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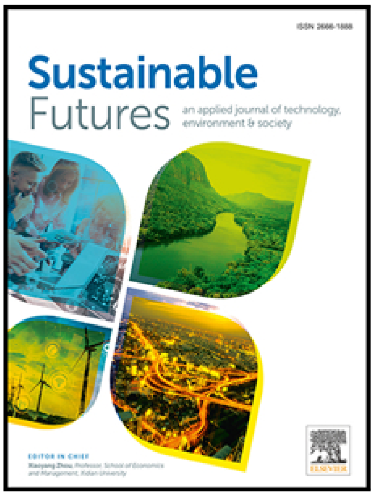

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Highlights

- Sorghum farming in wetlands is predominantly driven by women in eastern D.R. Congo.
- Twenty-two CSA practices are being used with varying adoption rates and drivers.
- Eight CSA practices significantly improved sorghum grain yields.
- Strong extension services are essential in optimizing CSA effectiveness in sorghum farming in South-Kivu.

Climate-smart agronomic practices and their appraisal among smallholder sorghum farmers in eastern Democratic Republic of Congo wetlands

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Abstract

Climate change is a major threat to food security and poverty alleviation in Sub-Saharan Africa (SSA). Climate-Smart Agriculture (CSA) adoption by smallholder farmers will significantly contribute to food security in the region, and particularly in South-Kivu, in the eastern Democratic Republic of Congo (DRC). This study specifically aims at identifying CSA practices in use and factors driving their adoption among sorghum farmers and assessing their efficiency in improving sorghum yield under smallholder farming in South-Kivu. A cross-sectional survey was conducted among 475 randomly selected smallholder sorghum farmers across wetlands in South-Kivu. Results showed a significant diversity in socio-demographic profiles of sorghum farmers, with a strong women involvement across wetlands (64%). A total of 22 CSA practices were identified, with varying adoption rates and drivers. Of these CSA practices, 13 were appraised by farmers as effective in improving sorghum yield though analytical results showed that only 8 CSA practices, namely tolerant varieties, Zaï pits, mulching, strategic intercropping, crop rotation and diversification, liming, and organic manure, actually improved sorghum grain yields. Sorghum yield was highest in the lowland agro-ecological zone (AEZ1) compared to mid-altitude (AEZ2) and high-altitude (AEZ3) zones. CSA practices appraised as effective recorded an average grain yield of 750 kg ha^{-1}, while less effective ones had ~560 kg ha^{-1}. Since sorghum farming is predominantly a female-driven activity, socioeconomic constraints—such as limited access to land, reliance on family labor, and a focus on subsistence rather than market-oriented farming (except in AEZ1)—hinder sorghum ability to substantially improve their family livelihoods. Extension services should be strengthened to empower farmers in implementing CSA practices and to optimize their effectiveness in improving sorghum yields under short-, medium-, and long-term climate variability.

Keywords: *Climate-smart agriculture (CSA), smallholder farming, sorghum, wetlands, South-Kivu*

1. Introduction

Climate change is a significant challenge in most regions of the world, requiring urgent and coordinated responses to mitigate its impacts on food security and ecological systems (Patz et al., 2005; Toimil et al., 2020). For climate change mitigation and adaptation, solutions have been proposed among which climate-smart agriculture (CSA) practices were mostly proposed for resource-poor and underdeveloped regions (Azadi et al., 2021). Developed by the United Nations Food and Agriculture Organization (FAO) to ensure food security while addressing climate change challenges, the CSA remains, however, a critical issue in terms of adoption, applicability, and effectiveness for low-income communities. It focuses on increasing agricultural productivity and incomes, enhancing resilience to climate variability, and reducing greenhouse gas (GHG) emissions. CSA involves practices and methods that improve agro-systems' productivity while reducing environmental impacts (Cooper et al., 2008; Karume et al., 2022; Tariku & Kebede, 2025).

There is already evidence of the effects of climate change on communities, particularly those in rural areas heavily relying on agriculture to sustain their nutritional and economic well-being. In these regions, CSA practices are proposed as an adaptation strategy (Barrios et al., 2006; Ofoegbu et al., 2017). Defined as agricultural techniques and strategies that enhance productivity, build resilience to climate change, and reduce GHG emissions while ensuring sustainable food production, CSA is however context-dependent, meaning it adapts to the local climate, ecosystem, and socio-economic conditions (Azadi et al., 2021). It is crucial in helping farmers, especially in vulnerable regions, cope with climate variability and ensure sustainable agricultural production (Torquebiau et al., 2018). In regions where agriculture mainly depends on smallholder and community farms, which have faced increasing and uncontrolled climatic disruptions for several years, CSA practices are presented as promising solutions. Farmers' perceptions play a crucial role in adopting CSA practices. Many may be skeptical of certain methods promoted by CSA initiatives or lack access to reliable information to assess their effectiveness. Additionally, socio-economic factors such as the cost of implementing such practices, access to necessary resources, and institutional support can significantly influence the adoption dynamics (Torquebiau et al., 2018; Mangaza et al., 2021; Karume et al., 2022; Gemtou et al., 2024).

The southern and eastern regions of the Democratic Republic of Congo (DRC) are highly vulnerable to climate change due to their heavy dependence on natural resources and shifting rainfall patterns (Bagula et al., 2022; Ahana et al., 2024; Mondo et al., 2024). The South-Kivu province, for instance, faces prolonged droughts in several areas, characterized not only by slight temperature increases but also by increasingly delayed rainfall. Heavy rains with high return frequencies are also reported (Bagalwa et al., 2021). These climate events severely disrupt local agriculture and threaten food security, exacerbating the socio-economic challenges in the region (Bagula et al., 2022; Mondo et al., 2024).

Several CSA practices have been adopted in eastern DRC, including those related to agronomy, agroforestry, livestock and aquaculture, post-harvest management, and energy systems (Chuma et al., 2022; Karume et al., 2022). Climate-smart agronomic practices (tolerant crop varieties, crop diversification, integrated soil fertility management, water conservation practices, etc.) contribute in optimizing productivity on marginal lands, income, and strengthening resilience to present and future climatic shocks (Rosenstock et al., 2016). Various practices are observed across all farming systems, from small-scale to large-scale farming, ranging from a few meter squares to several hectares, and at varying altitudes (Karume et al., 2022). Despite the potential benefits of CSA practices, their full adoption by all farmers in eastern DRC remains limited, often influenced by their perceptions, knowledge, and understanding of efficiency. Issues related to socio-economic conditions and access to resources also play a significant role in adoption of CSA practices (Atsiaya et al., 2023). Understanding farmers' perceptions of the effectiveness of these practices is crucial for designing interventions that align with local realities, enhance adoption of best practices, and thus strengthen climate resilience in sorghum production.

