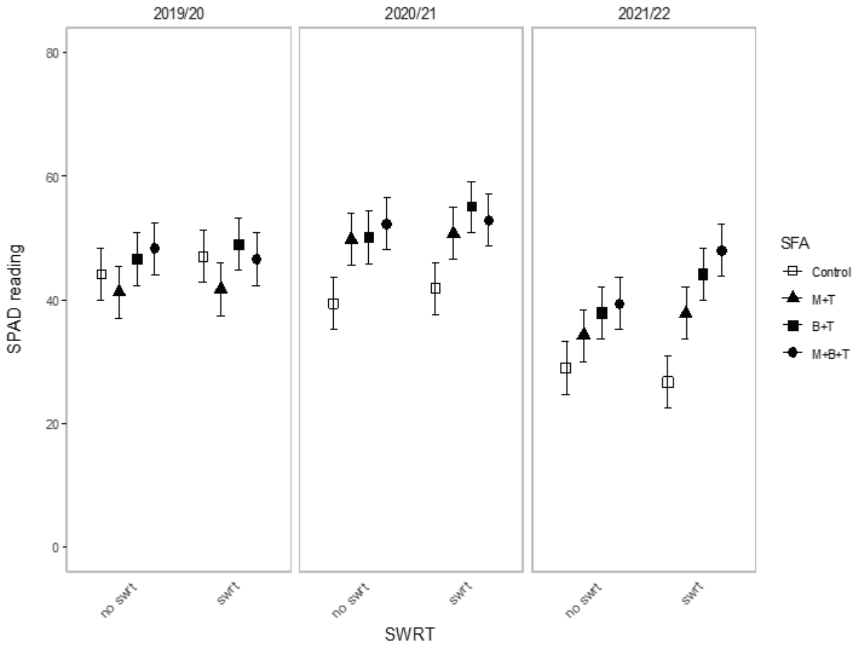



*Figure 15.* Confidence intervals of SPAD readings of chlorophyll in maize leaves before the second topdressing in the sub-surface water retention technology (SWRT) and soil amendment (SFA) treatments. Soil amendments: T1 manure (M) + topdressing (T); T2 basal fertiliser (B) + T; T3 M + B + T; T4 control (business as usual).

The interactive effect of SWRT and soil amendment significantly influenced SPAD readings of maize in the 2021/22 season. During that season, improving soil water management using SWRT in soil amendment treatment T3 led to an increase in SPAD readings. In addition, soil amendment treatment T1, T2 or T3 in either SWRT or the control (no SWRT) increased SPAD values (Figure 15).

For maize height at harvest, significant main effects of SWRT, soil amendment and season were observed. Improving soil water management with SWRT increased maize height. Use of soil amendments other than BAU (T4, control) also increased maize height (Figure 16).

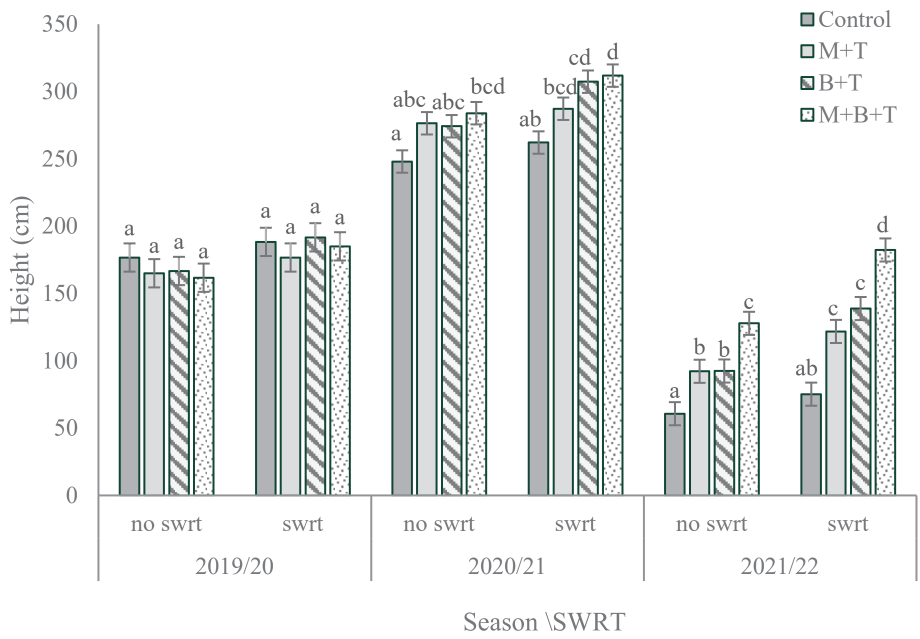



*Figure 16*. Height (cm) of the maize crop in different soil amendment treatments under sub-surface water retention technology (SWRT) or no-SWRT (control). Soil amendments: T1 manure (M) + topdressing (T); T2 basal fertiliser (B) + T; T3 M + B + T; T4 control (business as usual).

When all three years were combined, the results showed that there were significant ($p<0.05$) interactive effects of SWRT and soil amendment on maize height. Improving water management with every soil amendment tested increased maize height. Likewise, adding a soil amendment with water management through SWRT increased maize height. However, analysis of individual years showed that the interactive effect of SWRT × soil amendment was significant in the second season only. Significant effects of SWRT on maize height were observed in each season. There was a significant interactive effect of soil amendment × season on maize height. The effect of soil amendment on maize height was not apparent in the first season, but became clearer in the second and third seasons (Figure 16).

### 4.4.3 Effect of SWRT and soil amendments on soil nutrient status

The soil pH ($CaCl_2$) status after harvest in the third season at site B was acidic, ranging from 4.3 to 4.6 within the 0-15 cm layer and 4.0 to 4.9 within the 15-30 cm layer (Table 8). Available phosphorus decreased with depth in all SWRT and soil amendment treatments. Statistically significant differences in available phosphorus were observed between depths averaged over SWRT, no-SWRT and across all soil amendment treatments, where the 0-15 cm and 15-30 cm soil layers contained 14.7 ± 1.3 mg $kg^{-1}$ and 8.7 ± 1.2 mg $kg^{-1}$, respectively.

Table 8. *Content of available phosphorus (P), exchangeable cations (K, Ca, Mg), soil pH 0.01 M ($CaCl_2$) and soil organic carbon (SOC) in the 0-15 and 15-30 cm soil layers at site B, based on samples taken after the third growing season, in the T1 (manure (M) + topdressing (T)), T2 (basal fertiliser (B) + T), T3 (M + B + T) and T4 (control, business as usual) soil amendment treatments, with and without sub-surface water retention technology (SWRT)*

| Treatment | | Depth | Available P mg $kg^{-1}$ | $K^+$ | $Ca^{2+}$ | Mg2+ | SOC % | Soil pH ($CaCl_2$) |
|---|---|---|---|---|---|---|---|---|
| | | | | me $100g^{-1}$ | | | | |
| Control (no SWRT) | T4, BAU | 0-15cm | 14.51 | 0.18 | 1.10 | 0.38 | 0.50 | 4.58 |
| | | 15-30cm | 7.04 | 0.10 | 0.98 | 0.36 | 0.27 | 4.20 |
| | T1, M+T | 0-15cm | 13.67 | 0.18 | 0.94 | 0.48 | 0.79 | 4.57 |
| | | 15-30cm | 8.10 | 0.16 | 1.14 | 0.44 | 0.42 | 4.46 |
| | T2, B+T | 0-15cm | 14.47 | 0.25 | 0.90 | 0.31 | 0.65 | 4.27 |
| | | 15-30cm | 12.33 | 0.22 | 0.95 | 0.34 | 0.31 | 4.00 |
| | T3, M+B+T | 0-15cm | 20.67 | 0.20 | 1.06 | 0.41 | 0.62 | 4.60 |
| | | 15-30cm | 6.00 | 0.14 | 1.05 | 0.41 | 0.25 | 4.30 |
| SWRT | T4, BAU | 0-15cm | 9.06 | 0.09 | 0.97 | 0.45 | 0.27 | 4.47 |
| | | 15-30cm | 7.67 | 0.10 | 1.65 | 0.39 | 0.22 | 4.97 |
| | T1, M+T | 0-15cm | 15.62 | 0.20 | 1.03 | 0.49 | 0.69 | 4.47 |
| | | 15-30cm | 8.10 | 0.25 | 0.97 | 0.40 | 0.71 | 4.37 |
| | T2, B+T | 0-15cm | 13.33 | 0.14 | 0.76 | 0.37 | 0.43 | 4.40 |
| | | 15-30cm | 8.57 | 0.22 | 1.09 | 0.40 | 0.40 | 4.24 |
| | T3, M+B+T | 0-15cm | 15.97 | 0.22 | 1.22 | 0.46 | 0.54 | 4.39 |
| | | 15-30cm | 9.96 | 0.14 | 0.94 | 0.38 | 0.29 | 4.15 |

Available phosphorus increased in all treatments from the initial values recorded as part of soil characterisation at site B, except for T4 under SWRT where available phosphorus content did not change and was below 10 mg $kg^{-1}$. The concentrations of exchangeable potassium (K), calcium (Ca) and magnesium (Mg) varied, with no clear pattern across treatments and depth. Soil organic carbon (SOC) decreased with depth and tended to increase with in T1, T2 or T3 compared with T4. However statistically significant differences in SOC were only observed between T4 (0.31%) and T1 (manure + top dressing) (0.65%).


*Figure 17.* Photo observation from the field showing treatments, T1 manure + topdressing; T2, Basal fertiliser + topdressing; T3, manure + basal fertiliser + topdressing; T4, control, BAU farmer practice

# 5. Discussion

## 5.1 Farmers' awareness of extreme weather events, adaptation strategies and current yield status

In Paper I, smallholder farmers reported experiencing extreme weather events, indicating that they were aware of climate change variability and impacts on their crop production systems. These findings are consistent with farmers' experiences of extreme weather recorded across southern Africa (Mtambanengwe et al. 2012; Sani & Chalchisa, 2016; Mavhura et al. 2022), showing that farmers are active observers of environmental changes (Ramborun et al. 2020). In response, the farmers surveyed in Paper I reported using adaptation management practices and technological options based on the extreme weather events encountered. This has also been seen in other studies, where farmers adopted water management strategies, early planting and a change in crop type in response to drought (Sani & Chalchisa, 2016). Several barriers to adapting to extreme weather events highlighted by the farmers in Paper I, such as lack of inputs, lack of climate information, poor access to credit and low labour availability, have also been reported in previous studies (Fisher et al. 2015; Chingombe & Musarandega, 2021; Nyahunda & Tirivangasi, 2021; Sen et al. 2021). Reporting of these same barriers over time suggests lack of significant improvement in resource allocation to improve farmer adaptation to climate change and variability in marginal areas.

Average maize yield reported by farmers in Paper I for the 2018/19 season under the soil fertility and water management options they decided to adopt was below 0.8 t $ha^{-1}$. Extreme weather events could explain the low yield, since the rainfall received during the 2018/19 cropping season was above the average range for the agro-ecological region (450-650 mm according to Kubiku et al. (2022), but the distribution was uneven. In fact, >150 mm of rain was received in one week. These periods of high rainfall during the cropping season probably resulted in high nutrient leaching from the predominantly sandy soil, reducing the nutrient use efficiency of the already low amounts of fertilisers applied by the smallholder farmers. Due to resource constraints, smallholder farmers tend to apply <8.5 kg $ha^{-1}$ of chemical fertiliser (Twomlow et al. 2006) and <3 t $ha^{-1}$ of manure (Mtangadura et al. 2017) to field crops such as maize. In addition, maize production requires effective management of nitrogen fertiliser and manure in terms of timing, quantities, manure quality, weather conditions and available soil mineral nitrogen (Masvaya et al. 2017; Peng et al. 2022), which in combination determine final crop yield.

Self-reported soil moisture management strategies grouped as in-field (mulching, potholing, basins, ridges, and autumn ploughing) and out-field (standard contours, tied contours, infiltration pits, and terracing) gave poor yield responses (Paper I). These results contradict previous findings that in-field and out-field water harvesting techniques improve yields (Kugedera et al. 2020; Chiturike et al. 2022, 2024; Nyagumbo et al. 2022). This suggests that there are other factors affecting the adoption and management of adaptation strategies by smallholder farmers. Previous studies have observed that the effect of water harvesting technologies on crop yield can differ significantly from farmer to farmer, due to actual technical management and accuracy in construction of water harvesting structures (Chiturike et al. 2022). Overall, Paper I documented current farmer adaptation practices to extreme weather events in the study area and the effects on maize yield, where assumptions of socio-economic gradients, amount of fertilisers applied and irrigation water were not included.

