Discover Sustainability

Research

Climate change vulnerability and drivers of low maize yields under smallholder farming systems in semi-arid area of Marange in Zimbabwe

Tirirai Muoni[1,2,3] · Job Kihara[4] · Sandra M. Madamombe[1,5] · Ingrid Öborn[1,6] · George Nyamadzawo[5] · Christian Thierfelder[2] · Ngonidzashe Chirinda[7] · Stanley Karanja Ng'ang'a[8] · Libère Nkurunziza[1,9]

Received: 21 June 2024 / Accepted: 15 April 2025
Published online: 12 May 2025

Abstract
In semi-arid regions, smallholder farmers are vulnerable to the impacts of climate change due to naturally low rainfall. However, regardless of their vulnerability, farmers continue to grow maize (*Zea mays* L.) under rain-fed systems even though the chances of crop failures are very high, and their yields remain extremely low. This study used on-farm data to investigate how agronomic management practices chosen by farmers influence maize productivity in rain-fed smallholder farming systems in the semi-arid Marange area of Mutare district, Zimbabwe. A sample of 107 farmers were interviewed at household level. The collected information included socio-ecological data and maize yield data from small plots on each farm of an interviewed household. The results showed extremely low maize yields, ranging from 90 to 970 kg ha^{-1} and an average of 355 kg ha^{-1}. Several agricultural practices, including the strategic choice for where to plant the maize, the use of planting basins, weed management, and mulching, contributed to differences in maize yields among households. Socio-economic factors including access to agricultural information (market- and production-related), weather information services, and exposure to extension officers and researchers, enabled farmers to learn and achieve better maize yields. We conclude that maize yields are still terribly low, requiring additional efforts to develop measures that improve the production in these vulnerable communities. While most of the selected agronomic practices showed significant differences, overall yields were still low. A comprehensive overhaul of agronomic practices, land management practices, extension services, and access to weather and climate information is needed to sustainably improve maize productivity in smallholder farming systems vulnerable to climate variability and change.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s43621-025-01189-7.

✉ Tarirai Muoni, tarirai.muoni@slu.se; tarirai.muoni@gmail.com; ✉ Libère Nkurunziza, libere.nkurunziza@slu.se; Job Kihara, J.Kihara@cgiar.org; Sandra M. Madamombe, sandra.makaita.madamombe@slu.se; Ingrid Öborn, ingrid.oborn@slu.se; George Nyamadzawo, gmazakwi@gmail.com; Christian Thierfelder, c.thierfelder@cgira.org; Ngonidzashe Chirinda, Ngonidzashe.Chirinda@um6p.ma; Stanley Karanja Ng'ang'a, S.Karanja@CGIAR.ORG | [1]Department of Crop Production Ecology, Swedish University of Agricultural Sciences (SLU), P.O. Box 7043, 750 07 Uppsala, Sweden. [2]International Maize and Wheat Improvement Centre, P. O. Box MP163, Mount Pleasant, Harare, Zimbabwe. [3]Agriculture Research Trust, P. O Box MP 84, Mount Pleasant, Harare, Zimbabwe. [4]International Centre for Tropical Agriculture, P. O. Box 823-00621, Nairobi, Kenya. [5]Alliance of Bioversity International and International Centre for Tropical Agriculture, P. O. Box MP228, Mount Pleasant, Harare, Zimbabwe. [6]World Agroforestry (ICRAF), UN Avenue, Gigiri, P.O. Box 30677-00100, Nairobi, Kenya. [7]Mohammed VI Polytechnic University (UM6P), College of Agricultural and Environmental Sciences (CAES), Agricultural Innovations and Technology Transfer Centre (AITTC), Benguerir, Morocco. [8]International Centre for Tropical Agriculture (CIAT), National Agricultural Research Laboratories - Kawanda, P. O. Box 6247, Kampala, Uganda. [9]International Rice Research Institute (IRRI), Sustainable Impact through Rice-based Systems, FPLM Avenue 2698, P.O. Box 3658, Maputo, Mozambique.

Keywords Socio-ecological data · Maize yield · Rain-fed systems · Soil and water conservation · Semi-arid area

1 Introduction

Agricultural production systems are affected by complex interactions between social and ecological factors [1]. These factors include climate change and variability, soil type, and numerous decisions farmers make each growing season regarding fertilizer use, crop diversification strategy, weed and pest management, crop and varietal choice, tillage and other management factors [2, 3]. In addition to climatic conditions, other factors outside the control of farmers—such as the structure or position of the field in the landscape, available markets and access to knowledge and information—play an essential role in determining productivity levels. Agronomic surveys have been used in Tanzania and Ethiopia to understand the contributing factors to observed maize and wheat yield gaps among smallholder farmers [4, 5]. The study in Tanzania, a nutrient-rich and wet region, found that the slope level of a field, plant density and crop variety were among the prominent factors affecting maize yield levels. In the highlands of Ethiopia, the key factor influencing wheat yield differences was the levels of fertilizers used [6]. These analyses are essential for understanding the variability in crop performance, contributing to achievement of the United Nations Sustainable Development Goal number 2, "Zero Hunger". Our study sites are located in a region highly vulnerable to climate change and prone to extreme exposure to climatic shocks and stressors in an environmentally challenging production landscape [7]. Hence, small grain crops such as sorghum (*Sorghum bicolor* L.), pearl millet (*Pennisetum glaucum* (L.) R. Br.), and finger millet (*Eleusine coracana* L.) have been recommended as the best management practices [8]. However, despite their vulnerability, farmers still insist on growing maize annually, as it remains their food crop of choice.