Farmers should adopt adaptation strategies to sustain their agricultural production under changing climate realities (Aryal et al., 2018). However, while several CSA techniques have been introduced in eastern DRC, little is known about how wetland farmers perceive their efficiency in key crops. The success of climate adaptation strategies largely depends on farmers' willingness to adopt and maintain them (Alhassan & Haruna, 2024). Perceived risks, cost-effectiveness, labor demands, and yield benefits may, however, either promote or hinder their adoption. A lack of empirical evidence on these perceptions limits policymakers' and development agencies' ability to tailor interventions to local needs (Karume et al., 2022). This study focuses on sorghum, a neglected and underutilized crop, yet valued for its cultural, market value, nutritional benefits and strong adaptation in eastern DRC (Mondo, 2024). Sorghum has been proposed as a solution to climate variability due to its resilience to drought and poor soil conditions, making it essential for food security and rural livelihoods (Getachew et al., 2023; Yiridomoh et al., 2024). However, climate change increasingly threatens sorghum yields through erratic rainfall, rising temperatures, and soil degradation. To counter these challenges, CSA practices—such as conservation tillage, crop rotation, intercropping, and improved water management—have been promoted to enhance sorghum productivity and resilience (Mohammed & Misganaw, 2022 ; Yiridomoh et al., 2024).

This study proposes to investigate the situation of farmers who migrated to wetlands and adopted climate-resilient crops such as sorghum to overcome climate change challenges in eastern DRC. Specifically, this study aimed to (i) identify CSA practices adopted by sorghum farmers across South-Kivu wetlands, (ii) assess socioeconomic factors driving CSA adoption among sorghum farmers, and (iii) assess farmers' perceptions of CSA effectiveness to improve sorghum yield. These objectives will provide recommendations for improving the adoption of climate-smart agronomic strategies in marshland sorghum production. It is noteworthy that this study was based on a narrow geographic area, making its findings difficult to generalize to other SSA regions with different AEZs and socio-economic conditions. Besides, relying solely on self-reported data to assess CSA effectiveness may introduce biases. The cross-sectional design prevents assessment of long-term trends. Additionally, other factors such as market access, climate variability, and broader policy interventions influencing CSA adoption were not deeply explored.

2. Methodology

2.1 Study area description

This study was conducted in South-Kivu (**Figure 1**), one of the eastern provinces of the DRC, where the effects of climate change are already noticeable. The region is experiencing changes in rainfall onset and distribution (Mondo et al., 2024). Several scholars (e.g. Bagula et al., 2022; Karume et al., 2022; Mondo et al., 2024; Chuma et al., 2024a) have reported an increased rainfall coupled with slight temperature rises in the southern and northern areas of the South-Kivu, and a decline in rainfall in the east and southwest areas (mainly the Ruzizi Plain). The province is subdivided into eight territories with contrasting biophysical conditions, leading to four distinct agro-ecological zones (AEZs, Mondo et al., 2024).

Based on the ecological requirements of sorghum, its spatial distribution, as well as wetland distribution, only three AEZs across three territories were considered in this study. These include the AEZ1 distributed across low-altitude zones with a semi-arid climate (Sange and Luvungi), the AEZ2 spanning from mid- to high-altitude zones (1,000–1,400 m) with a humid tropical climate (Nyangezi), and the AEZ3 characterized by high-altitude zones (1,400–1,500 m) with a mountainous tropical climate (Bugobe and Lurhala).

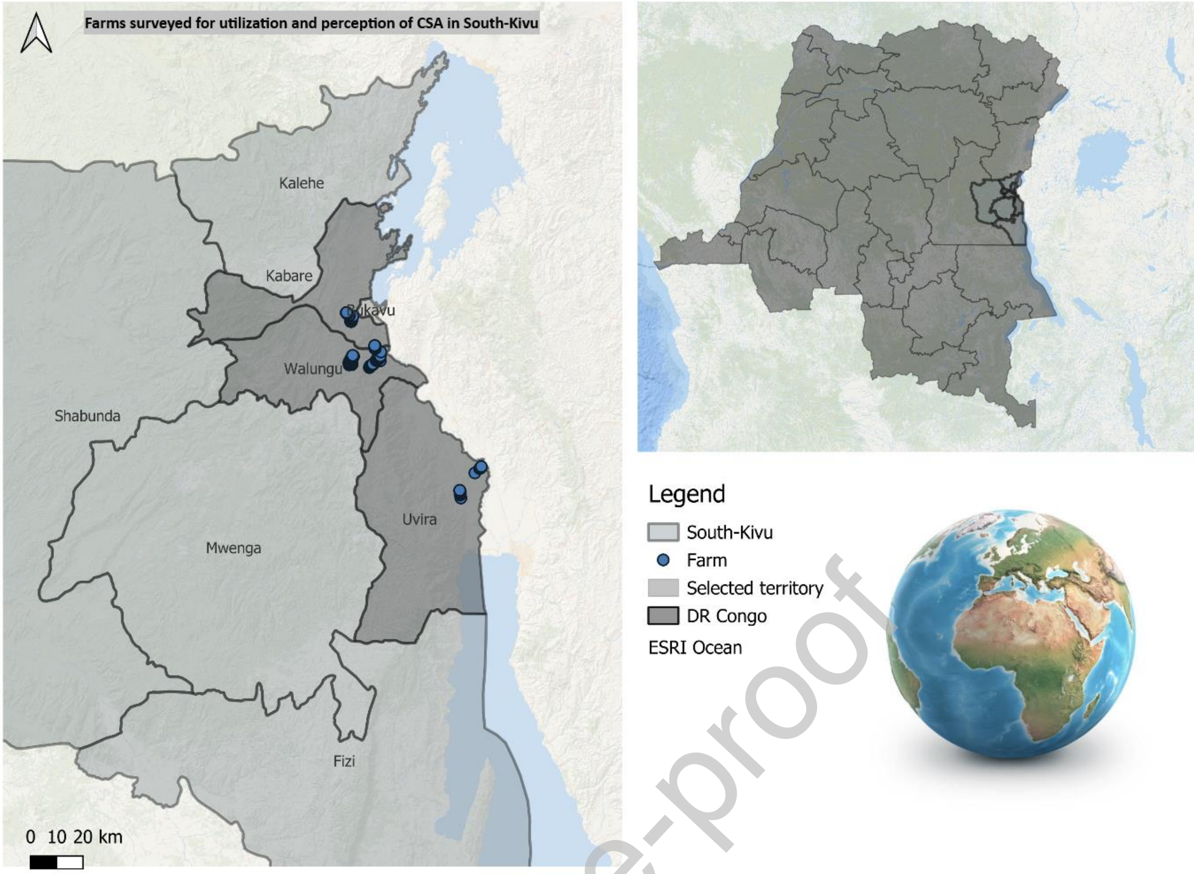


Figure 1. Study area, South-Kivu Province, eastern DRC.

2.2 Data collection methods

Data was collected from May to June 2024 using a semi-structured survey questionnaire that was beforehand tested to validate questions' relevance. Once validated, the questionnaire form was encoded in KoboCollect and uploaded to tablets for surveys. The survey questionnaire had five main sections, including (i) farmer socio-demographic information; (ii) knowledge and use of CSA practices; (iii) farm labor types, CSA applicability, and constraints to implement CSA practices; (iv) sorghum production and related constraints; and (v) yield assessment over the last three cropping seasons and CSA effectiveness in improving sorghum yield. More details on the questionnaire can be accessed at the following link: https://ee.kobotoolbox.org/x/3ahR621g.