## 5.2 Seasonal variations in rainfall patterns

Observation of rainfall patterns over the four years of fieldwork in this thesis (2019/20 to 2022/23 cropping seasons) showed how intra- and inter-seasonal variations and rainfall distribution affected maize yield. There were two wet seasons, the second (2020/21, with extremely high rainfall) and fourth (2022/23; with well-distributed normal rainfall). The first (2019/20) and third (2021/22) seasons were dry, with long dry spells late in the season, coinciding with the reproductive stages of maize. Intra-seasonal dry spells are a challenge in rainfed cropping systems under semi-arid conditions and their co-occurrence with critical maize growth stages negatively affects maize yield (Mbanyele et al. 2021; Bal et al. 2022; Adimassu et al. 2023). Consequently, maize yield response followed the rainfall patterns across seasons in Papers II and III, with the lowest yields recorded in the third season and the highest in the second season. These seasonal differences in maize yield provide confirmation of previous claims that maize yield declines as precipitation decreases (Mushore et al. 2017; Mugiyo et al. 2018; Feng & Hao, 2020; Sah et al. 2020). The variations in precipitation patterns observed in Papers II and III expose the vulnerability of rainfed maize production in semi-arid areas.

Seasonal weather forecasting is often used for agronomic management of crops, such as deciding when to plant or when to apply fertilisers and other management practices (Churi et al. 2013; Zougmoré et al. 2021). It should probably also be used when choosing alternative crops, varieties and management options (Zinyengere et al. 2011; Alexander & Block, 2022). Farmers have long-term experiences of their local weather (Paper I) and can adopt better technologies based on these experiences, but this does not guarantee food security if seasonal forecasts are not carefully considered when selecting a crop suitable for that particular season. Researchers should perhaps also consider seasonal weather forecasts and change their approach for CSA, *e.g.* consider alternative drought-tolerant maize or other crops (sorghum, millet) for forecast dry seasons to improve productivity.

## 5.3 Water management strategies

Soil moisture management is one of the main options for CSA and this thesis tested the effects of SWRT on rainfed maize production. The results revealed that use of SWRT increased maize grain yield by 21-24% and total biomass by 13-22%. The yield increase on applying SWRT can be attributed to the ability of the technology to add resilience to climate conditions by retaining reserves of soil moisture and nutrients in the crop root zone (Guber et al. 2015). The results were consistent with findings by Nkurunziza et al. (2022) in a one-year study on sandy soils in Kenya, where SWRT increased maize grain yield and biomass yield by 50% and 150%, respectively. Other studies have reported crop yield increases of 6.5-38% for *e.g*. rain-fed and irrigated wheat in Iraq (Hommadi et al. 2021), irrigated field tomatoes in Morocco (Lahbouki et al. 2022) and in Iraq (Aoda et al. 2021), and irrigated chilli pepper (Al-Rawi, 2017). In semi-arid areas of Zimbabwe, contour-based water harvesting techniques have been studied as a water management CSA option for improved productivity. For example, a three-year study by Chiturike et al. (2024) revealed that maize yield increased by 88% using tied contours and by 52% with the use of infiltration pits on sandy soils. A study by Gumbo et al. (2021) noted maize yield increases of 42-84% after implementing contour-based water harvesting methods in similar soil and environmental conditions. Another study obtained a 55%, 60% and 69 % yield increase due to use of Fanya juus, tied contours and infiltration pits, respectively, compared with standard contours (SC) over a period of three years (Nyagumbo et al. 2019). Kugedera et al. (2022) obtained a sorghum grain yield increase of 31% using tied contours over three seasons under semi-arid conditions. Contour-based water management options improve water availability to plants through intercepting and capturing runoff water, increasing groundwater recharge (Nyamadzawo et al. 2013). Moreover, rainwater use efficiency at the study site tended to be higher in SWRT than the control.

Technologies to improve soil moisture retention, such as mulching, rainwater harvesting and plastic mulching, enhance RWUE in semi-arid areas (Zheng et al. 2020; Mbanyele et al. 2021; Chiturike et al. 2023). In this thesis, SWRT, which can perform similar or more functions than these technologies, did not enhance RWUE. In a dry season with a long dry spell, SWRT can reach a limit in its water retention capacity, while abundant rainfall in a wet season can mask the effect of SWRT. The RWUE of the maize crop increased with the amount of rainfall received during the individual seasons. Maize yield is responsive to water availability and rainfall is important when evaluating water management options (Bekuma Abdisa et al. 2022). A single-season study in wheat by Hommadi et al. (2021) found that water use efficiency increased with use of SWRT and irrigation supplemented with rainfall.

## 5.4 Crop and nutrient management effects on maize production

### 5.4.1 Plant density

Climate-smart maize production involves adjusting plant density based on soil conditions (Zhang et al. 2020). Comparison of different maize density treatments in Paper II suggested that medium plant density gave higher productivity in terms of grain yield per hectare compared with low and high plant density. There was a reduction in grain yield at high plant density due to fewer cobs and lower grain weight, owing presumably to limitations in photosynthetic resource supply for cob and grain development (Al-Naggar et al. 2015). However, high plant density can result in increased grain yield under optimum water and nutrient supply (Lai et al. 2022), as observed in the second season of the experiments in this thesis. Previous studies have shown that water supply is important in determining plant density and that under differing conditions (wet to dry), plant density also changes (Friedman, 2016).

The medium plant density (74,000 plants $ha^{-1}$) yielded more than the other two plant populations, but only 58% of the initial plant population accounted for grain yield at harvest. This means that 42% of the plants failed, but the final plant population at harvest (42,920) exceeded that at the low density (37,000 plants $ha^{-1}$), hence the higher yield. At the low plant density, plant failure was apparently minimal, since the final plant population at harvest was 84% (31,080 plants $ha^{-1}$) of the initial plant density, but the low number of plants explains why the yield was lower despite higher crop productivity than at the other plant densities. For high plant density (111,111 plants $ha^{-1}$), the final plant density at harvest was 59% of the original level, which means that plants failed but the plant population remained the highest. However, this higher number of plants did not compensate for low individual crop productivity as regards final maize grain yield per hectare. Instead, that treatment had significantly lower harvest index, meaning there was more biomass than grain. High plant density of maize would thus be ideal for farmers interested in fodder rather than grain production, as demonstrated during the two lowest rainfall seasons in this thesis. The final plant density at harvest therefore affected yield, confirming previous findings (Vijayaprabhakar et al. 2021). The reduction in plant density stand could be explained by competitive growth, lodging and self-thinning of crops at the medium and high plant densities (Postma et al. 2021). High plant density requires much water, sunlight and nutrients (Boomsma et al. 2009) and water was a limiting factor in the experiments in this thesis, since the system was rainfed and mid-season droughts were observed. Competition for other photosynthetic resources can be high at higher plant densities and limitation of these resources can lead to crop failure (Deng et al. 2012).

Soil water management using SWRT did not influence maize yield response at the three plant densities. This could be due partly to yield differences between the main treatments being too small to show any interactions with the sub-plot plant density treatments. Although there were some interactive effects on chlorophyll and maize height at some growth stages, this did not translate to interactive effects on final yield. Environmental conditions determine optimum plant density (Tokatlidis, 2013) and this appears to be more apparent in rain-fed conditions. The significant season × plant density effect on maize yield observed in this thesis highlights the importance of crop management × environment interaction in crop production (Tsimba et al. 2013; Postma et al. 2021). The frequency and duration of mid-season dry spells affected total yield at all plant densities in wet and dry seasons.

Maize RWUE increased as plant density increased from the low level and the medium density had the highest RWUE, followed by the high and low densities. A study on maize in semi-arid areas by Jia et al. (2018) showed that moderate plant densities can increase RWUE. The uniform distribution of rainfall in the 2022-23 season allowed crops to have higher RWUE than in the drier 2019-20 and 2021-22 seasons, *i.e.* the crop efficiently utilised the greater amount of water available in the 2022-23 season. These results indicate that there is an optimum level of water supply for crop productivity (Liliane & Charles 2020). The RWUE results also explained why the final plant population at harvest under medium plant density performed better than the other plant densities.

### 5.4.2 Soil amendments

Most (80%) of the smallholder farmers surveyed in Paper I applied some form of organic or inorganic fertiliser, indicating that they prioritised the soil fertility management options for crop production. This knowledge helped to shape climate-smart options on how to improve soil health and ultimately crop production in the same environmental context for the smallholder farmers in Paper III. The results in Paper III revealed that yield increased with the amount of nitrogen added to the soil. The response of maize was greater when inorganic fertiliser (both basal fertiliser and topdressing) was added together with manure (treatment T3) than when either basal and topdressing (T2) or manure and topdressing (T1) were used. This is in agreement with previous findings (Fairhurst, 2013).

Although clear differences in chlorophyll content (SPAD value) of maize leaves were observed in the different soil amendment treatments during the second and third season, maize grain and total biomass yield followed a similar trend in the second season only and showed some tendency for an increase in the third season. The effect of soil amendments also varied across seasons. The first year of adding manure and inorganic fertiliser (treatments T1-T3) gave no clear differences in grain yield, probably due to the rainfall distribution in that dry year and slow mineralisation of organic fertiliser. The second season had an advantage of residual soil nutrients and a good rainfall distribution. The third season had residual nutrients (after three years of repeated application) but a poor distribution of rainfall, which affected maize yield responses to the soil amendments. Yearly application of manure is required to increase crop response to mineral fertiliser, by building up nutrients and replenishing soil health (Ayalew & Dejene, 2012). Integration of soil water and nutrient management only showed a tendency to improve maize yield in the short-term study in Paper III. Final maize yield was affected by application of SWRT or soil amendment, rather than their interactions.

Soil chemical properties slightly improved over time compared with the general status in initial soil characterisation at the site (site B). The field was initially deficient in available phosphorus, but after three years of treatments available phosphorus increased slightly to 15 cm depth. Soil organic carbon ranged between 0.5 and 0.8% in the top 15 cm soil layer. A study by Kurwakumire et al. (2015) established that the agronomic and economic efficiency of fertiliser is viable at SOC >0.44%. Previous studies on soil moisture and nutrient management have shown multiple benefits of these for soil fertility, including improvement of soil nutrient availability (Zhang et al. 2016), carbon sequestration (Mustafa et al. 2021), soil structure, microbial activity and moisture conservation (Mbanyele et al. 2021; Kubiku et al. 2022).

## 5.5 Implications for development of future CSA options

Adoption of CSA options requires resources and, due to financial limitations, smallholder farmers are constrained in fully realising the potential of CSA for improving agricultural production (Makate et al. 2019). Since there are small gains in terms of yield for SWRT compared with alternative water management practices (*in situ* and contour-based), smallholder farmers could consider combining SWRT with alternatives or sole use of alternatives. The reason for combining water management practices is for maximum utilisation of soil water, assuming that a farmer has the necessary resources. Furthermore, SWRT installed at the correct depth retains water and nutrients within the root zone (Guber et al. 2015b), while *in situ* water management, *e.g*. mulching, tied ridging planting basins *etc*., is applied at the soil surface or within the plough layer. These *in situ* practices harvest rainwater within the field, conserve moisture and, in the case of mulching, reduce surface evaporation of soil moisture (Munyasya et al. 2022; Kugedera & Kokerai 2024). Contour-based water management options, *e.g*. tied contours and infiltration pits, harvest rainwater at the field edges and the accumulated water recharges the moisture in the field (Chiturike et al. 2023). Studies indicate that the effect of contour-based rainwater harvesting techniques is affected by distance, with the greater the distance from the contour, the smaller their influence on soil moisture (Kubiku et al. 2022). Yield also decreases with distance from the rainwater harvesting structure (Kubiku et al. 2022). Both contour-based and *in situ* water harvesting techniques are easy to install and have low maintenance cost, but require much labour compared with SWRT, which is costly. In a future CSA scenario, precipitation and runoff could be captured by contour-based structures and *in situ* structures, evaporation loses could be minimised by mulching (*in situ*) and deep percolation could be limited by SWRT in the same system.