Erratic rainfall, poor rainfall distribution, and prolonged dry spells cause soil moisture scarcity during the growing season, a dominant challenge in dryland maize-based production systems in semi-arid regions [9]. In Southern Africa, several agronomic practices have been recommended for smallholder farmers to mitigate the negative impacts of climate change, such as low available soil moisture and other yield-limiting factors [10–12]. These practices include using water harvesting techniques (e.g., tied ridges, pot holes, water ways, and contour bunds), conservation agriculture (no-tillage, crop diversification and mulching), and the use of drought-tolerant species and varieties. However, the uptake of these techniques remains very low due to several factors, including shortage of financial resources to buy inputs, lack of information, technical know-how, high labour requirements and competing priorities on farm enterprises for example, using crop residues for conservation agriculture versus crop residues as supplementary livestock feed. As a result, most of these smallholder farmers remain highly exposed to the adverse effects of climate change.

Farm management practices to improve soil moisture at the field level often interact with other major challenges in maize production, such as weeds and pests [13–15]. To reduce weed pressure, farmers have been recommended to use herbicides in combination with successive hand-hoe weeding before weeds set seed [16], to incorporate legumes as green manure cover crops [17, 18] and to use other practices such as crop rotations or intercropping with maize and legumes [19]. However, several challenges, such as the unavailability and high cost of herbicides have prevented most farmers from affording them.

Low inherent soil fertility is another dominant challenge in maize production in semi-arid areas of Southern Africa. To address soil fertility issues, farmers have used both external farm inputs such as inorganic mineral fertilizers, and farm produced organic fertilizers (e.g., livestock manure and compost). However, financially constrained smallholder farmers rarely use inorganic fertilizers, as they are often beyond their reach [20, 21]. Additionally, the small herds of livestock that many smallholder farmer once owned, often in poor condition, have been decimated by infectious diseases such as *Thiriosis* (January disease) due to the lack of dipping facilities, resulting in very little livestock manure available for on-farm use. Perennial crops and the use of nitrogen-fixing agroforestry systems have been suggested as strategies to improve low soil fertility [22, 23]. However, the prevalence of free-range systems, where animals roam freely during the dry period on farmers' fields, has hindered the success of these measures, as most young trees are destroyed by over-browsing. Furthermore, it is challenging to establish trees for agroforestry systems in these low rainfall areas.

Despite many years of research and agronomic recommendations on improving maize yields in the semi-arid areas of Marange and Zimbabwe as a whole, farmers continue to experience very low maize production levels, ranging from 0.5 to 0.6 t ha^{-1} [24, 25], coupled with very low water-use efficiency. The reason for these low yields can only be understood by further exploring and interrogating factors that could improve maize yields in these marginal areas. Identifying the critical biophysical and socio-economic factors contributing to low maize yield will aid in designing strategies to enhance maize-based farming systems in semi-arid regions, both now and in the future. This study aimed to understand how agronomic and on-farm management factors affect maize yields in smallholder farming areas in semi-arid regions.

2 Materials and methods

2.1 Study site

The study was conducted in the Marange area of Mutare district, Manicaland province, Zimbabwe, which is dominated by sandy soils (Fig. 1). The study area is semi-arid and is located in Agro-ecological region IV, characterized by an annual rainfall of <450 mm (unimodal rainfall pattern from October to March) and a mean maximum air temperature of 28 °C [26]. Extended mid-season dry spells are common during the crop growing season, sometimes lasting as long as 50 days without rainfall. The area is suitable for drought-tolerant crops such as cowpea (*Vigna unguiculata* (L.) Walp.), groundnut (*Arachis hypogaea* L.), sorghum, millet and short maturing maize varieties (requiring 105–120 days to mature), as well as for extensive cattle ranching, rearing of small stock such as goats, and wildlife [26]. Seven wards within the district were selected to capture the variability of management practices in the region.

2.2 Agronomic survey

To determine minimum sample size, we used Slovin's formula for calculating the sample size for estimating proportions in a finite population (1). The formula is given as:

$$n = (Z^2 \times p \times q \times N) / \left[(Z^2 \times p \times q) + \left(e^2 \times (N - 1)\right)\right] \tag{1}$$

where: N represent required sample size, Z represent Z-value corresponding to the desired 95% confidence level = 1.96, p represent estimated proportion of households in each ward (we assumed 15% = 0.15) ; q = 1 – p = 0.8, e represent desired margin of error = 5% = 0.05, N represent total population size in the study area.

A total of 107 smallholder farmers who grow maize in the study area were surveyed. Stratified systematic random sampling approach was employed to select the desired sample size, ensuring representation of all relevant farmer groups such as women, men and the youth. Interviews were conducted in person by trained enumerators in March and April 2021. The survey questionnaire (Supplementary 1) had separate sections addressing household characteristics, farm size,