A total sample size of 475 sorghum farmers who migrated around wetlands were selected for the survey. Given the diversity of the study area, three AEZs were considered to ensure the study area realities are fully captured by the study (Mondo et al., 2024a). These included Luvungi and Sange in AEZ 1, Nyangezi, Hogola, Luzinzi, Nkombo, Kalamba, Cidorho, and Irambo, in the AEZ 2; Nalugana, Gombo, Chidubo, Nyamuziba, Kashanja, Cishasha, Cisheke, Nakadaka, and Nyarukundura in the AEZ 3. As mentioned above, these AEZs are mainly located in Kabare, Walungu, and Uvira territories. Since the total number of sorghum farmers was unknown, a probabilistic saturation sampling technique was used to define the sample size in each selected wetland (Pires, 1997). Our rationale in going for probabilistic sampling was rooted in the belief that additional data collection was unlikely to yield new insights (Mondo et al., 2024a). Apart from the survey form, discussions and in-depth interviews were also conducted. The structured questionnaire was administered to smallholder sorghum farmers to gather their perceptions on CSA in response to climate change, CSA practices adoption rate and drivers, and their contribution to reducing climate change vulnerability among smallholders. The structured questionnaire was administered to sorghum farmers directly in the fields, with each session lasting an average of 20–30 min. A pilot study was conducted to ensure the study's relevance and accuracy to the study areas. This process involved testing the questionnaire on a small sample of target respondents to assess the clarity of the questions, their comprehension by participants, and their relevance to the study objectives. To reduce biases, farmers were requested to participate and complete all the questionnaire. Eligible farmers were randomly selected based on only one criterion (cultivate sorghum in selected wetlands) and briefed on the study objectives. Focus group discussions were conducted at the end of the data collection period to settle all contradicting opinions. The report response rate was also used to acknowledge the transparency and credibility. Necessary adjustments were then made before large-scale administration. Identification of CSA practices was based on Rosenstock et al. (2016) checklist. CSA efficiency was assessed by comparing the yield (in kg per hectare) of different practices among farmers who adopted one or another CSA practice and those who did not. We first analyzed the variation in yield according to the AEZs and then based on farms where CSA practices were classified by farmers according to their efficiency using a three-level scale: low, moderate, and high effectiveness.

2.3 Analytical framework

The proposed analysis approach consisted of conducting a socio-demographic analysis of the surveyed farmers, followed by the identification of CSA practices and corresponding constraints in their use. This was followed by an analysis on the adoption and adoption rates of CSA practices. A global analysis was conducted based on AEZs to provide an overall perspective; then, farmers were grouped into adopters and non-adopters. A farmer was considered as adopter when a particular CSA practice has become an integral part of her/his farming routine. For each CSA practice, a logistic regression was performed to determine its adoption drivers. The regression model utilized is justified as it quantifies the relationship between CSA practices adoption and key driving factors while controlling for confounding variables as highlighted by many studies (e.g., Abegunde et al., 2020; Bojago & Abrham, 2023). The observed binary outcome for each CSA practice adoption's decision by a given farmer is given in Equation as follows:

$$\begin{cases} Y_i^* = x_i\beta + \xi_i \\ Y_i^* = Y_i^* \; if \;\; y_i^* > 0 \end{cases} \quad 0 \; otherwise$$

The probability of observed outcome j is given by:

$$P(y_i=j) = \Phi(\mu_j - Y^*_i\beta) - \Phi(\mu_j - Y^*_i\beta)$$

$$CSA_i = ln\left(\frac{P_i}{1-P_i}\right)$$

Adopt_SCA = β_0 + β_1×*Gender*+ β_2×*Age_class*+β_3×*Marital_status*+β_4×*Person_per_HH*+β_5×*Educational_level*+β_6×*Main_source_of_income*+β_7×*Monthly_income*+β_8×*Association_member*+β_9×*Land_tenure*+β_{10}×*Land_access*+β_{11}×*Area(ha)* +β_{12}×*Seniority(years)*+β_{13}×*Use_proportion(%)*+β_{14}×*Agricultural_purpose*+β_{15}×*Drainage_system*+β_{16} ×*Other_use*+β_{17}×*Fund_destination*+β_{18}×*Heavy_rainfall*+β_{19}×*Main_sorghum*+β_{20}×*Seed_origin* +β_{21}×*Seeding_method* +β_{22}×*Cropping_system*+β_{23}×*Yield_appreciation*+β_{24}×*Soil_fertility_appreciation*+β_{25}×*Change in practices* (for variable descriptions, see **Supplementary Table 1**)

Associations between sorghum farmers' demographic characteristics and agroecological zones were assessed using a χ^2 test, while the Kruskal-Wallis test was used to compare sorghum yield data between CSA practices adopters and non-adopters at a significance threshold of 5%. To estimate sorghum yield per hectare, a simple extrapolation rule was applied on reported average production and cultivated area. The effect of gender on CSA practices adoption was also assessed using χ^2 test. All analyses and visualizations were performed using RStudio and R 4.2.1, with the "*ggplot2"*, "*tidyverse"*, and "*vegan*" packages. To identify all sorghum varieties used by farmers, a wordcloud was used for visualization. The thickness of each word represents its frequency, while only cultivars mentioned at least five times are visible in the wordcloud. Other varieties with low citation rates appear but in a much smaller size.

3. Results

3.1 Sociodemographic characteristics of sorghum farmers across wetlands

Significant variations among farmer profiles are observed depending on the AEZ where wetlands are located (**Table 1**). Most farmers cultivating sorghum in wetlands are women (64%), except in the low-altitude wetlands. Most of these farmers are between 30 and 50 years old (50%), with a very low participation of elderly individuals in sorghum farming (5.9% for over 70 years old). Most farmers are married (85%), with nearly half having no formal education (48%) or only a very low education level (25%). Agriculture is the primary activity for 92% of these farmers, while only a tiny proportion had paid employment (2.7%) or engaged in small-scale trades (3.6%). However, despite these activities, income levels are generally very low, rarely exceeding \$100 per month for 96% of sorghum farmers. Overall, among these sociodemographic characteristics, gender, age, main occupation, monthly income, association membership, land tenure, and farm size varied significantly with AEZs ($p<0.05$).