In previous studies on SWRT, supplementary irrigation (Hommadi et al. 2021) or full irrigation (Abedalrahman et al. 2020) was used. Irrigation can also be an option for rainfed farming, particularly under semi-arid conditions, since mid-season dry spells can be of long duration and occur more frequently. However, due to socio-economic challenges, smallholder farmers resort to rainfed agriculture because irrigation of field crops requires high capital investment (Duker et al. 2020). In most smallholder farming set-ups, irrigation is concentrated to small gardens used for horticultural production (Mpala & Simatele 2024).

High-cost investment requires high returns, meaning that investing in SWRT for low-value field crops such as maize may not be ideal for smallholder farmers. They can improve their income through growing horticultural crops, where SWRT can be more applicable. However, maize is a good test crop in research on this technology, due to its water demands and low cost. In future work, sorghum could be used as the test crop, since it is more suitable for the semi-arid areas and more resilient than maize (Choudhary et al. 2020) and the same water management options have been proven to increase sorghum yield (Kubiku et al. 2022).

Soil amendments alone coupled with good agronomic practices improved yields compared with BAU practices (Paper III). Farmers can therefore make choices on adopting practices that suit their resource endowments (best-fit), although recommendations consider best-bet options (Fairhurst 2013; Marenya 2020). Thus, a farmer who cannot afford basal and topdressing inorganic fertiliser can opt for manure instead of basal fertiliser and save for a bag of topdressing. If a farmer can afford inorganic fertilisers and adds manure, they are assured of a good harvest (Paper III; Fairhurst, 2013). However, the fertiliser rates tested in Paper III might be too high for semi-arid regions and out of reach for smallholder farmers. The quality and quantity of manure are key factors for consideration to maximise its effectiveness in crop production (Rayne & Aula 2020; Khoshnevisan et al. 2021). Manure is not always available and labour requirements can be a challenge, since all farm operations are performed manually in smallholder farming (Mkuhlani et al. 2020).

Grain legumes are key crops in diversification of maize-based cropping systems in smallholder farming and are important in buffering the impacts of climate change-related extreme weather events (Thierfelder et al. 2024). They can be used to improve the resilience of the current cropping system and support nutrient management in combination with water management practices. Common legumes such as cowpea, Bambara nut and groundnuts have already been categorised as climate-smart complementary crops for food and nutrition security (Jiri et al. 2017).

Overall, a major factor limiting smallholder farmers in adopting various technologies is small land holding (2-3 hectares), which has to be used for crop production, to keep livestock and other enterprises (Fairhurst, 2013).

# 6. Conclusions and Recommendations

## 6.1 Conclusions

- Smallholder farmers confirmed experiencing extreme weather events and were aware of the risks posed to agricultural production. They were also aware of the need to take proactive steps to protect their crops and livelihoods from the potential damage caused by extreme weather events.
- The farmers implemented adaptation strategies such as soil and water management, use of improved varieties, mulching, planting trees, early planting, reducing the area under cultivation, and changing the types of crops in their crop production systems. Despite the reported adaptation strategies on fertility and water management, maize yields remained very low on the smallholder farms.
- SWRT increased maize grain by 21-24% and biomass yield by 13-22% over four years. In wet seasons, using SWRT resulted in high yield response. In dry seasons, there were similar maize yield responses with and without SWRT.
- SWRT showed a tendency to increase RWUE, indicating potential for improving RWUE. Maize yield and RWUE were affected by rainfall patterns in rainfed systems; wet seasons had high maize yield and RWUE compared with dry seasons.
- Medium plant density (74,000 plants $ha^{-1}$) was most favourable in terms of final plant population at harvest, yield and RWUE. High plant density (111,111 plants $ha^{-1}$ spacing) gave higher yield when there was abundance of precipitation (one crop-growing season only).

- Soil amendments (combining organic and inorganic fertilisers) resulted in higher yields compared with BAU smallholder farming practices. Applying either manure + topdressing or basal fertiliser + topdressing gave the same yield benefit. The response of maize yield to soil amendments was influenced by season. There were short-term improvements in soil phosphorus and SOC content due to the use of soil amendments.
- There were tendencies for higher maize grain and biomass yield on integrating SWRT and soil amendments compared with the control without SWRT, although SWRT or soil amendment alone significantly improved grain and biomass yield. Thus, integration of SWRT and soil amendments promises to improve maize productivity.
- Overall, climate-smart options such as management of maize density, soil water and nutrients, could significantly enhance maize productivity, even in challenging conditions. However, socio-economic aspects need to be considered, as an integral part of efforts to address low agricultural productivity and food security in semi-arid areas

## 6.2 Recommendations

- Smallholder farmers should receive training and support on the best evidence-based fertiliser and water management practices.
- Smallholder farmers should have access to climate and weather information services to help them carry out farming operations on time, adjust their management practices and minimise the impacts of extreme weather events on their crops. They should be encouraged to adopt drought-tolerant maize varieties and alternative crop options that are more resilient to extreme weather events and better suited to the local climate conditions.
- To improve the performance of SWRT, supplementary irrigation could be added to reduce the impact of prolonged droughts within cropping seasons. Investment in SWRT should be made for high-value crops, rather than field maize for grain.

- To maximise maize yields, minimise crop losses and allow efficient use of resources, plant densities between 37,000 and 74,000 plants $ha^{-1}$ should be targeted.
- To achieve the best effect from fertilisers, both organic and inorganic fertilisers, together with topdressing, should be used. Other cropping patterns including legumes can be included with soil amendments.
- Implementation of SWRT and/or soil amendments should be tailored to the specific needs and constraints of smallholder farmers.
- It is important that supporting policies and extension services promote adoption of climate-smart soil, water and crop management practices.

## 6.3 Future research

- Further research is needed to determine the exact amounts of fertiliser and water management inputs that farmers should apply to optimise the productivity of improved crop varieties.
- Further research is needed on integrating SWRT with other management practices such as legume intercropping surface mulching, basins *etc*.
- Further work is needed to understand the water balance in SWRT systems in rainfed maize production.
- Research in the future should assess long-term impacts of SWRT and soil amendments on soil health and crop resilience.
- Investigations are needed on the effect of SWRT in micro-managing the plant-soil environment in different smallholder and agro-ecological contexts.

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# Popular science summary

Smallholder farmers face significant challenges due to climate change, especially in semi-arid regions with sandy soils. Typical semi-arid conditions include high temperatures, erratic and unreliable rainfall patterns, which can result in prolonged mid-season dry spells. Due to climate change, the duration and frequency of these weather events have increased and are affecting crop production and food availability in semi-arid regions. Production of maize, one of the crops most commonly grown by smallholder farmers in rainfed systems, is particularly at risk in semi-arid areas. The prevalence of sandy soils in such areas also increases the risk of crop failure, due to poor water retention and low soil fertility. Climate-smart agriculture (CSA) adaptation and management options that address these crop production limitations are crucial in order to increase food security. This thesis evaluated some CSA options that can be used to improve crop production in semi-arid areas, using maize as a test crop.

To understand current crop production challenges among smallholder farmers in semi-arid areas, the first step in this thesis work was to conduct a survey in Mutare district, Zimbabwe. Climate change awareness, farmers' adaptation strategies and maize yield associated with current smallholder farmer agronomic practices were covered by the survey. In subsequent field experiments, management options for improving soil water, nutrient and crop management were tested in selected farmer fields. The first experiment integrated soil water management using sub-surface water retention technology (SWRT) with different maize densities over a period of four years. The maize densities tested were low (37,000 plants $ha^{-1}$, spacing 90 × 30 cm), medium (74,000 plants $ha^{-1}$, spacing 90 × 15 cm), and high (111,111 plants $ha^{-1}$, spacing 60 × 15 cm). The second experiment integrated SWRT with different soil amendments and farmer practices over three years. The

soil amendments comprised organic (cattle manure) and inorganic fertilisers, which were applied in different combinations and at different times throughout the three years.

Around 245 farmers participated in the survey. Their responses revealed that they were aware of climate change, based on the extreme weather events experienced. They had experienced drought, changes in temperature, unusual rainfall patterns such as flooding, etc. The farmers reported that they were adapting to changes using rainwater-harvesting options, mulching or changing the type of crops grown, among other practices. Despite the farmers stating that they use improved varieties and practise soil water and fertility management, their maze yield remained extremely low (0.6 t $ha^{-1}$). Such low yields indicate an influence of socio-economic factors on maize production and implementation of good agronomic management practices, suggesting that need for improvement.

Seasonal variations in precipitation influenced maize yield in the on-farm field experiments. During the study period, there were two dry years and two wet years. The two dry years received 305-350 mm rainfall during the cropping season, whereas the two wet years received 400-780 mm and the rainfall was more evenly spread over the crop-growing season. These seasons alternated, with a dry first and third season and a wet second and fourth season. Maize yield was lower in the dry seasons (0.3-1.4 t $ha^{-1}$) than in the wet seasons (3-5 t $ha^{-1}$) throughout all treatments.

Seasonal variations strongly affected maize yield response to SWRT, to different plant densities and to the different combinations of soil amendments tested (manure, basal fertiliser, topdressing). Use of SWRT increased maize grain yield by 21-24% and total biomass yield by 13-22%, demonstrating good potential of SWRT in enhancing the rainwater use efficiency (RWUE) of maize. In wet seasons, SWRT increased maize yield by 1.2 t $ha^{-1}$, while in dry seasons it only increased yield by 0.1 t $ha^{-1}$.

Increasing maize plant density from low to medium increased maize yield, but a further increase to high maize density reduced yield. Four-year average maize grain yield of 2.7 t $ha^{-1}$ and high RWUE were obtained with medium plant density. In wet seasons, up to 4 t $ha^{-1}$ of maize grain was obtained with medium plant density. At harvest, 58% of plants in the medium plant density remained, which indicates that 43,000 plants $ha^{-1}$ can be used instead of higher plant densities for optimum yield. High maize density responded well in very wet seasons only, yielding 5 t ha$^{-1}$, but it is not common to have such conditions in semi-arid areas.

Based on three-year averages, combining organic and inorganic soil amendments increased maize yield to 2.3-3.4 t ha$^{-1}$, compared with 1.4 t ha$^{-1}$ in smallholder farmer practice (control). Seasonal precipitation also affected maize yield response to the soil amendments. The results indicated that smallholder farmers can achieve maize yields of above 5 t ha$^{-1}$, provided they have sufficient resources to apply both manure and inorganic (basal and topdressing) fertilisers and that sufficient water is available.

In conclusion, this thesis demonstrated that climate-smart options, such as management of maize density, soil water and nutrients, could significantly enhance maize productivity, even in challenging conditions. However, socio-economic aspects need to be considered, as an integral part of efforts to address low agricultural productivity and food security in semi-arid areas.

# Populärvetenskaplig sammanfattning

Småbrukare står inför betydande utmaningar på grund av klimatförändringarna, särskilt i halvtorra regioner och i områden med sandjordar. Typiska halvtorra förhållanden kan innebära ökade temperaturer, oberäkneliga och opålitliga nederbördsmönster, ofta med långvariga torrperioder i mitten av odlingssäsongen. På grund av klimatförändringarna har varaktigheten och frekvensen av extrema väderhändelser ökat, vilket påverkar jordbruket, inte minst växtodlingen, och tillgången på mat. Majs är en av de vanligaste grödor som småbrukare odlar utan bevattning, dvs de förlitar sig på regn, vilket kan äventyra produktionen av majs och andra grödor i halvtorra områden. Förekomsten av sandjordar ökar också riskerna för missväxt på grund av dålig vattenhållande förmåga och låg markbördighet. Klimatsmarta metoder för att anpassa odlingen till förändrat klimat. och för att begränsa klimatpåverkan av jordbruket, går under benämningen ’klimatsmart jordbruk’ (climate-smart agriculture). Att utveckla klimatsmarta odlingsmetoder är avgörande får att möta de utmaningar och begränsningar som klimatförändringarna utgör för växtproduktionen och är avgörande för att öka livsmedelssäkerheten. I denna doktorsavhandling har jag utvärderat några ’klimatsmarta’ odlingsmetoder som kan användas för att förbättra växtodlingen i halvtorra områden, där jag har använt majs som försöksgröda.