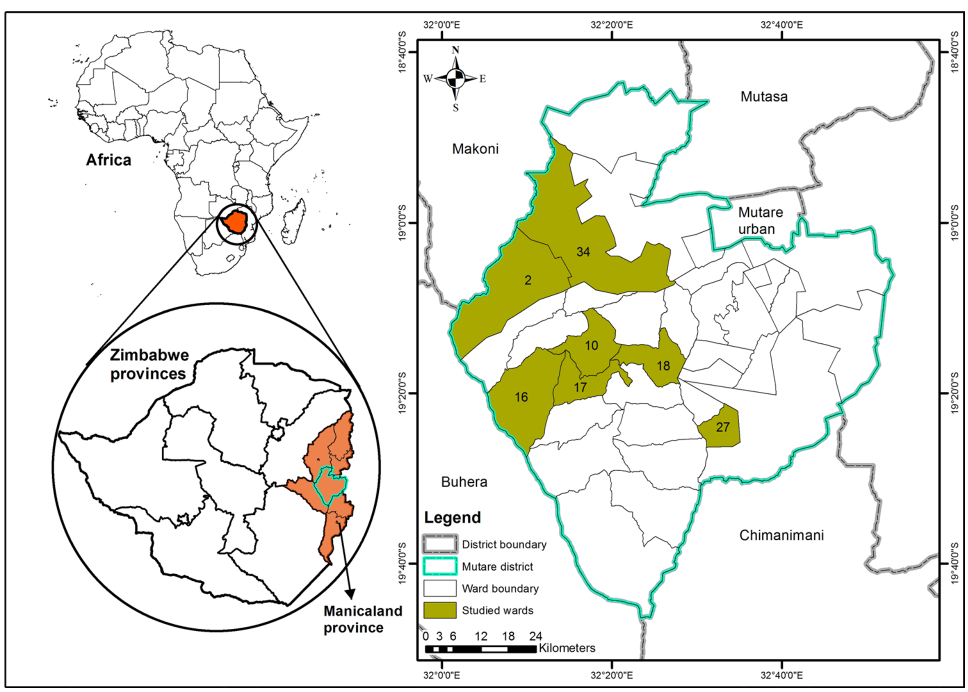

Fig. 1 Maps showing the location of Manicaland province in Zimbabwe (*left*) and the study sites (wards) in Marange, Mutare district (*right*). Adapted from Madamombe et al. (2024a)

land management and agricultural inputs, livestock, poultry and their products, labour source, gender-related aspects, access to capital and credit, extension services, external resources, climate and soil, food security, and wealth status.

To assess maize performance, a representative maize field was selected on each household's farm during the survey. With the farmers' permission, a sub-plot was harvested, and the grain was taken to the laboratory for processing, where yield levels were quantified. Two subplots with the same management practices, each measuring 3 m × 3 m plots, were harvested. Precautions were taken to avoid any observable biases, by ensuring all measured plots were at least 2 m from the field edge. During sub-plot harvesting, the number of maize plants and cobs in the two plots was counted, and maize cob samples were weighed in the field at harvest. Cob samples were further dried, shelled, and the grain yield in kg ha^{-1} was adjusted to 12.5% grain moisture content.

2.3 Data management and statistical analyses

Survey and field data were cleaned before analysis, whereby five farmers were removed many variables were not captured properly. The variables included in this analysis were gender, education level, weed density, field position, seed type, manure application, access to weather and climate information, mulching, intercropping, planting methods, fertilizer application, training attendance, and use of contour bunds. Field position was classified according to its location in the landscape. Manure application rate was categorized into four groups none, low, moderate, and high based on targeted maize crop yield. These categories were defined by the manure quantities required to achieve target yields of 4000, 7000, and >7000 kg ha^{-1}. Specifically, these yields corresponds to manure application rates of up to 6000 kg ha^{-1} (low), 6000–13,000 kg ha^{-1} (moderate), and >13,000 kg ha^{-1} (high), assuming the manure contains 1.5% nitrogen by weight [27]. We employed two statistical analyses: (i) the Classification Regression Tree (CART) approach [28] and (ii) the generalized linear models (GLM) to partitioning variations in the observed maize grain yield.

$$\text{Yield}\,(\text{kg ha}^{-1}) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \beta_8 X_8 + \beta_9 X_9 + \beta_{10} X_{10} + \beta_{11} X_{11} + \beta_{12} X_{12} + \varepsilon$$

where: Yield (kg ha)$^{-1}$ represent the inverse of maize yield per hectare, X_1, X_2,…,X_{12} are the predictor variables (e.g., management practices, socioeconomic factors), β_0 is the intercept, β1,β2,…,β12 are the coefficients for each predictor variable, ϵ is the error term. The model follows a Gaussian distribution with an inverse link function.

Variable importance was used to identify the factors influencing maize grain yield and guide the focus of the further analysis.

The CART analysis allowed the construction of a decision tree through recursive partitioning, starting from the root node (also known as the first parent). Each node was then split into left and right child nodes using the mean square error (MSE) statistical splitting criteria [29]. These nodes were then recursively split, with each parent nodes generating further child nodes. The CART procedure calculates the variability in grain yield attributed to each factor and assigns variables importance scores. The analysis was performed using the 'rpart' package in R (R Core Team, 2021). This approach enabled the investigation and selection of the most important predictor variables, leveraging CART's built-in tools for assessing their relative importance.

All the variables identified in the variable importance test were subjected to a GLM analysis using the R statistical package (R Core Team, 2021) to assess their effect on maize grain yield. Mean separation was performed using the Tukey test method at a 95% probability level in the "emmeans" package in R [30].

3 Results

3.1 Common characteristics of households

Most interviewed farmers (98%) rely on family labour for farming activities. Family size ranged from 2 and 20 individuals, with a median of six per family. The age of farmers varied from 21 to 90 years, with a median age of 48. Approximately 80% of the interviewed farmers grew crops for subsistence, using improved varieties. The medium household land size was 3 ha, with a range from 1 to 15 ha. Most farmers depend on farming for their livelihood, with some engaging in off-farm activities to supplement household income. Additionally, 96% of farmers involved in crop production did not have crop insurance, although they acknowledged that drought insurance was essential in the area since they receive low rainfall and are highly vulnerable to changes in climate.