Table 1. Sociodemographic characteristics of sorghum farmers across South-Kivu wetlands, eastern DRC

Characteristics	***Modalities***	**Agroecological zones**				χ^2	***p-value***
		AEZ1	**AEZ2**	**AEZ3**	**Total**		
Sex	*Female*	23.1	66.8	65.9	64.0	20.03	*< 0.001****
	Male	76.9	33.2	34.1	36.0		
Age category	*≤30 years*	15.4	13.4	17.0	15.4	36.10	*< 0.001****
	30-50 years	46.2	59.9	43.7	50.7		
	50-70 years	11.5	24.3	32.8	28.0		
	≥70 years	26.9	2.4	6.5	5.9		
Marital status	*Married*	96.2	84.7	84.2	85.1	6.28	*0.182ns*
	Single	3.8	6.9	10.5	8.6		
	Widow(er)	0.0	8.4	5.3	6.3		
Education level	*No level*	69.2	44.6	49.0	48.2	5.81	*0.214ns*
	Primary	15.4	27.2	24.3	25.1		
	Secondary	15.4	28.2	26.7	26.7		
Main activity	*Agriculture*	92.3	91.1	94.3	92.8	23.75	*0.006***
	Other	7.7	0.0	0.8	0.8		
	Paid employment	0.0	5.0	1.2	2.7		
	Small trade	0.0	4.0	3.6	3.6		
Monthly income (US$)	≤50	80.8	74.8	88.7	82.3	21.70	*< 0.001****
	50-100	15.4	17.8	10.9	14.1		
	100-200	3.8	7.4	0.4	3.6		
Association membership	No	65.4	89.1	75.3	80.6	17.66	*< 0.001****
	Yes	34.6	10.9	24.7	19.4		
Land tenure	*Community*	0.0	7.9	1.6	4.2	38.78	*< 0.001****
	Mwami	0.0	9.9	24.7	17.1		
	Other	0.0	4.0	0.8	2.1		
	Ownership	100.0	78.2	72.9	76.6		
Land access mode	*Buy*	15.4	20.8	27.1	23.8	14.43	*0.071ns*
	Donation	15.4	7.9	13.8	11.4		
	Other	0.0	1.0	0.4	0.6		
	Rental	15.4	30.2	28.3	28.4		
	Inheritance	53.8	40.1	30.4	35.8		

Farm size (ha)	*≤0.5ha*	15.4	74.8	80.6	74.5	96.10	*<0.001****
	0.5-1ha	61.5	16.8	19.4	20.6		
	1-2ha	23.1	3.5	0.0	2.7		
	≥2ha	0.0	5.0	0.0	2.1		
Seniority (years)	*≤5*	19.2	21.3	17.0	18.9	3.21	*0.524ns*
	5-10	23.1	12.9	15.0	14.5		
	≥10	57.7	65.8	68.0	66.5		
Farm proportion allocated to sorghum	*≤20%*	0.0	0.5	0.4	0.4	5.23	*0.515ns*
	20-50%	3.8	3.5	0.8	2.1		
	50-75%	15.4	11.4	10.1	10.9		
	≥75%	80.8	84.7	88.7	86.5		

*AEZ: agroecological zone, ns: not significant, *: significant (p<0.05), **: highly significant (p<0.01), ***: very highly significant (p<0.001)*

Most farmers are not members of associations (81%). Regarding land access, three main modes of land access were observed: over a third (36%) of wetland farms are inherited from parents, nearly another third (28%) is rented, and ~24% of wetland farms have been purchased. Regarding land tenure status, more than three-quarters (77%) of farmers owned their lands, while 17% of lands belonged to local chiefs or "mwami", and 4% consisted of community lands. These fields are generally small, with 75% being less than 0.5 ha and 21% ranging between 0.5 and 1 ha. Very few fields exceed 2 ha (2.1%). Regarding experience in wetland sorghum farming, more than half of the farmers (67%) have been engaged in wetland agriculture for over 10 years, while only 19% of them had less than five years of experience. Finally, not all owned wetland farmland is allocated to sorghum production; more than 75% of the farm size is used for sorghum production by most farmers (87%). The remaining land portion is often used for brickmaking and fodder production or left uncultivated due to a lack of resources for its exploitation.

3.2 Information related to sorghum farming in South-Kivu wetlands

In wetlands, sorghum is one of the most preferred crops by farmers, cultivated for various purposes. It is mainly produced for household consumption (59%) or both consumption and market (36%), while only 5% farmers produce sorghum solely for market (**Table 2**). However, reasons for cultivating sorghum in wetlands depend on the AEZs: it is mainly grown for household consumption (68%) in AEZ2 and AEZ3 while the market participation dominates in the AEZ1 (73%). There is a substantial proportion of farmers (19%) that produces sorghum for consumption and brewery of local alcohol, known as "Kasiksi". Wetland parcels are partially (60%) or completely drained (32%), with only a small proportion (8%) remaining intact. Wetlands provide additional goods and services to local communities apart from the agriculture; forage for livestock (43%), brickmaking (5%), or a combination of forage, water supply, and fuelwood provision. Income from wetland activities is used for various purposes, including covering family needs such as food, health expenses and school fees. Heavy rainfall (65%) is a major constraint in wetland farmers, with high intensity in the AEZ1 (92%).
Since sorghum is an underutilized crop species in eastern DRC, access to information and inputs for its production, mainly through agricultural extension services, remains limited, prompting overreliance on traditional farming practices and landraces. For instance, almost all sorghum farmers (97%) had no contacts with extension agents regardless of AEZs. Sorghum farmers rely on informal delivery of low-quality seeds dominated by farmer-saved seeds (76%), local market (9%), and farmer seed exchanges (2%). Formal seed is only accessible to AEZ1 farmers who acquire it from neighboring country Burundi.

Table 2. Information on sorghum farming in eastern DRC wetlands

Characteristics / *Modalities*	Agroecological zones				χ^2	*p-value*
	AEZ1	AEZ2	AEZ3	Total		
Production objectives						
Both consumption and sale	23.1	32.7	39.3	35.6	270.20	*<0.001****
Consumption	3.8	66.8	59.1	59.4		
Sale	73.1	0.5	1.6	5.1		
Drainage appreciation of the wetland						
Completely	23.1	17.3	45.7	32.4	134.29	*<0.001****
Intact	53.8	2.0	8.1	8.0		
Partially	23.1	80.7	46.2	59.6		
Providing ES						
No	42.3	40.1	41.7	41.1	0.14	*0.934ns*
Yes	57.7	59.9	58.3	58.9		
Other uses						
Agriculture	46.2	58.4	25.5	40.6	129.93	*<0.001****
Brickmaking	11.5	7.4	2.4	5.1		
Fishing	0.0	3.0	0.8	1.7		
Fodder and livestock	30.8	21.3	61.6	42.7		
Water supply	0.0	1.5	0.0	0.6		
Wood and fuelwood	11.5	2.0	0.0	1.5		
Fodder, water, and agriculture	0.0	3.0	5.7	4.3		
Fund destination						
Multiple family needs	50.0	29.2	40.9	36.4	49.04	*<0.001****
Fees and family needs	11.5	3.5	8.1	6.3		
Healthcare expenses	0.0	1	0.0	0.5		
Healthcare and family needs	15.4	1.5	1.6	2.3		
Family needs	19.2	64.4	49.0	53.9		
School fees	3.8	0.5	0.4	0.6		
Occurrence of heavy rainfall						
No	7.7	37.6	35.6	34.9	9.18	*0.011***
Yes	92.3	62.4	64.4	65.1		
Reasons for sorghum production in marshlands						
Consumption (a)	0.0	67.8	75.7	68.2	259.24	*<0.001****
Trade (b)	73.1	1.5	2.8	6.1		
Alcohol (c)	7.7	1.5	1.2	1.7		
All (a,b,c)	7.7	2.0	0.4	1.5		
(a) and (b)	0.0	7.4	0.0	3.2		
(a) and (c)	11.5	19.8	19.8	19.4		
Information access						
No	96.2	98.0	96.4	97.1	1.73	*0.784ns*
Yes	3.8	2.0	3.6	2.9		
Seed origin						
Exchange farmer	3.8	3.5	0.8	2.1	34.95	*<0.001****
Pervious harvest and market	3.8	7.4	3.6	5.3		
Market	23.1	9.9	6.1	8.6		
Pervious harvest	50.0	68.3	85.4	76.2		
All the above	19.2	10.9	4.0	7.8		
Seed quality appraisal						
Mixture	10.0	98.5	97.6	92.6	34.5	*<0.001****
Pure	90.0	1.5	2.4	7.4		