För att förstå de nuvarande utmaningarna för växtodlingen bland småbönder i halvtorra områden genomförde vi en intervjuundersökning i Mutare-distriktet i Zimbabwe. Vi undersökte medvetenheten om klimatförändringar, jordbrukarnas anpassningsstrategier och majsavkastningen i på småböndernas gårdar. I fältförsök testade vi sedan brukningsmetoder som förbättrade markens förmåga att hålla vatten i rotzonen, former och tidpunkter för gödsling, och olika utsädesmängder av majs. Försöken utfördes i utvalda fält på två gårdar. Det första experimentet kombinerade att försöka öka mängden markvatten med hjälp av vattenretentionsteknik (installation av membran på olika djup under markytan, s.k. 'soil-water retention technology' (SWRT) med olika utsädesmänger av majs under en period av fyra år. Utsädesmängden av majs var låg (37,000 plantor $ha^{-1}$, avstånd 90 cm mellan rader × 30 cm inom raden), medium (74,000 plantor $ha^{-1}$, avstånd 90 × 15 cm) och hög (111,111 plantor $ha^{-1}$, avstånd 60 × 15 cm). Det andra experimentet kombinerade SWRT med olika gödslingsmetoder för att förbättra markbördigheten under tre år. Jordförbättringsmedlen bestod av organiska (nötkreatursgödsel) och oorganiska gödselmedel (grundgödsling vid sådd samt övergödsling i växande gröda) som applicerades i olika kombinationer och tider under de tre odlingssäsongerna.

I intervjuerna deltog cirka 245 bönder och de berättade att de var medvetna om klimatförändringar baserat på de extrema väderhändelser som de upplevt. De hade upplevt torka, temperaturförändringar, och ovanliga nederbördsmönster som översvämningar, etc. Bönderna rapporterade att de anpassade sig till dessa förändringar genom att ta tillvara regnvatten, täckodla för att minska avdunstningen eller ändra vilken typ av grödor som odlas, mm. Trots att många bönder rapporterade att de i viss mån använder moderna sorter, samlar regn för bevattning och tillför gödsel så förblir avkastningen på deras fält mycket låg (0,6 t majs $ha^{-1}$). Sådana låga skördar tyder på att det finns socioekonomiska faktorer som påverkar majsproduktionen och användningen av goda agronomisk brukningsmetoder, och att det finns stort utrymme för förbättringar.

Säsongsvariationer spelade stor roll för hur majsavkastningen påverkades av olika utsädesmängder och de olika kombinationerna av gödselmedel och tidpunkter för gödsling (stallgödsel, grundgödsling, N-gödsling i växande gröda). Försöket med att öka markensförmåga att hålla markvatten (installation av membran - SWRT) ökade skörden av majskorn med 21-24% och majsens totala biomassaskörd med 13-22%, och det visade också potentialen att förbättra effektiviteten i majsens nyttjande av regnvatten ('rain-water use effeciency' -RWUE). Studien visade att förändring av utsädesmängden från låg till medium ökade skörden av majs, medan ytterligare justeringar till höga utsädesmängder minskade skörden. Vi uppmätte ett fyraårsgenomsnitt på 2,7 ton $ha^{-1}$ av majskorn med medel utsädesmängd och hög RWUE. Under växtsäsongerna med god nederbörd uppnådde vi upp till 4 t majs ha$^{-1}$ med samma utsädesmängd. Vid skörd räknades antalet plantor till 43 000 ha$^{-1}$, dvs 58% av vad som såddes vid medium utsädesmängd, och detta är den utsädesmängd som kan användas för optimal avkastning. Hög utsädesmängd svarade bra endast under mycket regnrika odlingssäsonger då 5 t ha$^{-1}$ kunde uppnås, men det är inte vanligt att ha sådana förhållanden i halvtorra områden.

Genom att kombinera stallgödsel och mineralgödselmedel ökade majsskördarna från 1,4 t ha$^{-1}$ i kontrollen (jordbrukarnas praxis) till 2.3-3.4 t ha$^{-1}$ genom att tillämpa olika kombinationer av gödselmedel, baserat på treåriga genomsnittliga skördar. Nederbördens säsongsvariationer påverkade också hur majsskörden svarade på de olika gödselmedlen. Resultaten visade att småbrukare kan få en majsskörd över 5 t ha$^{-1}$, förutsatt att de har tillräckligt med resurser för att gödsla med både stallgödsel (eller andra organiska gödselmedel) och mineralgödsel (grundgödsling och/eller övergödsling i växande gröda) och att tillräckligt med vatten finns tillgängligt. Av avhandlingsarbetet drar jag slutsatsen att klimatsmarta odlingsmetoder som hantering av utsädesmängd, markvatten och näringsämnen avsevärt kan förbättra majsproduktiviteten även under utmanande förhållanden. Socioekonomiska aspekter måste dock betraktas som en integrerad del av ansträngningarna för att öka jordbrukets produktivitet och livsmedelstrygghet i halvtorra.

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# Climate change awareness and adaptation strategies by smallholder farmers in semi-arid areas of Zimbabwe

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**ABSTRACT**
Agricultural production, food, nutrition and income security of smallholder farmers in sub-Saharan Africa are threatened by extreme weather events, such as increased frequency of mid-season dry spells and increased temperatures. Their impacts are exacerbated by the prevalence of sandy soils, characterized by limited water and nutrient retention capacity leading to low crop productivity. In this study, we aimed at assessing farmers' awareness of extreme weather events, identify adaptation strategies and evaluate maize yield from different soil fertility and water management practices. A household survey including 245 smallholder farmers in Marange, Zimbabwe was carried out. The results revealed that farmers were aware of and had experienced extreme weather events. Among adaptation strategies used were soil water-harvesting, use of improved varieties, mulching and planting trees. Maize yield remains significantly low, averaging 0.62 t $ha^{-1}$ among farmers using some forms of soil fertility and water management strategies. To further understand the reason for low maize yields and improve climate change related adaptation strategies, more research is needed to quantify and confirm management practices applied by farmers, such as fertilizer use and rates, water and nutrient management, use of improved varieties as well as socio-economic factors.

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Extreme weather; maize; soil and water management

## 1. Introduction

Agricultural production and the related food, income and nutrition security of smallholder farmers in developing countries are under threat from extreme weather events caused by climate change (Belay et al., 2017). Altered patterns of rainfall, increased frequency of mid-season dry spells, and increased temperatures are some of the extreme weather events that are evident in sub-Saharan Africa (Arslan et al., 2014; Brazier, 2015; Serdeczny et al., 2017), including Zimbabwe (Chanza & Gundu-Jakarasi, 2020; Makate et al., 2017; Belloumi, 2014). Nearly 68% of the Zimbabwean population lives in rural areas, and agriculture is their primary source of livelihood (Lachaud et al., 2018; ZIMSTAT, 2017). However, since most of the crop production on smallholder farms is rain-fed (Bhatasara, 2017; Nciizah et al., 2022; Nyagumbo et al., 2019), recurrent droughts cause low maize crop productivity, which has generally resulted in yields averaging less than a tonne per hectare over

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the past 10 years (Mujeyi et al., 2021; Ngema et al., 2018).

In Zimbabwe's semi-arid areas, drought impacts are exacerbated by the prevalence of sandy soil, which constitutes 70% of arable land (Nyamapfene, 1991). These sandy soils are characterized by limited water and nutrient retention capacity and high water permeability, leading to low crop productivity (Bruand et al., 2005; Leogrande & Vitti, 2019). Farmers attempt different adaptation strategies to overcome extreme weather events and challenges related to sandy soils. These strategies include soil management practices that improve water and nutrient holding capacity and use efficiencies. For instance, previous research conducted in rural Zimbabwe has shown that combining soil water harvesting, manure and inorganic fertilizers increases crop yields (Biazin et al., 2012; Gram et al., 2020; Kubiku et al., 2022; Nyagumbo et al., 2019). A combination of manure and the deployment of rainwater harvesting technologies improves moisture and nutrient retention within the root zone, thus improving biomass production (Kubiku et al., 2022; Kugedera et al., 2020). A study on sandy and clay soils in Harare showed that cattle manure improved water retention and nutrient availability, resulting in a maize grain yield increase of 3.7 times (Shumba et al., 2020) compared to unfertilized treatments. Since sandy soils have a low water holding capacity, supplementary irrigation may improve soil moisture management and support crop growth and yields. However, due to prohibitively high initial investment costs, irrigation is uncommon in smallholder farming areas of Zimbabwe, especially for cereals. Usually, irrigation is done on high-value horticultural crops, which are typically located close to water sources to reduce irrigation labour costs.

Despite evidence from research on the problem of limited crop productivity of sandy soils in semi-arid regions, costly potential solutions and bleak socio-economic realities cause farmers to continue with business-as-usual (BAU) practices. In this context, BAU practices refer to the use of farming methods that are not well suited for the unique characteristics of the soil and the climate of the region. The BAU practices may include reliance on non-resilient crops, smallholder farmers may continue to grow crops that are not well adapted to specific temperature and rainfall patterns without exploring more climate resilient crop varieties (Cacho et al., 2020; Newsham et al., 2023). Inadequate implementation of water management technologies such as rain water harvesting and irrigation improvements (Magombeyi et al., 2018). Inappropriate planting techniques such as monocropping poor soil fertility management such as insufficient use of organic matter, cover crops and poor mineral fertilizer management are other BAU methods (Mupambwa et al., 2022). The prevalence of BAU agricultural practices seems to suggest a lack of adoption of management options that could increase farmer adaptation to recurrent drought conditions. Several possible reasons for the lack of adoption of best-bet options include farmers having limited knowledge of best-bet options, inadequate technical skills and a shortage of financial resources to support the adoption of best-bet options (Makate et al., 2017; Mehmood et al., 2022). Sustainable solutions for climate change and variability adaptation require an assessment of the levels of awareness on the occurrence and impacts of climate change amongst rural smallholder farmer households and an in-depth understanding of the reasons for their choices and the impacts of those choices on crop production.

This study aimed to assess climate change awareness; in this study, awareness refers to farmer consciousness of extreme weather events. Furthermore, our objective was to compile a catalogue of methods employed by smallholder farmers for coping with harsh weather conditions in the semi-arid Marange area, Mutare district of Zimbabwe, primarily distinguished by its sandy terrain and frequent periods of drought. The specific objectives were to (i) assess farmer awareness of extreme weather events caused by climate change, (ii) identify adaptation strategies implemented and which factors underlying them, and (iii) evaluate maize yield outcomes from different soil fertility and water management practices.

## 2. Materials and methods

### *2.1. Study area*

The study was conducted in the Marange region of the Mutare district and Manicaland province of Zimbabwe (18°59′ – 19°25′ S; 32°1′ – 32°37′ E) (Figure 1). The choice of the Marange area was guided by the extensive area of sandy soils, which can accrue enormous potential benefits from adopting soil and water management practices to improve crop production under recurrent seasonal droughts (Kubiku et al., 2022). The area is located in Agro-ecological Region IV, characterized by an annual rainfall of

<650 mm (unimodal rainfall pattern from October to March) and a mean maximum air temperature of 28° C (Manatsa et al., 2020). Mid-season dry spells are common during the crop-growing period. The vegetation in the area is typically a semi-arid Savanna comprising deciduous trees and shrubs interspaced with overgrazed grass. The landscape is relatively flat, with scattered rocky outcrops. The area is suitable for drought-tolerant crops such as cowpeas (*Vigna unguiculata L.*), maize varieties requiring 105–120 days to maturity, extensive cattle ranching, rearing small livestock such as goats, and wildlife (Manatsa et al., 2020). Farmers in the area grow crops such as maize (*Zea Mays L.*), sorghum (*Sorghum bicolor L.*), pearl millet (*Pennisetum glaucum (L.) R. Br.*), finger millet/rapoko (*Eleusine coracana L.*) and groundnuts (*Arachis hypogea* L.) (Chiturike et al., 2022).