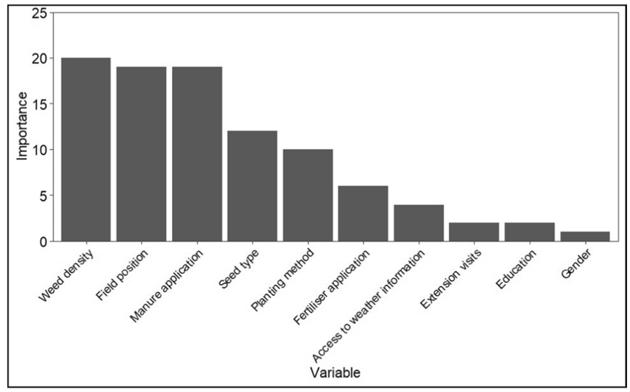

Fig. 2 The classification regression tree (CART) variable importance using maize grain yield as the response variable of 107 smallholder farmers in Marange

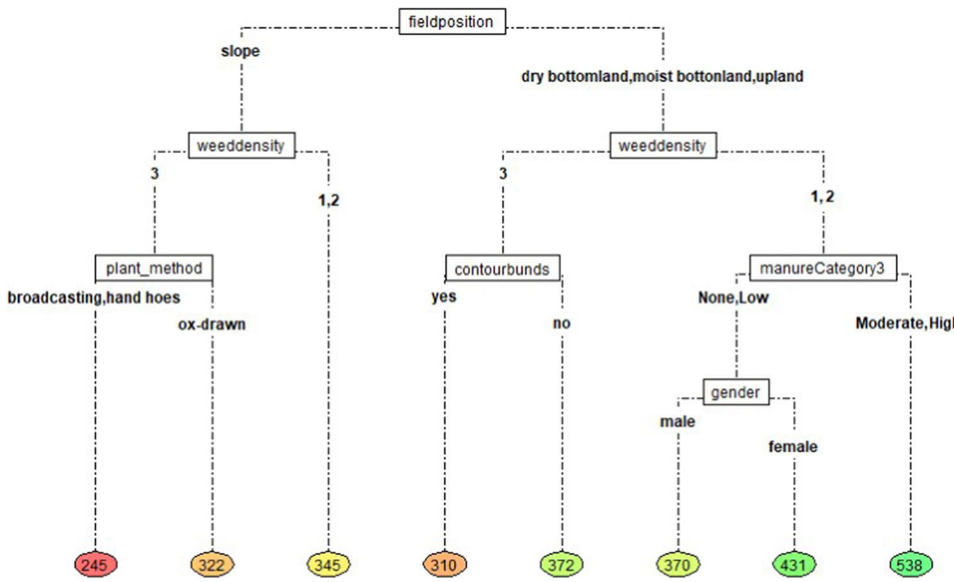

Fig. 3 The classification regression tree results partitioning maize grain yield as influenced by field position, planting methods, weed density, seed type and soil fertility amendment regimes. The numbers in circles are maize grain yields (kg ha^{-1}) and weed densities 1, 2 and 3 show low, medium and high weed density respectively

3.2 Driving factors for maize yield variability

Using CART analysis, essential variables influencing maize grain yields include household characteristics, field-related factors and agronomic practices (Fig. 2). The top three most important variables were weed density, field position, manure application and market information, while the three least important factors were gender, education and the number of extension visits.

The results from the classification regression tree showed that farmers who grew maize on slopes or sloppy land yielded lower than those growing on dry bottom land, moist bottom land and upland areas (Fig. 3). Farmers lacked improved knowledge of agronomic methods suitable for growing crops on sloppy lands (Fig. 3). In slope fields, medium and high weed densities, as well as the use of hand hoes for crop establishment, further reduced the maize grain yields (Fig. 3). High weed density reduced maize yields in all field positions. In bottom and uplands fields, those with contour bunds had lower maize yields compared to the fields without contour bunds, raising questions about the effectiveness of constructing water-disposing contour bunds in low rainfall areas. Improved seed varieties and high manure application rates increased the maize grain yields (Fig. 3). Approximately 85% of the interviewed farmers use improved seeds and maize varieties for crop establishment.

The results from the GLM analysis of all the variables indicate that education levels had no significant effect on maize yield; most farmers had at least completed primary education (96%), and 56% had reached the secondary level.

However, the gender of the household head significantly affected maize grain yield (Table 1). Female headed households had significantly higher maize yields compared to male-headed households (Table 2).

Table 1 Effects of socio-ecological factors on maize productivity in smallholder farms in semi-arid Marange

Source	DF	LR Chisq	Pr(>Chisq)
Gender	1	14.45	0.0001***
Education	2	1.21	0.55
Weed density	2	11.62	0.003**
Field position	3	10.26	0.02*
Seed type	1	3.13	0.07
Manure application	3	24.56	<0.001***
Extension visits	1	2.19	0.14
Access to weather information	1	2.72	0.09
Mulch application	1	0.18	0.67
Intercropping	1	4.17	0.04*
Planting methods	6	10.23	0.11
Fertilizer application	1	5.83	0.02*
Contour bunds	1	0.13	0.72
Trainings attendance	1	0.0003	0.99

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

Table 2 Effects of weed density, field position, manure, intercropping, and fertilizer on maize yield in Marange smallholder farms (±standard errors)

Factors	Grain yield (kg ha^{-1})
Gender	
Female	373 ± 21^{a}
Male	337 ± 13^{b}
Weed density	
Low	385 ± 25^{a}
Medium	326 ± 20^{b}
High	334 ± 21^{b}
Field position	
Dry-bottom land	396 ± 24^{a}
Moist-bottom land	357 ± 23^{ab}
Slope	303 ± 17^{b}
Upland	362 ± 27^{ab}
Manure application	
None	365 ± 27^{b}
Low	306 ± 31^{b}
Moderate	476 ± 16^{a}
High	517 ± 53^{a}
Intercropping	
No	367 ± 18^{a}
Yes	343 ± 21^{b}
Fertilizer application	
No	271 ± 27^{b}
Yes	635 ± 15^{a}

Most interviewed farmers (62%) relied on extension staff for crop production-related information, with an additional 9% also utilizing extension staff and radio. Only 14% of the farmers depended on fellow farmers, relatives or personal experience or trying out new ideas for information on maize production.