*AEZ: agroecological zone, ns: not significant, **: highly significant (p<0.01), ***: very highly significant (p<0.001), ES: ecosystem services*

3.3 Farmers' perception of climate change and main sorghum varieties in South-Kivu marshlands

Table 3. Sorghum farmers' perception of climate change in eastern DRC wetlands

Characteristics/*Modalities*	Agroecological zones				χ^2	*p-value*
	AEZ1	AEZ2	AEZ3	Total		
Climate change in the region						
Agree	34.6	65.8	63.6	62.9	10.71	*0.031**
Disagree	65.4	34.2	36.0	36.8		
Neutral	0.0	0.0	0.4	0.2		
Effect on grain yield						
Increased	11.5	23.3	8.5	14.9	19.31	*<0.001****
Reduced	88.5	76.7	91.5	85.1		
Effect on soil fertility						
Very low	0.0	0.5	1.6	1.1		
Low	7.7	3.0	4.0	3.8	17.89	*<0.001****
High	73.1	37.1	37.2	39.2		
Quiet high	19.2	59.4	57.1	56.0		
Effect on change in agricultural practices						
Yes	61.5	92.5	64.4	76.2	92.24	*<0.001****
No	38.5	7.5	35.6	23.8		
Impact on sorghum farming						
Weed occurrence	3.8	0.0	0.0	0.2	118.13	*<0.001****
Flooding	0.0	5.9	0.0	2.5		
Tellering	23.1	9.9	2.0	6.5		
Heavy rainfall	0.0	4.0	2.4	2.9		
High fertilizer demand	0.0	2.5	0.8	1.5		
Yield decrease	34.6	65.3	64.8	63.4		
Shedding	23.0	2.5	8.5	7.3		
Pests increase	15.4	8.3	19.8	14.1		
Yield increase	0.0	1.5	1.6	1.5		

*AEZ: agroecological zone, *: significant (p<0.05), ***: very highly significant (p<0.001)*

Figure 2. Wordcloud of the main varieties used by sorghum farmers in South-Kivu wetlands, eastern DRC

It emerges from the analysis of farmers' perceptions that more than half (63%) of the farmers acknowledge the presence of climate change effects in the region. However, a significant proportion

(37%) disagrees. This perception varied slightly across AEZs. Nevertheless, most farmers (88%) unanimously confirmed that they have recently observed a decline in yields. These changes affect not only the crops but also the soils on which they are grown (73%). Consequently, farmers have had to adjust their farming practices (76%). Regarding sorghum production, these climate perturbations significantly impact the crop by reducing yields (as reported by 63% of farmers). Other effects, such as excessive rainfall (7%), shedding (7%), pests (14%), and several others, have also been identified as consequences of these climate perturbations.

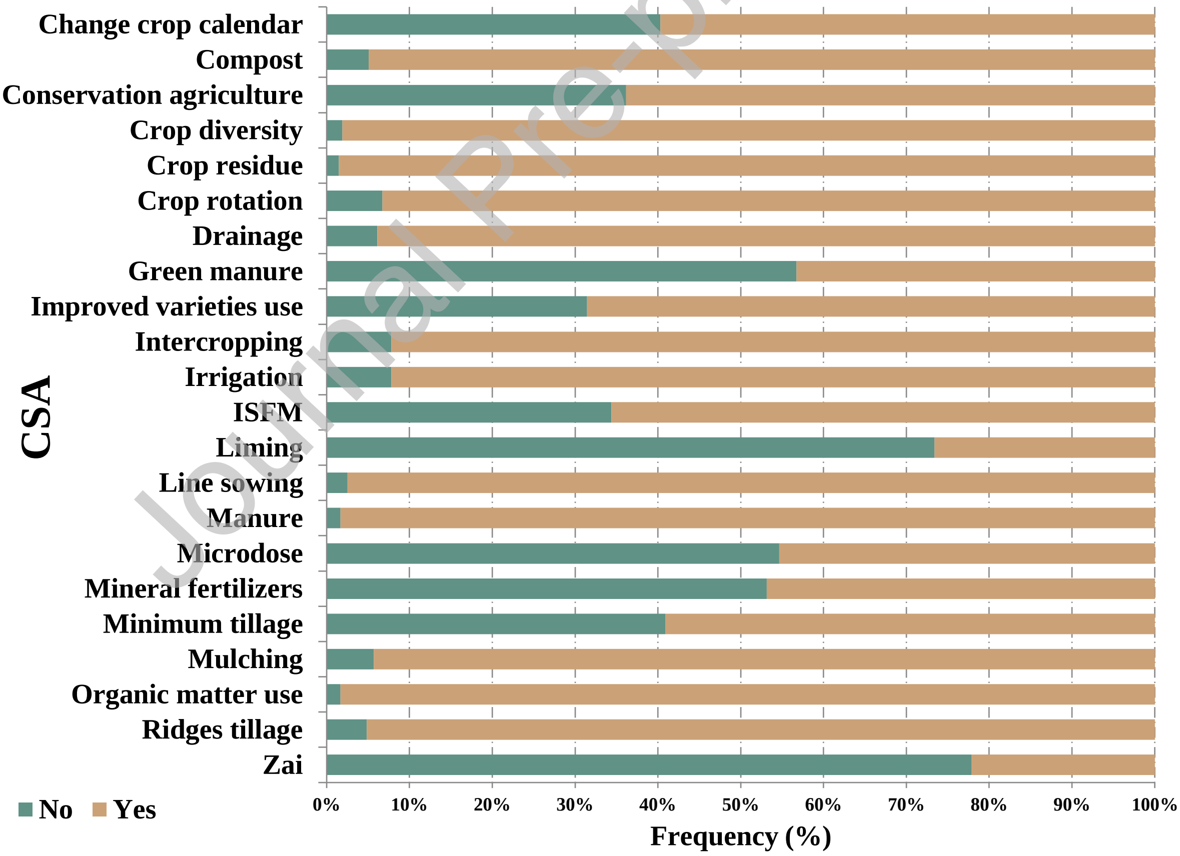
To cope with these challenges, more tolerant and productive sorghum varieties have been adopted as alternatives. Farmers frequently mentioned around ten sorghum varieties, among which Lusoke, Kijambere, Mbogo Mbogo, Mudogo, Burundi, Rouge, Chiboza, and Kaburhwe are mostly used to adapt on these changes (**Figure 2**). However, their distribution and use varied significantly across different AEZs.