### 2.2. Data collection

Seven wards within the Marange area were selected to capture the variability in the awareness of climate change and adaptation strategies. The seven wards included Mutanda, Nyagundi, Mafararikwa, Nyachityu, Takarwa, Mudzimundiringe and Munyoro. Data was collected using a structured household questionnaire survey conducted in September 2019. The sample for the population-based household survey was selected using a non-probability-based snowballing sampling approach (Naderifar et al., 2017 ) to provide a statistically representative sample of the project implementation wards in Marange, Mutare district, selected through the help of extension officers (Figure. 1). Snowballing sampling technique was applied because farmers were not easily accessible (i.e. they were unattainable using probability sampling methods), and the data collection team had to rely on strong networking among farmers to identify those who were available and willing to take the interview. Therefore, interviewing farmers by the enumerators was a gradual process, with one farmer leading the interviewer to the next, continually until saturation of at least 35 farmers was interviewed from each of the selected wards. Two hundred forty-five smallholder farmers within the seven wards of the study zone were each subjected to in-person interviews and their responses were recorded on printed questionnaires by trained local enumerators. Key farming indicators grouped in modules were collected at the household level. Among the modules, the survey questionnaire had socio-economic data, land management and agricultural inputs, crop information, livestock, poultry and their products, labour source, gender-related aspects, access to capital, credit, extension services and external resources, climate and soil, food security and wealth status (Appendix 1). To understand climate awareness and adaptation strategies, relevant variables were selected. The most relevant indicators to answer the objectives of this study were farmer awareness of extreme weather events, types of events, adaptation strategies, barriers to adaptation, and maize production per hectare.

### 2.3. Data management

In order to evaluate the effect of adaptation strategies on maize yield (a common crop among the 245 farms), data from different modules were combined and only farmers with maize crops were considered. The combination of data from the different modules yielded farmer categories based on a single or combination of soil or water management strategies. Farmers with NA or missing values were removed from the study. At the household level, maize yield (in tonnes per hectare) was calculated using the information obtained from crop information in the farmland and farm sizes module. Soil fertility management options comprising mineral fertilizer and organic fertilizer categories were derived from sections of mineral fertilizer application and manure use in the land management and agricultural inputs module. For example, the fertilizer category was derived from questions asking if the farmer uses any mineral fertilizer, followed by a follow-up question to specify the crop on which the fertilizer is applied. The same was done for the manure category. If a farmer responded to both fertilizer and manure use sections, they were categorized as using manure + fertilizer. If a farmer had a maize crop and stated that they neither use mineral fertilizer nor manure, they were assigned to the no fertilizer category. The retained soil fertility categories were (i) manure only, (ii) fertilizer only, (iii) manure + fertilizer, and (iv) no fertilizer (Table 1). The manure quality in the study area was characterized as low in total nitrogen (N) (0.72 ± 0.22%), phosphorus (P) (0.23 ± 0.07%) and potassium (K) (0.55 ± 0.19%).

Farmers were also grouped according to the water management strategy applied over the past five years. This information was obtained from irrigation and other water management practices in the land management and agricultural inputs module. Soil moisture

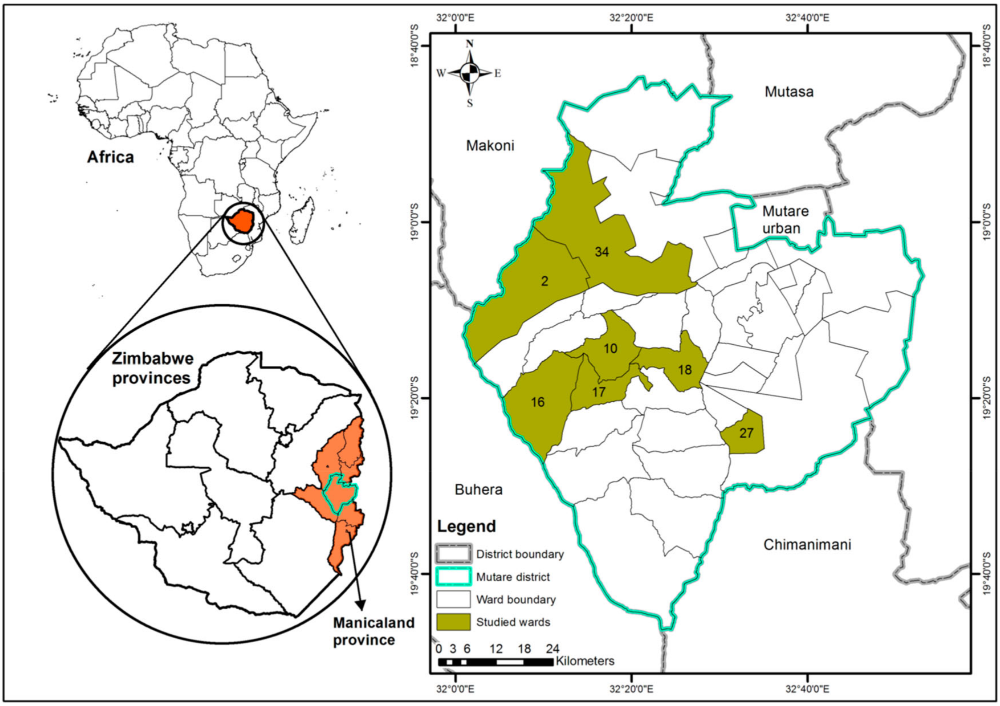


**Figure 1.** Maps showing the location of Manicaland province in Zimbabwe (left) and the study area (wards) in Marange, Mutare district (right). The 7 wards are 2 (Mutanda), 34 (Nyagundi), 16 (Mafararikwa), 10 (Nyachityu), 17 (Takarwa), 18 (Mudzimundiringe) and 27 (Munyoro), indicated on the map (right).

management strategies such as mulching, pot-holing, basins, ridges, and autumn ploughing were set as in-field water management options. Standard contours, tied contours, infiltration pits, and terracing were set as out-field water management strategies. This approach was taken because multiple responses were obtained for soil moisture management on most of the farmers. Thus, the categories for soil moisture management were as follows: (i) Irrigation, (ii) In-field, (iii) Out-field, (iv) Irrigation + In-field, (v) Irrigation + Out-field, (vi) Irrigation + In-field + Out-field, and (vii) No soil water management (Table 1).

Yield depends on the interactions between genotype, management and environment (G × M × E) (Mahmood et al., 2022 ). To further understand the effect of soil moisture and fertility management, maize variety was considered an additional factor influencing yield. Only two categories of maize variety emerged from the data: improved and non-improved varieties. The information on variety was extracted from the improved seeds section in the land management and agricultural inputs module.

The module on climate change awareness highlighting the farmers' experience with extreme weather events, adaptation strategies and reasons for no adaptation was used to obtain general farmer perspectives and responses to climate change and variability.

### 2.4. Statistical analyses

The data was analysed using the IBM SPSS statistical package and R v 4.2.1(R Core Team, 2022). Data analysis involved descriptive statistics of percentages of farmers who experienced extreme weather events. Cross tabulations were done for adaptation options and reasons for no adaptation linked to the weather event experienced. Linear models using the linear model function were used to analyse variances in the management categories explored by farmers to improve maize yield.

Maize yields were either expressed as a function of water management, soil fertility management

**Table 1.** Soil fertility and water management categories and respective percentages of Farmers per category, $n = 151$.

| Management category | category meaning | percentage of farmers |
|---|---|---|
| **Soil fertility** | **A factor with four levels** | |
| Manure only | Cattle manure, compost, poultry manure used on maize crop | 10 |
| Fertilizer only | Mineral fertilizer (ammonium nitrate, compound D) | 32 |
| Manure + fertilizer | Use any manure type and mineral fertilizers to enhance crop growth | 38 |
| No fertilizer | Neither organic nor inorganic fertilizers was applied to the maize crop | 20 |
| **Soil moisture management** | **A factor with seven levels** | |
| Irrigation | Pouring water by hand using a bucket | 33 |
| In-field | Mulching, pot holing, basins, ridges, autumn ploughing | 7 |
| Out-field | Standard contours, tied contours, infiltration pits, terracing | 5 |
| Irrigation + In-field | Irrigation + one or multiple in-field soil moisture management | 36 |
| Irrigation + Out-field | Irrigation + one or multiple out-field soil moisture management options | 6 |
| Irrigation + In-field + Out-field | Categories as defined above combined | 1 |
| No soil water management | Not using any of the soil water management options stated above | 11 |
| **Variety** | **A factor with two levels** | |
| Improved variety | Certified maize hybrid seed variety | 63 |
| Non improved variety | Seed returned from previous seasons | 37 |

practices or crop variety (Eq. i) (Welham et al., 2015).

$$y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + e_{ijk} \qquad (i)$$

Where:

$y_{ijk}$ is the average $k$th reported maize yield by farmers in the $i$th level or category of either soil fertility management or water management,

$\mu$ is an intercept, $\alpha_i$ is the effect of the $i$th level or category of either soil fertility management or water management, $\beta_j$ is the effect of the $j$th level or category of maize variety,

$(\alpha\beta)_{ij}$ is the effect of the interaction between the $i$th level of either soil fertility or water management and the $j$th level of maize variety on maize yield and $e_{ijk}$~$(N, 0\sigma_e{}^2)$. Maize yield was assigned as the response variable, soil fertility management with four levels, water management with seven levels and crop variety with two levels as factors (Table 1) for the analysis of variance.

Where there were no significant interactions, the Kruskal–Wallis test was used to test if there were differences within groups. A significant Kruskal Wallis test was followed by a post-hoc pairwise multiple comparison to separate the different groups using Wilxocon Mann–Whitney test.

To understand the factors that influence farmers to adopt adaptation strategies, a generalized linear regression model (glm) with a logit link was used (Eq. ii) (James et al., 2022)

$$\text{logit } E(Y) = \eta$$

$$\eta = \beta_O + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_{14} d_{14} \qquad (ii)$$

Where:

E(Y) is the expected value of the adaptation strategy, and logit E(Y) = ln(E(Y))/(1 – E(Y)). Furthermore, $\beta_0$ is an intercept, and $\beta_1$ through $\beta_{14}$ are the regression coefficients for the predictor variables $X_1$ through $X_{14}$and dummy variables $d_1$ through to $d_{14.}$

This study's response variables (Y), which were all binary, were crop diversification (where farmers had more than one crop per farm), improved seeds, irrigation, soil water management, crop-livestock integration, early planting, and planting trees (Table 2). Explanatory variables included in the model were socio-economic characteristics, age and household size as continuous variables, education as a factor with five education levels dummy variables of gender and access to land (Table 2). The other explanatory variables were derived from the farmer's reasons for not using adaptation strategies such as dummy variables shortage of labour, no loans, no information on climate change and adaptation (Table 2). Other dummy explanatory variables were derived from different modules on access to extension services, association with farmer groups, and knowledge of adoption projects in the area (Table 2).

**Table 2.** Definition of variables used in the GLM model.

| Variable name | Variable defination | Source |
|---|---|---|
| *Response variables* | | |
| Crop diversification | Binary variable, 1 = where farmers had more than one crop per farm, 0 = where farmer reported only one crop | Crop production module |
| Improved seeds | Binary variable, 1 = yes the farmer uses improved seeds, 0 = otherwise | Improved seeds Module and climate change awareness module |
| Irrigation | Binary variable, 1 = yes the farmer uses irrigation, 0 = otherwise | Irrigation use module and climate change Awareness module |
| Soil water management | Binary variable, 1 = yes the farmer uses soil water management, 0 = otherwise | |
| Crop-livestock integration | Bbinary variable, 1 = yes the farmer use crop-livestock integration as a response to extreme weather event, 0 = otherwise | Climate change Awareness module |
| Early planting | Binary variable, 1 = yes the farmer practices early planting, 0 = otherwise | Climate change awareness module |
| Planting trees | Binary variable, 1 = yes the farmer has planted some trees, 0 = otherwise | Integrated farming modue and climate Change awareness module |
| *Explanatory variables* | | |
| Age | Continous variable, Age of household head | Respondent information module |
| Household size | Continous variable, number of people staying in the house | Household population module |
| Gender | Binary variable, 1 = male, 0 = female (household head gender) | Respondent information module on gender |
| Education | Factor, education level experessed as 1 = no school, 2 = primary, 3 = secondary, 4 = post – secondary, 5 = adult education literacy school or parish | Respondent information module on education level |
| Access to land | Binary variable, 1 = access to land, 0 = no access to land | Climate change Awareness module |
| Shortage of labour | Binary variable, 1 = yes there is a shortage of labour, 0 is otherwise | climate change Awareness module |
| No loans | binary variable, 1 = yes the farmer has no access to loans or credit, 0 is otherwise | Climate change Awareness module |
| No information on climate change and adaptation | Binary variable, 1 = yes the farmer has not come across any information on climate change and adaptation strategies, 0 is otherwise. | climate change Awareness module |
| Access to extension services | Binary variable, 1 = farmer has access to extension services, 0 otherwise, | Extension access module |
| Association with farmer groups | Binary variable, 1 = farmer is a member of a farmer group, 0 = farmer is not a member of any farmer group | Social capital module |
| Knowledge of adoption projects in the area | Binary variable, 1 yes the farmer knows of any project or program targeting farmers in the area that promotes the adoption of specific technology, 0 is otherwise | External support Information module |

## 3. Results

### 3.1. Farmer characteristics

About 73% of the respondents out of the 245 farmers interviewed were household heads, while 37% comprised either the spouse, child or other family members (Table 3). The composition of the households head by gender was 73% and 26% for men and women, respectively. The mean age for men and women household heads in the study area was 50 and 56 years, respectively (Table 3). About 53% and 36% of the farmers had attained secondary and primary education, respectively. Only 8% of the farmers had no formal education (Table 3). All the farmers in the study owned agricultural land on which they grew crops and kept some livestock. Out of the 245 farmers studied, 90%, 7% and 2% reported having owned, rented and had access to common land, respectively (Table 3). Owned farms had sizes ranging between 2.8 ha to 3.8 ha per farm (Table 3).