The results also show that weed density significantly affected maize grain yields (Table 1). Fields with low weed density yielded higher maize crops than those with medium to high weed density (Table 2). Therefore, effective weed management is crucial for optimizing yield level.

Field position significantly affected maize grain yields (Table 1). Fields along the slope had significantly lower maize yields compared to fields in dry bottom land (Table 2). There were no significant differences between uplands and moist bottom fields (Table 2).

The results also showed that maize grain yield was influenced by the application of manure and fertilizers (Table 1). Application of manures at high and moderate rates resulted in higher maize grain yield (517 and 476 kg ha^{-1}, respectively) compared to no manure and low manure applications (365 and 306 kg ha^{-1}, respectively) (Table 2). Farmers who applied fertilizer had higher maize grain yield (635 kg ha^{-1}) than those without fertiliser application (271 kg ha^{-1}).

Intercropping had a significant effect on maize grain yield (Table 1). Specifically, intercropping reduced maize grain yields more than sole cropping, especially under low rainfall conditions. Maize yield reduction due to intercropping was approximately 25% under low rainfall compared to sole maize cropping.

4 Discussion

Among the 14 factors analyzed, six were found to influence maize production in the Marange district. However, additional factors beyond these selected ones will also be discussed. Significant differences in grain yields were observed with respect to weed density, field position, manure application and gender of the household head. Despite these influences, overall maize grain yields were very low, averaging 355 kg ha^{-1} and ranging from approximately 90 to 970 kg ha^{-1}. These results are consistent with the district averages for Mutare for the last decade [31] and comparable to averages for other semi-arid regions of southern Africa [11]. Contour bunds had no significant effect on grain yield, however the adoption of simple water harvesting technologies could lead to increased maize yields. For instance, yields ranging from 1.4 and 2.2 t ha^{-1} have been reported using tied contour and infiltration pits [24, 32]. Additionally, yields of up to 4.6 t ha^{-1} can be achieved using field edge and in-field water harvesting technologies [25].

According to the FAO in Zimbabwe, the national average maize yields between 2000 and 2020 were approximately 900 kg ha^{-1}, with a particularly low average of 286 kg ha^{-1} in 2008. These annual maize yields are insufficient to support smallholder families per year, requiring approximately 1.2 tonnes of maize meal per year for a family of six. In contrast, the average yield in Marange has been only 400 kg ha^{-1}, which is by far below both the district and the national averages. As a result residents of Marange have often relied on food handouts to address food shortages.

The study sites are in a low rainfall area naturally vulnerable to climate variability. The sandy soils have low inherent soil fertility and high water infiltration rates, causing the minimal rainfall to be lost to deep percolation. This lack of adequate soil moisture and nutrients adversely affectmaize grain yields. Growing maize on slopes reduced the grain yield. This is due to increased runoff, resulting in a high magnitude of soil moisture scarcity in these low-rainfall areas [33]. Furthermore, soil erosion and nutrient leaching are more pronounced on slopes contributing to decreased crop yields [34]. Water harvesting technologies offers a cost-effective solution to address low yields in fields with contours. Simple water harvesting methods such as ridging, infiltration pits, potholing, and tied contours achieved by modifying the configuration of the existing contour bunds have been shown to improve yields. Earlier studies in Marange [24, 32] showed that with proper management infiltration pits and tied contour could increase maize yields by from <1.4 to >2.2 t ha^{-1}. These practices not only enhance yields but also improve soil health, reduce erosion, increase carbon storage, and optimise nutrient cycles, aligning with fundamental agroecological principles. Implementing water harvesting practices at the field edges and within fields reduces soil erosion, enhances water retention in the soil, and ultimately result in increased crop productivity.

The use of planting basins to establish the maize crop on slopes further reduced maize yield. This was probably because basins require much labour to construct, and working during the dry season when the soil is hard and dry makes it challenging; thus, farmers often fail to establish their crops with the first effective rains [35]. Due to high rainfall variability, short seasons in the region, high temperatures and high evapotranspiration, farmers must establish their crops with first adequate rains as a coping strategy [36]. This challenge can be overcome using mechanized or ox-drawn implements that reduce labour requirements and encourage timely and precise land preparation and planting operations. Hence, farmers establish their crops with the first adequate rains [37].

Weed density was also a crucial factor that influenced maize grain yield. Reports of new weeds that are difficult to control have been made in several regions of Marange. The lower yield observed in fields with medium and high weed density can be attributed to increased competition between weeds and crops for limited available resources such as soil moisture/water and nutrients [38]. Also, high weed density leads to more frequent weeding, resulting in high evaporation due to soil movement, posing a significant challenge for agricultural practices in regions that receive low rainfall [39]. The choice of seed type also significantly influenced grain yield in fields categorized as moist bottom land, dry bottom land, and uplands, especially in instances of low weed density. In semi-arid regions, crop performance is usually better in lower slopes because of residual moisture and higher nutrient concentrations. Nutrients and sediments are deposited in low-lying areas after they are washed off from uplands. Most of the farmers in Marange interviewed already use improved varieties in their fields. Extension officers and policymakers should leverage this by encouraging drought-tolerant varieties to be developed for dry regions.