3.4 Adoption of climate-smart agronomic (CSA) practices by sorghum farmers

3.4.1 Knowledge and use of main CSA practices across South-Kivu wetlands

Climate-smart agricultural (CSA) practices were investigated from different perspectives. First, knowledge of the practices was assessed, followed by the identification of which CSA practices were actually being implemented. The CSA practice's applicability and the labor type involved to implement them were also examined. Results related to CSA awareness and use are presented in **Figure 3**.

(a)



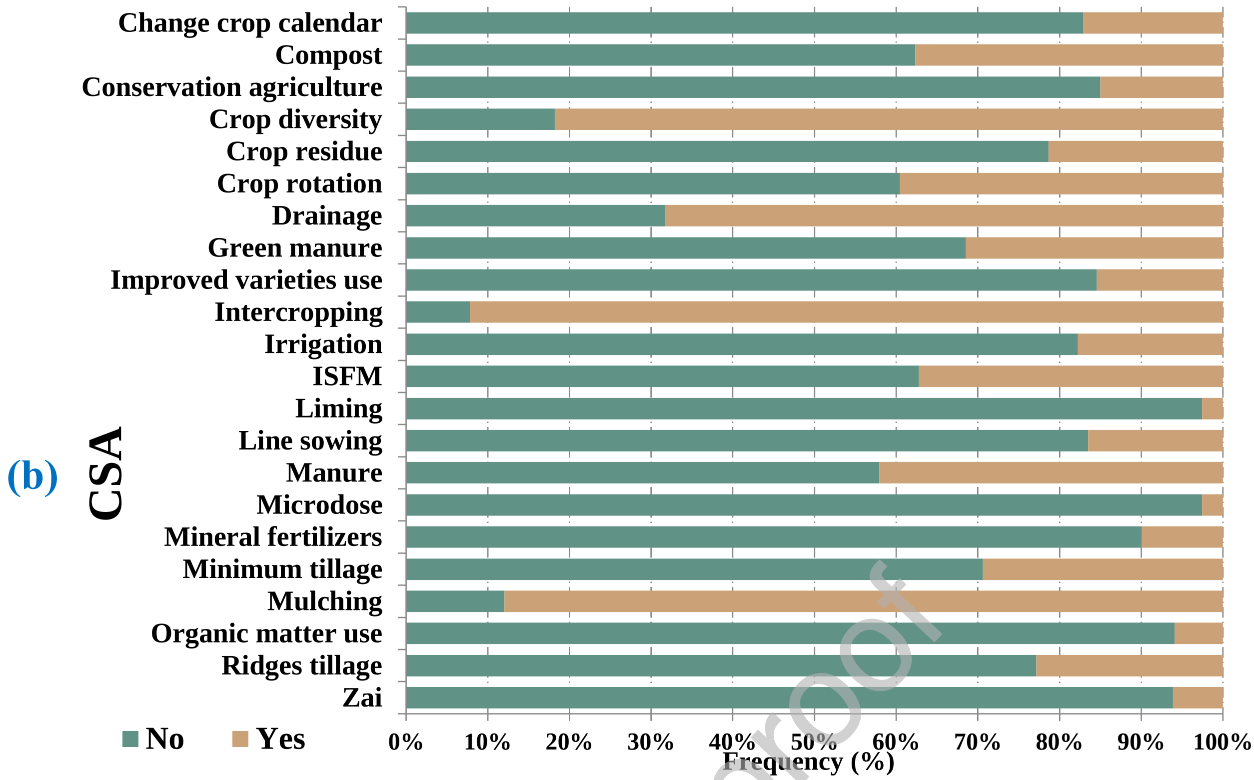


Figure 3. Awareness (a) and use (b) of CSA practices by sorghum farmers in wetlands in eastern DRC

More than 22 CSA practices are known by sorghum farmers in South-Kivu wetlands (**Figure 3a**). This awareness varied significantly with practices ($p<0.05$), with some CSA practices being more widely recognized than others (**Figure 3a**). A similar trend was observed for the implemented CSA practices (**Figure 3b**), though the proportions of knowledge and actual use differed across practices. Twelve CSA practices were most widely known, including irrigation, drainage, line sowing, ridge tillage, mulching, crop residue management, composting, manure application, organic manure use, crop rotation, intercropping, and crop diversification, all known by more than 95% of sorghum farmers. Compost is mostly obtained from food waste and poultry manure after three or four months; some grass can be added into the compost to enrich it. While manure is mainly sourced from cow, poultry, cattle or mini-livestock (guinea-pig, rabbit, etc.) farms, slurry directly without composting. Organic manure is a broader term that includes either compost, green manure, or decomposed crop residues.

Other CSA techniques, such as Zaï pits (78%), liming (74%), green manure (55%), and micro-dosing (54%), are less commonly known. However, regarding the implementation at the farm level, only eight CSA practices are commonly and widely adopted. The four most practiced techniques include drainage (68%), mulching (88%), intercropping (92%), and crop diversification (88%). Other practices, such as composting (38%), green manure (32%), crop rotation (40%), and ISFM (35%), are also applied but a limited extent. Adopting these CSA practices varies significantly with AEZs and strongly depends on farmers' knowledge of the practice. The most well-known CSA practices also tended to be the most implemented.

3.4.2 Gender considerations on the CSA adoption across South-Kivu wetlands

Results showed that six out of 22 identified CSA practices were significantly dependent on gender ($p<0.05$, **Figure 4**). These include practices such as changes in the agricultural calendar, conservation agriculture, drainage, microdosing application, and intercropping. Crop diversification and intercropping are more commonly practiced by women (82% and 95%, respectively), whereas men predominantly adopt micro-dosing, drainage, and mulching.