**The most common type of labour to facilitate farm activities is household labour (86%), followed by social arrangement with community members and extended family (10%), while hired labour is used the least (4%).**

About 69% of the farmers in the study area grow maize as the main cereal crop. The proportion of farmers growing pearl millet**,** soghum, and rapoko were 42%, 26% and 9%, respectively. About 35% of farmers grew groundnuts**,** 20% grew roundnuts **(***Vigna subterranea***)** and 8% grew cowpea. Other crops grown in the area include cotton (*Gossypium hirsutum*), tobacco (*Nicotiana tabacum*), sesame (*Sesamum indicum*), and sunflower (*Heliantus annuus***)** grown by 11%, 10%, 5% and 3% of farmers respectively (Table 3).

**Table 3.** Farmer household characteristics in Marange, Mutare district, Zimbabwe ($n = 245$).

| Household characteristic | Percentage of famers per category | |
|---|---|---|
| **Interviewed respondents** | | |
| Household head | 73 | |
| Spouse, child or other family member | 37 | |
| **Gender of households head** | | *Mean age of household heads* |
| Female | 26 | 56 |
| Male | 73 | 50 |
| **Education of household heads** | | |
| Secondary education | 53 | |
| Primary education | 36 | |
| No formal education | 8 | |
| **Household ownership of land** | | *Farm size (ha)* |
| ownership of land | 90 | 2.8–3.8 |
| rented land for own use | 2 | 1–1.8 |
| rented out land for others | 1 | 0.4–2 |
| common land | 7 | 2.2–2.4 |
| **Farm labour source** | | |
| family | 86 | |
| arrangement | 10 | |
| Hired | 4 | |
| **Crop types** | | |
| Maize | 69 | |
| Cotton | 11 | |
| Sorghum | 26 | |
| Rapoko | 9 | |
| Groundnut | 35 | |
| Tobacco | 10 | |
| Cowpeas | 8 | |
| Groundnut | 20 | |
| Pearl millet | 42 | |
| Sesame | 5 | |
| Sunflower | 3 | |
| **Food insecurity, months** | | |
| January | 55 | |
| February | 25 | |
| March | 14 | |
| April to July | 2 | |
| August | 10 | |
| September | 30 | |
| October | 42 | |
| November | 48 | |
| December | 50 | |

Out of the 245 farmers included in the study, 50%–55% reported having suffered from food insecurity from December to January. About 25% and 14% of the farmers experienced food insecurity in February and March, respectively. Only 2% of the farmers experienced food insecurity from April to July. In August, September, October and November, 10%, 30%, 42% and 48% of farmers experienced food insecurity, respectively (Table 3).

Farmers in the study area receive aid in the form of food, cash and agricultural inputs such as fertilizer and seeds. Food aid alone was received by 46% of farmers, whereas 44% of farmers did not receive any form of aid during the last 12 months. Only 10% of the farmers received agriculture inputs, cash or packaged aid (containing food and agriculture inputs). The government is the primary source of aid (91%) among other sources such as NGOs and Gifts (from family, friends and neighbours).

### *3.2. Farmers' awareness and adaptation strategies to extreme weather events*

All 245 interviewed households confirmed that they had experienced extreme weather events in the past five years. Drought was the most experienced extreme weather event reported by 46% of farmers. The other extreme weather events reported were higher than average temperatures, strong winds, and floods, which were correspondingly reported by 26%, 12% and 10% of the farmers. Lower than average winter temperatures were also reported by 5% of the farmers. A few farmers (<5%) had also experienced erratic rainfall patterns, short crop growing seasons and cyclones (0.3%).

Out of the eight types of reported extreme weather events, farmers have adaptation strategies for five, including drought, floods, strong winds, and increased and reduced temperatures (Appendix 2). Ten adaptation strategies were reported against drought, whereas three to five were reported for other types of extreme weather events. Common adaptation strategies against drought are water harvesting, changing planting dates, soil moisture management, alternative crops and use of improved seeds (Appendix 2).

Farmers highlighted several reasons why they fail to adapt to extreme weather events. The most important reason is the lack of resources (i.e. agricultural inputs and financial credit facilities) and information on climate and adaptation practices (Figure 2). Some farmers reported facing labour availability challenges (Figure 2) to implement best-bet adaptation practices as some technological options, such as the construction of water harvesting structures, are very labour-intensive.

Results from the generalized linear model indicate that a farmer's association with farmer groups positively impacts planting trees, early planting and irrigation strategies for adapting to extreme weather events (Table 4). Farmer access to extension services positively impacts adopting soil water management

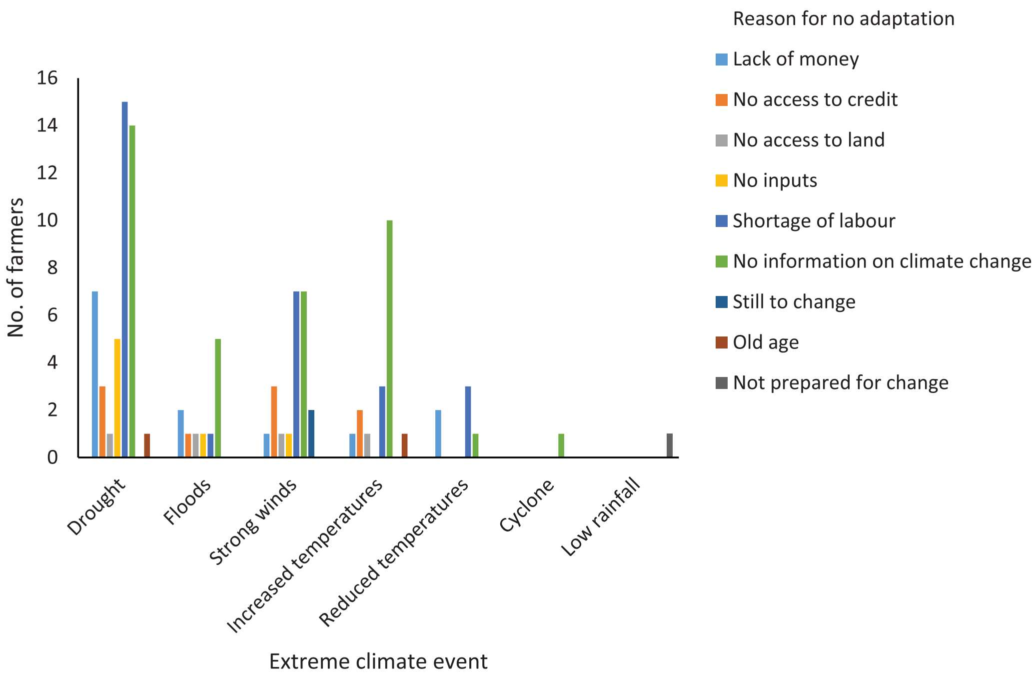


**Figure 2.** Farmer reasons for not using adaption practices to deal with each of the extreme weather events experienced in Marange, Mutare district.

strategies whereas it negatively impacts adopting planting of trees and use of irrigation. Farmer knowledge of other projects or programmes promoting the adoption of specific technologies negatively impacts the adoption of irrigation. A farmer´s education level of either primary or secondary education positively impacts the adoption of irrigation. Household size positively impacts farmer adoption of irrigation and crop-livestock integration (Table 4). Gender, age and secondary education level positively impact adopting crop diversification, whereas adult education level negatively impacts crop diversification (Table 4).

### 3.3. Effect of soil fertility, maize variety and water management strategies on maize yield

Results from the analysis of variances had no significant interactions effect of management practices soil fertility, maize variety and water management strategies on maize yield reported by farmers.

#### 3.3.1. Soil fertility management effect

The grouping of farmers according to soil fertility management showed that 10%, 32%, and 38% of the farmers apply manure, fertilizers, and a combination of manure and fertilizers, respectively. The other 20% do not apply any fertilizers (Table 1).

Farmers who reported applying fertilizer only obtained an average maize yields (0.614 t $ha^{-1}$), whereas those who applied manure only reported harvesting an average of 0.621 t $ha^{-1}$ (Figure 3). The farmers stating that they used organic and inorganic fertilizers had an average maize yield of 0.327 t $ha^{-1}$. In contrast, the farmers who reported that they neither applied inorganic fertilizer nor organic fertilizer got 0.197 t $ha^{-1}$ (Figure 3). The Kruskal–Wallis *p*-value for the soil fertility categories suggested a significant difference in the reported maize yields ($p = 0.03044$), and pairwise comparisons using the Wilcoxon Mann–Whitney test did find some significant differences in the soil fertility management categories (Figure 3). The reported maize yield for farmers who stated that they neither applied organic nor inorganic fertilizer significantly differed from the maize yield of farmers who applied manure only, fertilizer only and a combination of both manure and fertilizer (Figure 3).

**Table 4.** Estimated socio-economic factor coefficients explaining the farmers´capacity to adopt adaptation strategies in Marange.

| Variables | Crop diversification | Improved seeds | Irrigation | Soil water management | Crop livestock integration | Early planting | Planting trees |
|---|---|---|---|---|---|---|---|
| Gender | 0.827 (0.409)** | 0.148 (0.348) | −0.060 (0.409) | 0.024 (0.423) | 0.553 (0.577) | 0.614 (0.462) | 0.249 (0.414) |
| Age | 0.034 (0.014)** | 0.012 (0.011) | 0.018 (0.013) | −0.007 (0.014) | 0.013 (0.018) | −0.009 (0.014) | 0.009 (0.414) |
| Education2 | 0.710 (0.699) | −0.161 (0.603) | 1.143 (0.667)* | 0.391 (0.768) | −16.36 (1495) | −0.148 (0.890) | 0.095 (0.721) |
| Education3 | 1.373 (0.775)* | 0.309 (0.659) | 1.532 (0.754)** | 0.153 (0.819) | −15.80 (1495) | 0.532 (0.924) | 0.371 (0.782) |
| Education4 | −2.478 (1.418)* | −0.082 (1.381) | 0.547 (1.443) | −17.21 (3552) | −19.08 (1495) | −17.22 (5503) | −15.25 (1340) |
| Education5 | 14.12 (882) | 13.98 (882) | 13.70 (882) | −16.54 (6523) | −1.967 (6691) | 34.4 (11490) | −15.97 (2400) |
| Shortage of labour | 0.528 (0.755) | 0.775 (0.618) | 0.141 (0.615) | −1.529 (1.07) | 1.118 (1.299) | −34.17 (2818) | 0.634 (0.619) |
| Knowledge of adoption projects in the area | −0.581 (0.393) | 0.223 (0.315) | −0.670 (0.361)* | 0.425 (0.365) | −0.507 (0.599) | 0.108 (0.373) | 0.540 (0.381) |
| No loans | −0.438 (0.708) | −0.605 (0.628) | −0.055 (0.765) | 0.399 (0.699) | −1.423 (1.050) | −19.15 (2904) | −0.746 (0.742) |
| Access to extension services | −0.083 (0.553) | 0.650 (0.443) | −1.163 (0.606)* | 1.383 (0.785)* | 0.833 (0.625) | −0.530 (0.542) | −0.845 (0.503)* |
| Access to land | 0.963 (1.387) | 1.614 (1.344) | −0.151 (1.316) | 17.07 (3638) | 2.081 (1.660) | −18.33 (2029) | 15.57 (1375) |
| Association with farmer groups | −0.074 (0.418) | 0.155 (0.337) | 0.856 (0.415)** | −0.317 (0.398) | 1.231 (0.835) | 0.811 (0.396)** | 1.082 (0.379)** |
| No information on climate change and adaptation | 0.095 (0.713) | 0.199 (0.539) | 0.337 (0.728) | −17.1 (1456) | −1.092 (0.838) | −1.804 (1.108) | 0.870 (0.564) |
| Household size | 0.034 (0.049) | 0.003 (0.034) | 0.142 (0.056)** | 0.034 (0.036) | 0.170 (0.100)* | −0.038 (0.044) | 0.038 (0.037) |
| Constant | −2.747 (1.932) | −2.957 (1.718)* | −0.849 (1.829) | −19.63 (3638) | 13.683 (1495) | 17.630 (2029) | −17.510 (1375) |

Standard errors within brackets, * significance at $p < 0.1$, **significance at $p < 0.05$

### 3.3.2. Maize variety

Most smallholder farmers in Marange use improved maize varieties; 63% use certified maize hybrid seed, whereas 37% use seed returned from the previous season (Table 1).