Female-headed households produced higher maize grain yields than male-headed households. This difference could be related to the fact that females usually conduct more agronomic practices, such as weed management, than males; hence, their crops are less vulnerable to competition from weeds [40, 41]. Also, females tend to allocate more time to agricultural activities than males; hence, high productivity is expected in their households [40]. A study by Doss [41] showed that reallocating labour and fertilizers from male-to-female plots in the same households increased overall household productivity. Hence, targeting females by improving their opportunities and knowledge of farming systems can increase productivity in smallholder farming systems [42]. However, there is a need to address issues to do with gender during trainings. For example, in most cases, males would want to attend trainings as household heads but would not share the acquired knowledge with women or put it into practice.

Low soil fertility as highlighted in previous studies, is a key challenge in smallholder farms in this region [32]. The sites we studied are dominated by sandy soils with inherently low soil fertility. This is accompanied by an increased frequency of drought attributed to climate change, resulting in declining crop yields. Using soil fertility amendments, including fertilizer and application of high manure quantities, integrated nutrient management, which mixes organic manures and reduced quantities of inorganic fertilisers [7], can produce positive crop yield responses. Unfortunately, most farmers cannot afford inorganic fertilizers, and they do not get enough organic manures for use in the maize fields as their livestock is low and has been decimated by diseases such as *Thriosis*.

Farmers could also address common N challenges by improving manure quality or by combining manure with mineral fertilizers. Additionally, incorporating legumes into cropping systems such as using them as intercrop, can enhance soil N through biological fixation of atmospheric nitrogen [43]. Legumes also play important roles in carbon sequestration, serving as forages, and nutrient cycling. Residual N from legumes may also increase yields of subsequent cereals and provide protein-rich food for both humans and animals.

The yield reduction in intercropping is within our expectations since, if not well optimized, intercropping increases the competition for resources, resulting in yield penalties. Similar observations were made by Nyamadzawo et al. [44] in Marange, where it was observed that when rainfall is low, and distribution poor, intercrops result in low maize yields, while yields will be good during seasons with high rainfall. This challenge can be addressed by introducing strip cropping, e.g., a mbili mbili arrangement, which maintains both crops' plant populations and creates more legume space, reducing shading from light. In addition, proper selection of legumes for the intercrop is required.

The use of weather information services did not significantly affect yields for the smallholder farmers. This might be because most farmers do not have access to such weather information systems services available in their areas, increasing their vulnerability to the impacts of climate change. Similar observations were made in Cameroon by Njoya et al. [45], who also reported the unavailability of climate and weather data from local meteorological stations in the region. However, though there is limited access to climate and weather information through the radio and television, the challenge is that it is too general and not region specific. Our experience during the work we have carried in Marange is that in areas with limited rainfall with sandy soils and poor water holding capacities, timely excutions of activities such as land preparation, planting, fertilizer application and top dressing determine your success or failure of the crop. In Marange and most semi-arid regions of Zimbabwe, weather data is available in real time. However, farmers and, to a large extent, extension staff do not know about it or have access to it. This is because of the lack of technical know-how and equipment, e.g., smartphones and data services, to access such crucial information. Therefore, there is a need to build the capacity of both farmers and extension workers and provide low-cost gadgets to increase access to climate and weather information services. We think that such an approach will contribute towards reducing community vulnerability to climate change's impacts.

The results show that contour bunds did not affect yields. The contour bunds were designed following the Land Husbandry Act of 1951 [44] to dispose rainfall off the field and prevent erosion. Pilots that were done in Marange and other semi-arid regions from 2012 to 2023, have shown a simple conversion of standard contour ridges (bunds) from water disposing structures to water harvesting structures through placing cross ties (tied contours) or placing infiltration pits along the channel [24, 32] resulted in yield increases from 400 kg ha^{-1} to ranges between 1.8 and 2.2 t ha^{-1}

depending on season quality. When the tied contours are integrated with other in-field technologies, further maize yield increases to >4 t ha^{-1} were observed [25]. These simple water harvesting technologies also increased sorghum yields from 0.7 to 1.5 t ha^{-1} [46, 47]. If we are to transform food production systems in these semi-arid regions, we also need to transform land management practices at scale and one such strategy will be to convert contour bunds into water harvesting structures.

5 Conclusions

This study reports unsustainably low maize yields in the smallholder farming sector of semi-arid Marange, Zimbabwe. It highlights the driving factors, including socio-economic conditions and agricultural practices, that affect maize grain yield. Key agronomic practices influencing yield include field positions, the use of planting basins to capture initial rainfall, weed management, and mulching. Among socio-economic factors, access to information on new innovations and extension services is crucial for exposing farmers to better cropping methods suited to their locations, which can lead to improved maize yields. In addition, access to climate and weather information services, which are essential to inform the timing of field operations, will be vital to the success of the smallholder farmers, especially in the semi-arid region where rainfall is limited and vulnerability to climate change is high. We also suggest to transform land management practices at scale and integrate practices such as water harvesting and planting drought varieties into the smallholder cropping systems to improve maize yields in these semi-arid regions.

Acknowledgements We thank the farmers who participated in the interviews and allowed us to take measurements in their fields. We also thank the Agritex extension officers who assisted us in reaching the farmers. This study was funded by the Swedish Research Council VR's call on Sustainability and Resilience (2018-05790) through the Swedish University of Agriculture Sciences (SLU) in partnership with the Alliance of Bioversity International and CIAT.

Author contributions J.K., G.M., S.K.N and L.N. designed the questionnaire; G.M. and S.M. collected the data; L.N. and I.O. supervised data analysis and the initial draft; T.M. analyzed the data; and all authors contributed to writing and reviewing the manuscript.

Funding Open access funding provided by Swedish University of Agricultural Sciences.