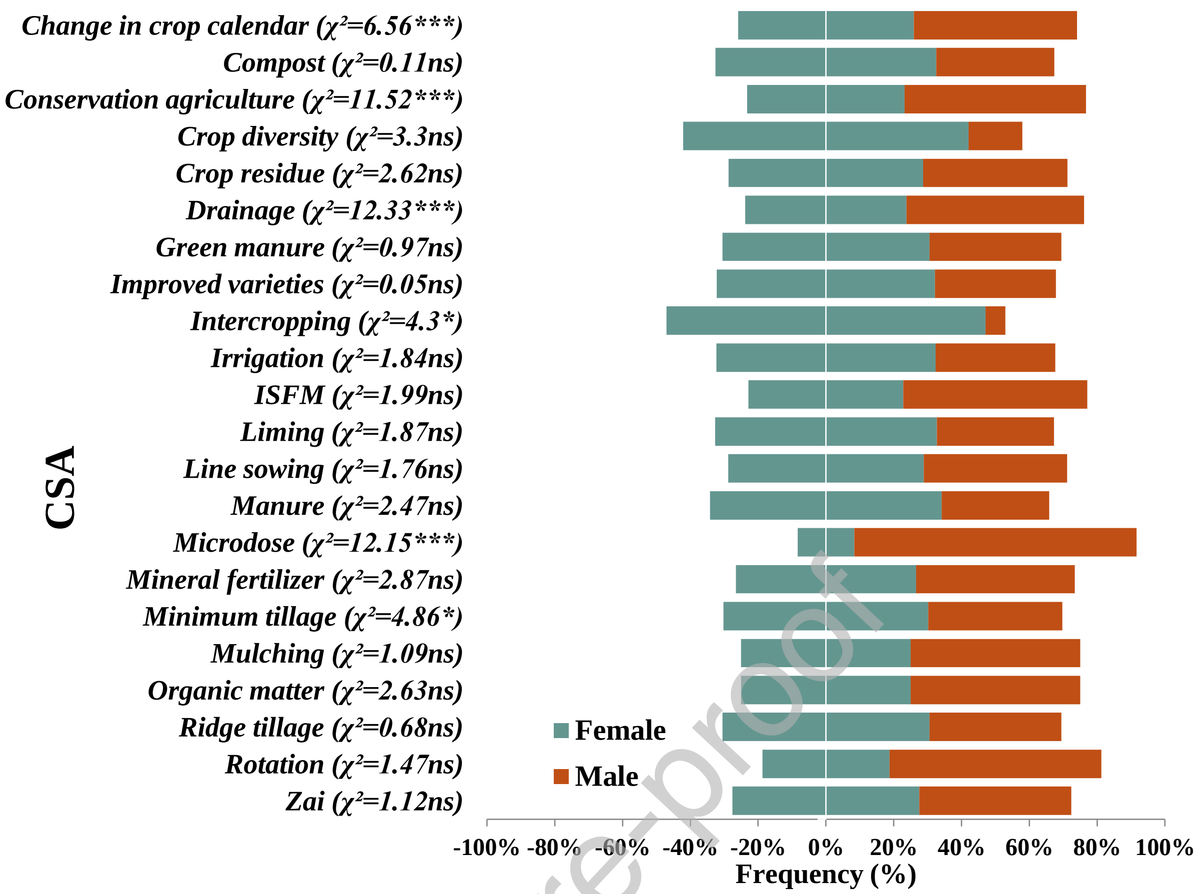
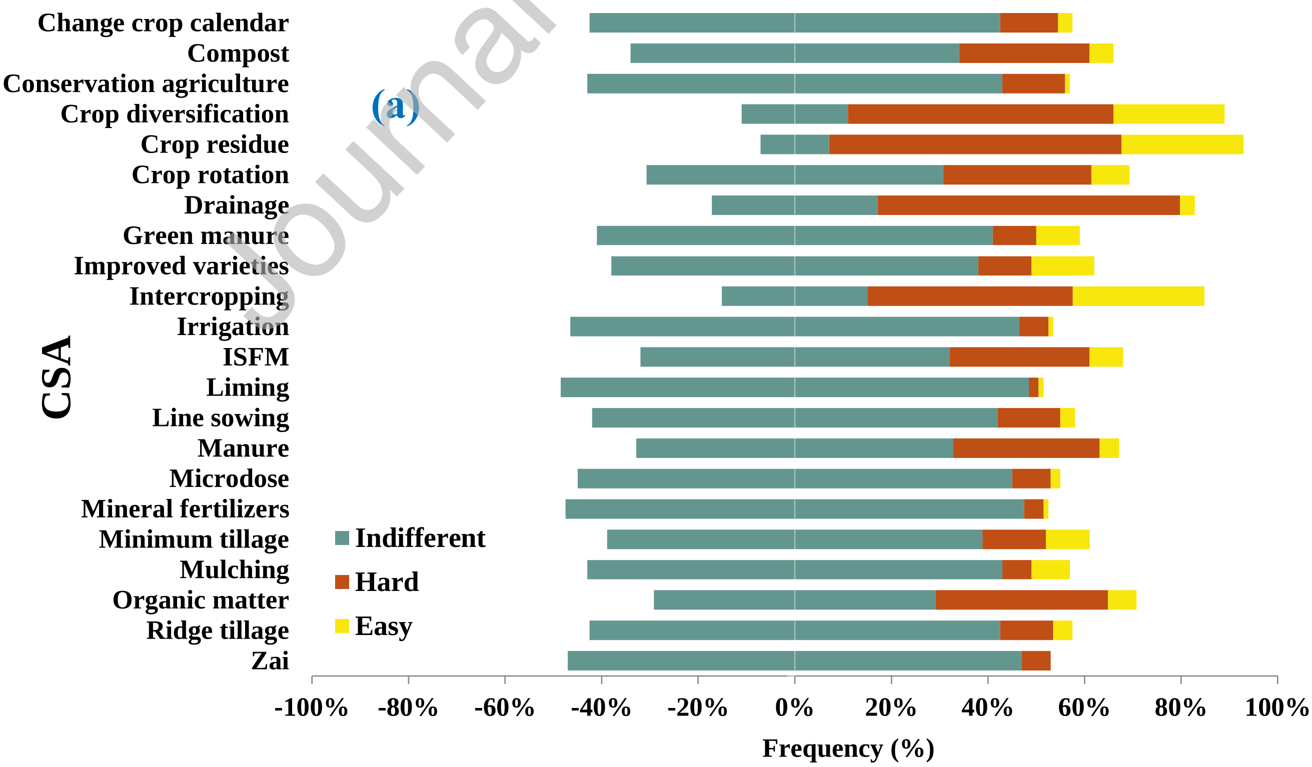