Where farmers reported the use of improved seed variety maize yields were significantly higher ($p =$ 1.268e-05) than those farmers who stated that they use non-improved seeds (Figure 4).

### 3.3.3. Soil water management

Smallholder farmers in Marange use different soil water management strategies on field crops, such as irrigation and in-field and out-field water management technologies. The grouping of farmers according to soil water management showed that about 6% use in-field, 34% use irrigation (low technology), 37% use a combination of irrigation and in-field, 2% use a combination of irrigation, in-field and out-field, 6% use a combination of irrigation and out-field, 5% use out-field water management only whereas 10% of the farmers do not use soil water management strategies (Table 1).

The maize yields reported for farmers who applied soil water management strategies had no significant differences compared to yield reported for farmers who did not use any water management strategy ($p = 0.05$) (Figure 5).

## 4. Discussion

### 4.1. General discussion on farmer characteristics

For male-headed households, the average age of the family head was 50 (median age 47), suggesting that testing and implementing new technology might not be challenging. Similarly, in female-headed households, the family head had an average age of 56 (median age 55). Female-headed households constitute 26% of the study population. Young farmers can also provide labour much easier as they are agile, and the age of the household head is an essential factor in making decisions associated with adopting new technologies (Uhunamure et al., 2019). Most farmers have acquired basic education since 53% have secondary education, which suggests that they can understand simplified agricultural operations and make sound observations of their experiences in farming. Generally, 90% of farmers in the study area own land, which is essential for the livelihoods

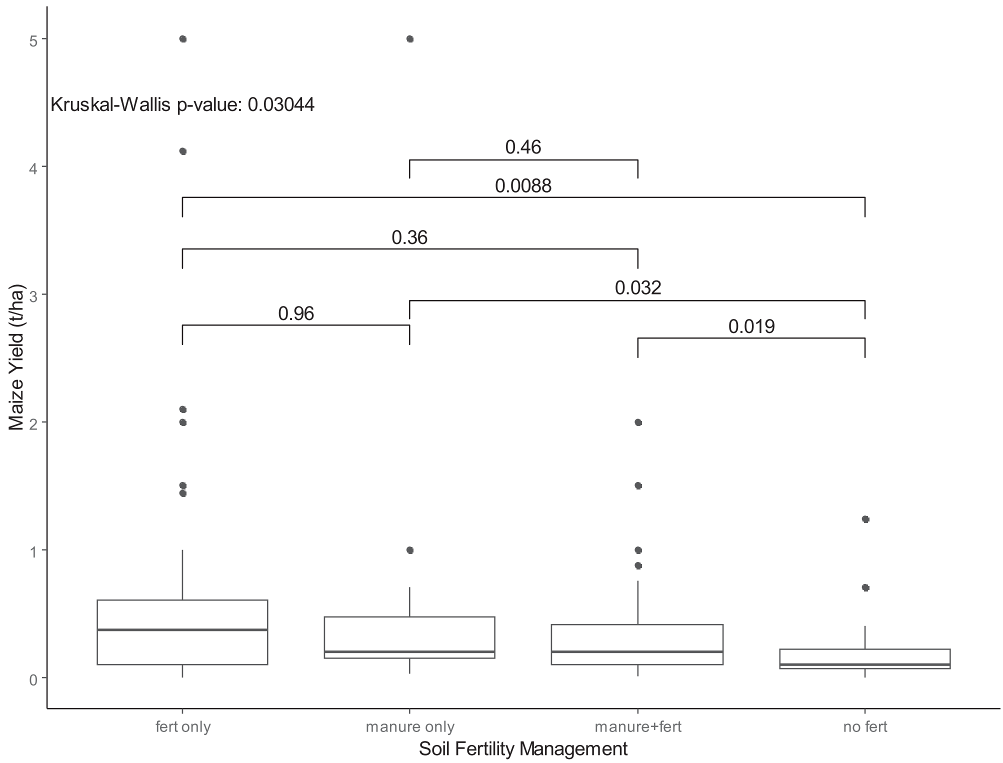


**Figure 3.** Average maize yield response to soil fertility management reported by smallholder farmers in Marange area, Mutare district. The bars connect compared groups of soil fertility management and the numbers above each bar are Wilcoxon *p*-values. (Fert represents fertilizers).

and welfare of rural households in agricultural-based rural economies (Holden & Tilahun, 2020). Household labour is the most common type of labour, which is usually common in smallholder farm set-ups (Musara et al., 2019).

Farmers in the Marange area grow various crops, including cereals, legumes, oil seeds, and cash crops. The crop diversity suggests that smallholder farmers are working towards addressing food security issues. However, most farmers are food secure for a very short period, only three months, from April to July. Most field crops are harvested in April, shelled and stored for future use. The percentage of farmers who are food insecure rises from August to January. The reason is that farmers in this area are not harvesting enough grain to sustain them until the next harvest, as there is only one crop harvest per year for rainfed agriculture, and the yield is very low. Therefore, some farmers receive food aid from August to January to alleviate the food insecurity challenges, which are provided by the government and NGOs. However, during the cropping season (October–March), farmers must balance working in their fields and simultaneously looking for food. The trade-off is that one of these priorities is compromised, and less time and resources are allocated to managing their farms. Hence, the food insecurity cycle persists. The percentage of food insecure farmers decreases towards February and March, suggesting the availability of food options from the field, such as green mealies and cowpeas.

### 4.2. Farmer’s awareness and adaptation strategies to extreme weather events

Confirmation of experiencing extreme weather events by farmers shows that they are aware of climate change and variability and its impacts on their agricultural production systems. This is consistent with experiences recorded across Southern Africa (Mavhura et al., 2022; Mtambanengwe et al., 2012; Sani & Chalchisa,

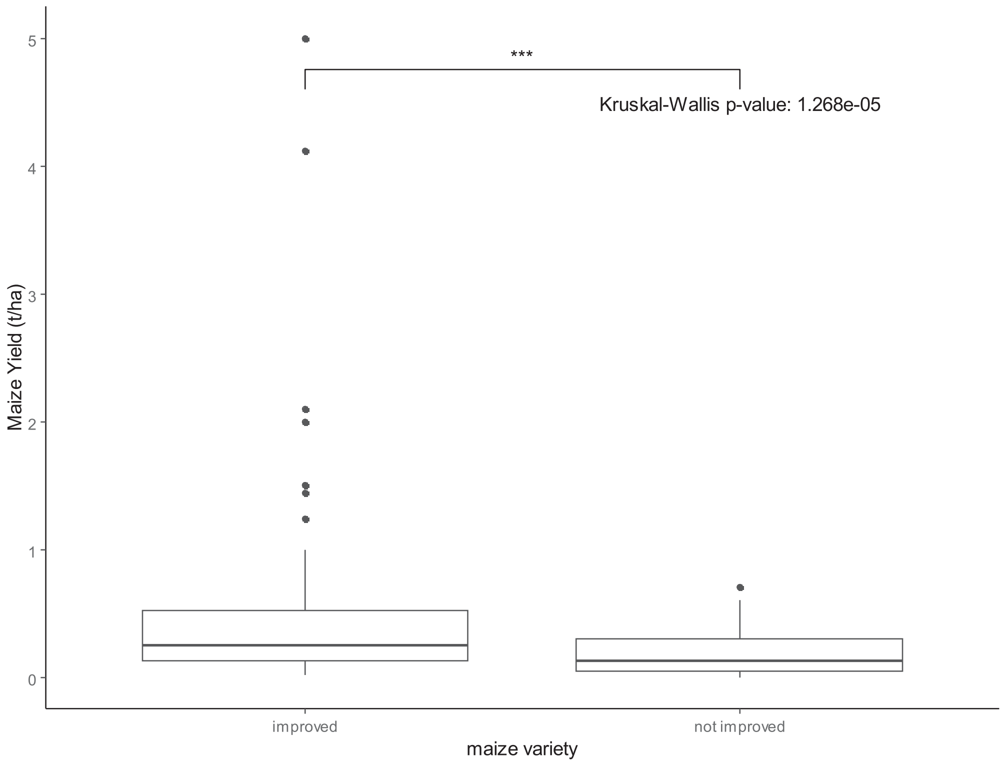


**Figure 4.** A comparison between maize yield reported for improved and non improved maize variety by smallholder farmers in Marange area, Mutare district. The bar with ***connects different maize variety groups significant at $p < 0.05$.

2016), showing that farmers are active observers of environmental changes (Ramborun et al., 2020). To respond to these extreme weather events, several farmers reported adopting management practices and technological options based on the extreme weather events they frequently encountered. For example, farmers responded to the drought by adopting water management strategies, early planting and changing the crop type (Sani & Chalchisa, 2016). This is in line with findings by Abid et al. (2020) who reported that farmers adopted planting early and use drought tolerant varieties after experiencing drought. However, farmers also highlighted several barriers to adapting to extreme weather events, such as lack of resources in the form of inputs or access to credit, information on climate and adaptation practices and labour availability.

The fact that other previous studies have also highlighted the same adaption barriers (Chingombe & Musarandega, 2021; Fisher et al., 2015; Nyahunda & Tirivangasi, 2021; Sen et al., 2021) suggests that while the problem and its impacts are known, there is no significant improvement in the way resources are allocated to improve farmer adaptation to climate change and variability in marginal areas. Farmers have adopted possible adaptation technologies and practices despite limited progress based on their socio-economic resource endowment (Mutenje et al., 2019; Sani & Chalchisa, 2016). Since the resource endowments of rural farmers only allow slow changes, smallholder farmers remain constrained, and it is not easy to achieve food self-sufficiency. For transformational change that increases food self-sufficiency in marginal semi-arid regions, there is a need for an integrated approach encompassing innovations in policies, credit facilities, and technological and management options.