Data availability The authors will provide data upon reasonable request.

Declarations

Ethics approval and consent to participate This study was approved by the ethics committee in The CIAT International Review Board. The authors declare no competing conflicts of interest. The informed consent to participate was obtained from all the participants.

Competing interests The authors declare no competing interests.

References

1. Nkurunziza L, Watson CA, Öborn I, Smith HG, Bergkvist G, Bengtsson J. Socio-ecological factors determine crop performance in agricultural systems. Sci Rep. 2020;10(1):4232.
2. Dube T, Moyo P, Ncube M, Nyathi D. The impact of climate change on agro-ecological based livelihoods in Africa: a review. J Sustain Dev. 2016;9(1):256–67.
3. Rosen SL, Shapouri S. Factors affecting food production growth in Sub-Saharan Africa. Amber Waves Econ Food Farming Nat Resour Rural Am. 2012;3:1–7.
4. Kihara J, Tamene LD, Massawe P, Bekunda M. Agronomic survey to assess crop yield, controlling factors and management implications: a case-study of Babati in northern Tanzania. Nutr Cycl Agroecosystems. 2015;102:5–16.

5. Kihara J, et al. Contributions of integrated soil fertility management (ISFM) to various sustainable intensification impact domains in Tanzania. Agric Syst. 2022;203: 103496.
6. Elias E, Okoth P, Smaling E. Explaining bread wheat (Triticum aestivum) yield differences by soil properties and fertilizer rates in the highlands of Ethiopia. Geoderma. 2019;339:126–33.
7. Naazie GK, Dakyaga F, Derbile EK. Agro-ecological intensification for climate change adaptation: Tales on soil and water management practices of smallholder farmers in rural Ghana. Discov Sustain. 2023;4(1):27.
8. Mugandani R, Wuta M, Makarau A, Chipindu B. Re-classification of agro-ecological regions of Zimbabwe in conformity with climate variability and change. Afr Crop Sci J. 2012;20(2):361–9.
9. Mhlanga B, Thierfelder C. Long-term conservation agriculture improves water properties and crop productivity in a Lixisol. Geoderma. 2021;398: 115107.
10. Kuyah S, et al. Innovative agronomic practices for sustainable intensification in sub-Saharan Africa. A review. Agron Sustain Dev. 2021;41(2):1–21.
11. Nyagumbo I, Nyamadzawo G, Madembo C. Effects of three in-field water harvesting technologies on soil water content and maize yields in a semi-arid region of Zimbabwe. Agric Water Manag. 2019;216:206–13. https://doi.org/10.1016/j.agwat.2019.02.023.
12. Thierfelder C, Wall PC. Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. Soil Tillage Res. 2009;105(2):217–27. https://doi.org/10.1016/j.still.2009.07.007.
13. Chipomho J, Rugare JT, Mabasa S, Zingore S, Mashingaidze AB, Chikowo R. Short-term impacts of soil nutrient management on maize (*Zea mays* L.) productivity and weed dynamics along a toposequence in Eastern Zimbabwe. Heliyon. 2020;6(10):e05223. https://doi.org/10.1016/j.heliyon.2020.e05223.
14. Lunduka RW, Mateva KI, Magorokosho C, Manjeru P. Impact of adoption of drought-tolerant maize varieties on total maize production in south Eastern Zimbabwe. Clim Dev. 2019;11(1):35–46. https://doi.org/10.1080/17565529.2017.1372269.
15. Sangakkara UR, Stamp P. Influence of different weed categories on growth and yields of maize (*Zea mays*) grown in a minor (dry) season of the humid tropics/Einfluss verschiedener Schadpflanzengruppen auf Wachstum und Ertrag von Mais (*Zea mays*) in einer humiden Tropenzone während der Trockenzeit. J Plant Dis Prot. 2006;113(2):81–5.
16. Muoni T, Rusinamhodzi L, Thierfelder C. Weed control in conservation agriculture systems of Zimbabwe: identifying economical best strategies. Crop Prot. 2013;53:23–8. https://doi.org/10.1016/j.cropro.2013.06.002.
17. Mhlanga B, Cheesman S, Maasdorp B, Mupangwa W, Thierfelder C. Contribution of cover crops to the productivity of maize-based conservation agriculture systems in Zimbabwe. Crop Sci. 2015;55(4):1791–805. https://doi.org/10.2135/cropsci2014.11.0796.
18. Rugare JT, Pieterse PJ, Mabasa S. Effect of short-term maize–cover crop rotations on weed emergence, biomass and species composition under conservation agriculture. South Afr J Plant Soil. 2019;36(5):329–37.
19. Franke AC, van den Brand GJ, Vanlauwe B, Giller KE. Sustainable intensification through rotations with grain legumes in Sub-Saharan Africa: a review. Agric Ecosyst Environ. 2018;261:172–85. https://doi.org/10.1016/j.agee.2017.09.029.
20. Rusinamhodzi L, Corbeels M, Zingore S, Nyamangara J, Giller KE. Pushing the envelope? Maize production intensification and the role of cattle manure in recovery of degraded soils in smallholder farming areas of Zimbabwe. Field Crops Res. 2013;147:40–53. https://doi.org/10.1016/j.fcr.2013.03.014.
21. Zingore S, Murwira HK, Delve RJ, Giller KE. Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. Agric Ecosyst Environ. 2007;119(1–2):112–26.
22. Mosier S, Córdova SC, Robertson GP. Restoring soil fertility on degraded lands to meet food, fuel, and climate security needs via perennialization. Front Sustain Food Syst. 2021;5: 706142.
23. Chikowo R, Mapfumo P, Nyamugafata P, Giller K. Woody legume fallow productivity, biological N2-fixation and residual benefits to two successive maize crops in Zimbabwe. Plant Soil. 2004;262(1):303–15.
24. Chiturike P, et al. Evaluation of different rainwater harvesting techniques for improved maize productivity in semi-arid regions of Zimbabwe with sandy soils. J Sustain Agric Environ. 2023;2(1):26–39.
25. Madamombe SM, et al. Climate change awareness and adaptation strategies by smallholder farmers in semi-arid areas of Zimbabwe. Int J Agric Sustain. 2024;22(1):2293588.
26. Manatsa D et al. Revision of Zimbabwe's agro-ecological zones. Produced by the Government of Zimbabwe under Zimbabwe National Geospatial and Space Agency (ZINGSA) for the Ministry of Higher and Tertiary Education, Innovation. Sci Technol Dev Zimb Gov Print, 2020.
27. FAO. Plant nutrition for food security: a guide for integrated nutrient management. in FAO fertilizer and plant nutrition bulletin, no. 16. Rome: Food and Agriculture Organization of the United Nations; 2006. https://www.fao.org/4/a0443e/a0443e00.htm. Accessed 10 Sep 2024.
28. Breiman L. Classification and regression trees. Milton Park: Routledge; 2017.
29. Gordon L, Olshen RA. Almost surely consistent nonparametric regression from recursive partitioning schemes. J Multivar Anal. 1984;15(2):147–63.
30. Lenth R, Singmann H, Love J, Buerkner P, Herve M. Emmeans: Estimated marginal means, aka least-squares means. R Package Version. 2018;1(1):3.
31. Nyamangara J, et al. Effect of conservation agriculture on maize yield in the semi-arid areas of Zimbabwe. Exp Agric. 2014;50(2):159–77.
32. Chiturike P, et al. The effects of contour-based rainwater harvesting and integrated nutrient management on maize yields in semi-arid regions of Zimbabwe. CABI Agric Biosci. 2024;5(1):41.
33. Ma B, Liu G, Ma F, Li Z, Wu F. Effects of crop-slope interaction on slope runoff and erosion in the Loess Plateau. Acta Agric Scand Sect B. 2019;69(1):12–25.
34. Koomson E, Muoni T, Marohn C, Nziguheba G, Öborn I, Cadisch G. Critical slope length for soil loss mitigation in maize-bean cropping systems in SW Kenya. Geoderma Reg. 2020;22: e00311.
35. Dahlin AS, Rusinamhodzi L. Yield and labor relations of sustainable intensification options for smallholder farmers in sub-Saharan Africa. A meta-analysis. Bundesgesundheitsbl. 2019;2019(63):25–31.

36. Cooper PJM, Dimes J, Rao KPC, Shapiro B, Shiferaw B, Twomlow S. Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: an essential first step in adapting to future climate change? Agric Ecosyst Environ. 2008;126(1):24–35. https://doi.org/10.1016/j.agee.2008.01.007.
37. Nyagumbo I, Mkuhlani S, Mupangwa W, Rodriguez D. Planting date and yield benefits from conservation agriculture practices across Southern Africa. Agric Syst. 2017;150:21–33. https://doi.org/10.1016/j.agsy.2016.09.016.
38. Lee N, Thierfelder C. Weed control under conservation agriculture in dryland smallholder farming systems of southern Africa. A review. Agron Sustain Dev. 2017;37(5):48. https://doi.org/10.1007/s13593-017-0453-7.
39. Kuzucu M, Dökmen F. The effects of tillage on soil water content in dry areas. Agric Agric Sci Procedia. 2015;4:126–32. https://doi.org/10.1016/j.aaspro.2015.03.015.
40. Awan ZA, Akhtar K, Khan LA, Imran AU. Women's participation and their constraints in livestock management activities: a case study of district Bahawalpur in Punjab, Pakistan. Int J Vet Sci Res. 2021;7(2):083–7.
41. Doss CR. Women and agricultural productivity: reframing the issues. Dev Policy Rev. 2018;36(1):35–50.
42. Senda TS, Peden D, Tui SH-K, Sisito G, Van Rooyen AF, Sikosana JL. Gendered livelihood implications for improvements of livestock Water productivity In Zimbabwe. Exp Agric. 2011;47(S1):169–81.
43. Jensen ES, Carlsson G, Hauggaard-Nielsen H. Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: a global-scale analysis. Agron Sustain Dev. 2020;40(1):5. https://doi.org/10.1007/s13593-020-0607-x.
44. Nyamadzawo G, Wuta M, Nyamangara J, Gumbo D. Opportunities for optimization of in-field water harvesting to cope with changing climate in semi-arid smallholder farming areas of Zimbabwe. Springerplus. 2013;2:1–9.
45. Njoya HM, Matavel CE, Msangi HA, Wouapi HAN, Löhr K, Sieber S. Climate change vulnerability and smallholder farmers' adaptive responses in the semi-arid Far North Region of Cameroon. Discov Sustain. 2022;3(1):41.
46. Kubiku FN, Nyamadzawo G, Nyamangara J, Mandumbu R. Effect of contour rainwater-harvesting and integrated nutrient management on sorghum grain yield in semi-arid farming environments of Zimbabwe. Acta Agric Scand Sect B. 2022;72(1):364–74.
47. Kugedera AT, Nyamadzawo G, Mandumbu R. Augmenting Leucaena leucocephala biomass with mineral fertiliser on rainwater use efficiency, agronomic efficiency and yields on sorghum (*Sorghum bicolor* [(L.) Moench]) under rainwater harvesting techniques in semi-arid region of Zimbabwe. Heliyon. 2022;8(7):9826.