Some level of education such as primary or secondary education, positively impacts crop diversification and irrigation adoption. This suggests that education

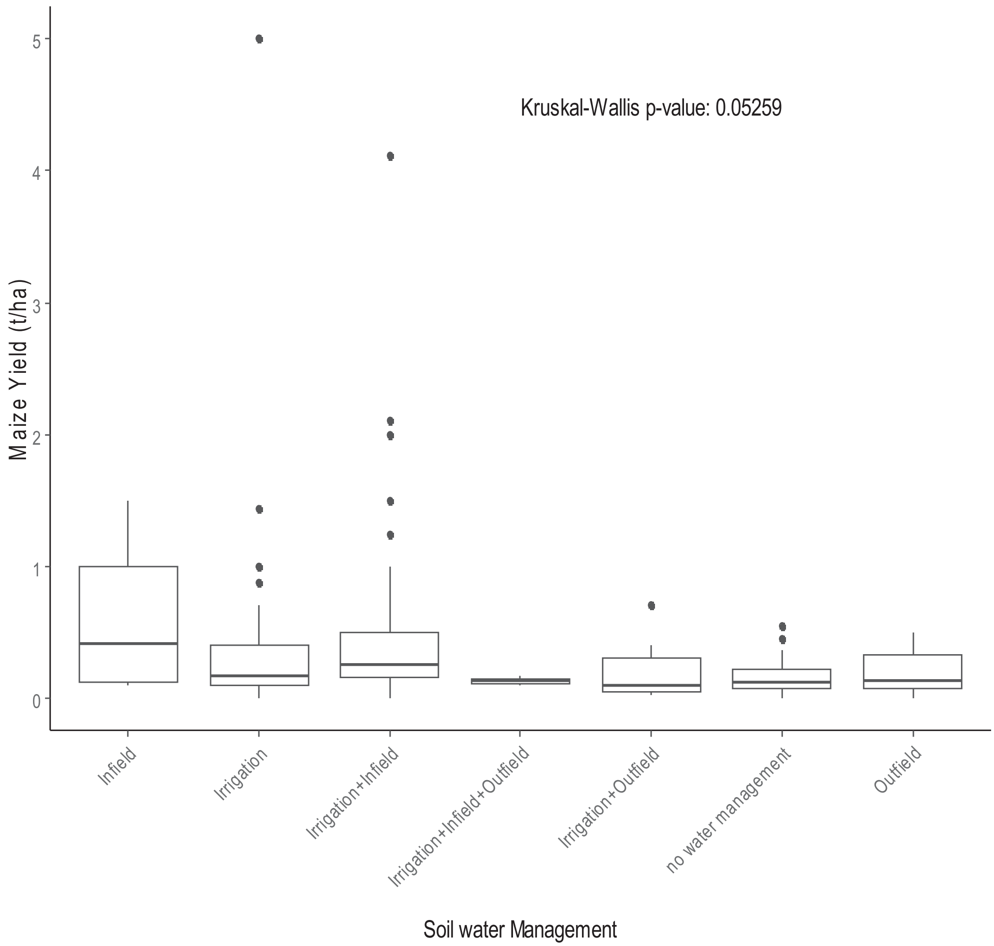


**Figure 5.** Average maize yield response to soil water management use by smallholder farmers in Marange area, Mutare district.

translates to a better understanding of agricultural practices and decision-making to adopt (Vanlauwe et al., 2023). However, primary and secondary education alone may not guarantee the adoption of a technology; other factors, such as practical training, are crucial.

Association with farmer groups positively impacts adopting adaptation strategies such as planting trees, early planting and irrigation. Farmers learn by doing and experimenting on platforms such as farmer groups. These farmer groups are often used to speed up technology adoption (Norton & Alwang, 2020). Sharing information and experiences among farmers in farmer groups can create a positive learning environment that encourages the exchange of knowledge and best practices (Fisher et al., 2018), leading to greater awareness and understanding of the benefits of planting trees, early planting, irrigation, and an increased willingness to try them out. Household size positively impacts irrigation adoption and use of crop-livestock integration, which translates to the availability of labour from the household members.

Farmer access to extension services positively impacts the adoption of soil water management strategies. Extension services are vital in disseminating new technologies and effectively assisting smallholder farmers in managing climate risks and impacts (Antwi-Agyei & Stringer, 2021). New technologies are promoted through field days and workshops (Antwi-

Agyei & Stringer, 2021; Makate et al., 2019). However, in the study area, farmer access to extension services negatively impacts the adoption of irrigation and planting of trees, and this can mean that farmers selectively choose options that suit them. Therefore, while access to extension services is essential, it is not the only factor influencing the positive adoption of irrigation practices or planting of trees. In the current study, the type of irrigation practised is watering using a bucket which they can encourage each other in farmer groups. Farmer knowledge of other adoption projects in the area negatively impacts the adoption of irrigation. When farmers have information about successful projects that their peers have implemented, they may be more likely to adopt similar practices, especially if they have been shown to improve agricultural productivity (Fisher et al., 2018).

### 4.3. Maize yields in relation to management strategies

Adopting soil fertility and water management practices is expected to improve maize productivity (Chiturike et al., 2022; Ndegwa et al., 2023); however, the average maize yields remain below 0.8 t $ha^{-1}$ in Marange, Mutare district. Extreme weather events could explain these low yields (Kubiku et al., 2022). For example, according to Kubiku et al. (2022), rainfall in the area during the 2018–2019 season was above 650 mm and more than expected (450–650 mm) for the agro-ecological region. These high rainfalls in Marange probably resulted in high nutrient leaching on the predominantly sandy soils, reducing the nutrient use efficiencies of already low amounts of fertilizers applied by smallholder farmers. The total rainfall may have been above average, but the distribution may have been poor. During the 2018–2019 season, > 150 mm was received in 1 week. Consequently, this reduces crop growth and yield unless fertilizer is applied again to compensate for the leaching losses.

Generally, extreme weather events affect the response of crops to applied fertilizers (Rosenstock et al., 2019). Farmers who apply less than 8.5 kg $ha^{-1}$ of fertilizers and manure often see insignificant differences in yields compared to those who apply sole fertilizer or sole manure (Twomlow et al., 2006). Due to the risk of crop failure during droughts and dry spells in semi-arid areas, smallholder farmers tend to apply fertilizers below the recommended rates (Nezomba, Mtambanengwe, Chikowo et al., 2015) to mitigate losses (Mashingaidze et al., 2013). The recommended fertilizer application rate for maize grown in agroecological zone where Marange is located is 250 kg $ha-^{1}$ compound D (7% N, 14% $P_20_5$, 7% K) and at least 100 kg $ha-^{1}$ of ammonium nitrate (FAO, 2006). Smallholder farmers, who are often resource-constrained, may find mineral fertilizer expensive and out of reach (Fairhurst, 2013; Nezomba, Mtambanengwe, Tittonell et al., 2015). Manure application also depends on availability and is often allocated to many crops, including family gardens resulting in farmers applying less than 3 t $ha^{-1}$ to field crops like maize (Mtangadura et al., 2017). Socio-economic challenges, such as resource constraints and competing demands for fertilizer resources, may prevent farmers from recognizing the yield benefits of applying fertilizers.

Management practices and soil types influence the effectiveness of applied fertilizers. For maize production, the effective management of nitrogen fertilizers requires split application considering the timing, quantities, weather conditions, and available soil mineral nitrogen (Masvaya et al., 2017). Manure management from the kraal to the field is crucial to maintaining manure's nutrient quality. If the manure stays too long in the open, the mineral nitrogen volatilizes as $NH_3$ or $N_2O$ (Peng et al., 2022). In the study area manure was found to be of low quality with 0.72% nitrogen thus emphasizing the need for maintaining manure nutrient quality. Broadcasting vs. precise application of manure also determines the ultimate crop yield. Nitrogen is lost into the atmosphere from broadcasted manure, and the remaining organic fraction decays slowly on the surface, resulting in very little proportion of nutrients available for root uptake (Nkebiwe et al., 2016).

Soil moisture management strategies grouped as in-field (mulching, potholing, basins, ridges, and autumn ploughing) and out-field (standard contours, tied contours, infiltration pits, and terracing) water management strategies did not give significant yield responses. Although a greater percentage of farmers, 34%, use the traditional irrigation method, such as bucket irrigation on maize crops. The traditional irrigation method has no proper scheduling, is manually implemented and is affected by the distance from the water source. Such irrigation systems may not be sustainable for field crops such as maize. Previous studies have shown that in-field water harvesting techniques with improved nutrient management significantly increased maize yields in sandy soils (Chiturike et al., 2022; Kugedera et al., 2022). However, this was not the case with the farmers in this study. In the previous studies, it was observed that the effect of water harvesting technologies on crop yield could significantly differ from farmer to farmer due to technical management and accuracy in the construction of water harvesting structures (Chiturike et al., 2022) . Perhaps this was the case in the current study, where poor management and faulty construction of water harvesting may have contributed to the lack of significant yield increases.

The use of improved varieties is one of the ways of adapting to extreme weather events, and the results from this study are in line with the previous findings (Fisher et al., 2015; Makate et al., 2017; Mashingaidze et al., 2013; Parwada et al., 2022). Maize yields for improved varieties were highly significant, but the average maize yield reported shows that farmers are still within the category of low yields, less than 0.8 t $ha^{-1}$. Overall, based on the rainfall received in the 2018–2019 season and information collected from the farmers about using fertilizers, water management options and improved varieties, the average maize grain yields would have been significantly above 0.8 $tha^{-1}$. Since this study was based on practices that farmers in Marange were currently practising and not an experiment where other factors that can affect yield were controlled, the response of maize yield may have been influenced by other socio-economic factors. Thus, a robust approach of trans-disciplinary action is required to reach smallholder farmers in semi-arid areas and assist them in adopting good skills and practices for improved crop production and adaptation to extreme weather.

## 5. Conclusions

Farmers in Marange, Mutare district, confirmed experiencing extreme weather events and are aware of the risks posed on agricultural production. They are aware of the need to take proactive steps to protect their crops and livelihoods from the potential damage caused by extreme weather events. Farmers have also prioritized adopting some strategies to cope with extreme weather events. The farmers implemented adaptation strategies such as soil and water management, use of improved varieties, mulching, planting trees, early planting, reducing the area under cultivation, and changing the types of crops in their crop production systems. Despite the reported adaptation strategies on fertility and water management, maize yields remain very low for smallholder farmers.

To improve yields, further research is needed to determine the exact amounts of fertilizer and water management inputs needed to optimize the productivity of improved crop varieties. Therefore, we recommend that farmers receive training and support on the best evidence-based fertilizer and water management practices. Access to climate and weather information services by farmers will also help them carry out farming operations on time, adjust their farming practices and minimize the impacts of extreme weather events on their crops. Finally, there is a need to promote and adopt drought-tolerant maize varieties and alternative crop options that are more resilient to extreme weather events and better suited to the local climate conditions.

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# Appendices

## Appendix 1: The questionnaire used for the household survey

The survey questionnaire comprised of separate modules addressing the following topics:

- General comments (introducing the objective and aims)
- Metadata
  - Respondent information
- Farmland and their sizes
  - Crop information
  - Vegetable information
  - Information on fruits
- Land management and agricultural inputs
  - Mineral fertilizer
  - Manure
  - Chemical
  - Improved seeds
  - Inputs for harvest storage
  - Irrigation
  - Other water management practices
  - Integrated farming
  - Preventive measures utilized
- Livestock, Poultry, Bees and their products
  - Livestock information
  - Livestock products – milk, skin and hides
  - Purchased feeds
  - Veterinary medicines
  - Livestock manure
  - Poultry information
  - Beekeeping
- Labour source
- Gender related aspects
- Access to capital, credit, extension support, and external support
  - Social capital
  - Access to credit and loan
  - Extension services
  - External support
- Climate and soil
  - Climate change awareness
  - Soil water retention technology
- Food security and wealth status
  - Food security issues
  - Household wealth status

## Appendix 2: The number of farmers in the Marange area that reported the use of different adaptation strategies to extreme weather events (n = 245)

| Climate event | Adaptation strategy | Number of farmers |
|---|---|---|
| Drought | Increase the acreage under crop production | 9 |
| | Reduced area under cultivation | 16 |
| | Irrigation | 8 |
| | Water harvesting | 23 |
| | Use improved seeds | 7 |
| | Early planting | 46 |
| | Soil moisture management | 9 |
| | Crop-livestock integration | 2 |
| | Surface mulch to prevent cold on vegetables | 3 |
| | Change crops grown | 11 |
| Floods | Water harvesting | 4 |
| | Early planting | 16 |
| | Soil moisture management | 5 |
| Strong winds | Reduced area under cultivation | 5 |
| | Water harvesting | 3 |
| | Use of improved seeds | 3 |
| | Early planting | 18 |
| | Plant trees | 2 |
| Increased temperatures | Reduce the area under cultivation | 5 |
| | Water harvesting | 10 |
| | Use improved seed | 7 |
| | Early planting | 31 |
| | Soil moisture management | 14 |
| Reduced temperatures | Use of improved seed | 3 |
| | Early planting | 3 |
| | Soil moisture management | 3 |

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This thesis assessed climate change awareness, farmers´ adaptation strategies and evaluated climate-smart options for soil water and crop management under semi-arid conditions. The results reveal how smallholder farmers are aware and adapt to climate change. The tested soil water and crop management options have shown potential of improving maize production of smallholder farmers in semi-arid areas and their implementation considers socio-economic factors.

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