Figure 4. Gender effect on CSA utilization

3.4.3 Applicability, experience, and labor use for CSA implementation



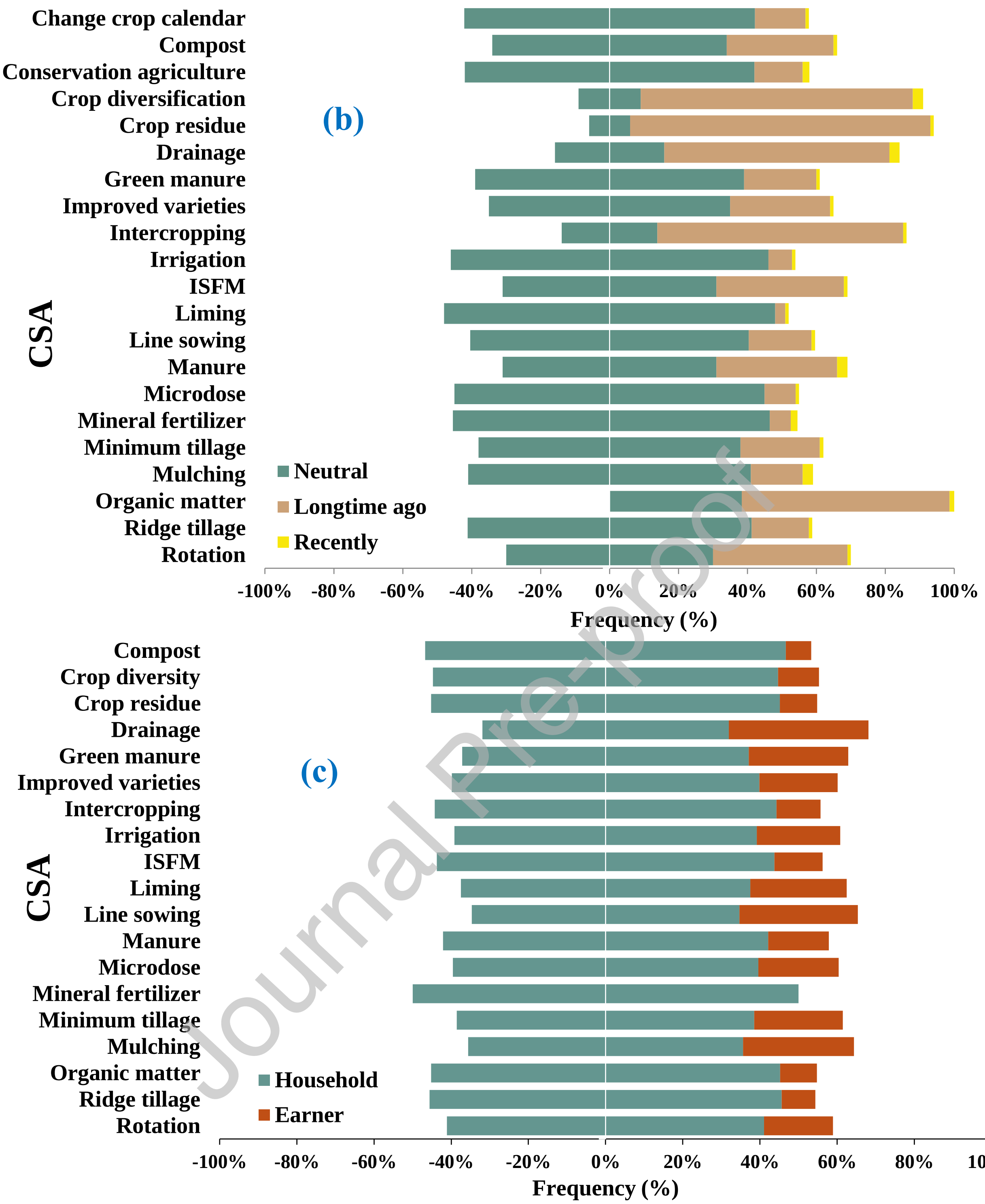


Figure 5. Applicability (a), seniority (b) and (c) labor used to implement CSA practices in sorghum farms in South-Kivu wetlands, eastern DRC

Significant variations were observed across different CSA practices regarding applicability, seniority or experience with the practice, and the type of labor used. For applicability, which was assessed on a three-level scale, most farmers remained neutral about the ease of implementing CSA practices, except for specific practices such as liming, for which the majority found it challenging to implement at the farm level. A similar trend was observed for drainage, crop residues, crop diversification, and intercropping in sorghum cultivation within wetlands. Among all the CSA practices, only management of crop residues, intercropping, and crop diversification seemed easy to apply by sorghum farmers (**Figure 5a**). Regarding seniority in CSA practices, most farmers did not express a clear (neutral) opinion about how long these practices were being used. However, practices such as intercropping, crop diversification, organic manure, crop residues, and drainage were considered as integral part of the sorghum farming agro-systems in South-Kivu wetlands for ages. Only a tiny proportion (less than 5%) recently adopted practices like drainage, manure application, or crop diversification (**Figure 5b**). This adoption was mainly driven by recent climatic events that forced some farmers to adjust their agricultural practices to better adapt to local conditions over the last three seasons. The type of labor used in implementing CSA practices also varied with the practice. However, family labor remained predominant, with household members providing labor for field work. Practices such as intercropping (80%), crop diversification (84%), crop rotation (84%), composting (90%), and crop residue management (82%) were primarily carried out by family labor. On the other hand, CSA practices such as drainage, line sowing, green manure application, and mulching involved a significant proportion of external casual labor.

3.4.4 Determinants of adoption of CSA practices in sorghum cropping systems in South-Kivu wetlands, eastern DRC

Table 4 presents the results on the determinants of the adoption of CSA practices among sorghum producers across South-Kivu AEZs. The logistic regression analyses performed, combined with additional data on the estimated and marginal effects (**Supplementary Materials 1**), elucidate the determinants of CSA adoption in the study areas. These determinants varied significantly with CSA practices.

Out of 25 variables included in the regression model, 12 influenced intercropping adoption. These included factors such as AEZ, membership in farmers' association, mode of land access, experience, the availability of a drainage system in the wetland, the allocation of funds obtained from agricultural activities, the occurrence of extreme rainfall events, the seed origin, the cropping system, the perceived yield, perceived soil fertility level, and changes in practices implemented compared to previous seasons. In contrast, only six variables influenced the adoption of crop diversification: household size, monthly household income, farm size (ha), alternative wetland land use, seed origin, and the sowing method used.

Six variables, including AEZ, education level, the primary income source, the proportion of land cultivated in the wetland, the presence of a drainage system, and alternative wetland land uses, also influenced the adoption of crop rotation. Thus, the cultivated area and water management in the plots are key factors influencing the choice to practice crop rotation in wetland fields (**Table 4**). Several factors, including AEZ, land access, experience, the presence of a drainage system, alternative wetland land uses, and extreme rainfall events, had influenced ISFM adoption. Three additional variables included the cropping system, soil fertility perception, and changes in past practices. The adoption of microdosing in wetland sorghum fields is mainly influenced by farmers' monthly income, farming objectives, the sowing method used, the cropping system, and previously adopted practices. The use of mineral fertilizers is influenced by only three factors: AEZ, wetland land uses, and changes in practice. Nine variables influence the application of organic matter or organic fertilizers in wetlands: AEZ, gender, land access, farming objectives, and sorghum as the main crop. Three additional factors influencing this practice included the cropping system, perceived yield, perceived soil fertility, and past practice changes. Six variables showed significant effects on compost use: AEZ, land access, farm size, proportion of land allocated to sorghum cultivation, main crop, and changes in practices. Multiple factors influenced green manure adoption, including AEZ, monthly income, land tenure status, the proportion of land cultivated in wetlands, farming objectives, primary crop, and perceived yield. Two additional factors included soil fertility and changes in past practices. Eight factors influenced the adoption of crop residues, including average household income, land tenure status, other wetland uses, production income allocation, heavy rainfall occurrence, primary crop, perceived yield, and soil fertility. Another practice is mulching, which is influenced by five factors: AEZ, gender, education level, presence of a drainage system, and other wetland land uses. Another CSA practice adopted by sorghum producers is the use of improved cultivars. Its adoption was influenced by monthly income, farm size, years of wetland farming experience, the proportion of land allocated to sorghum, other wetland land uses, the origin of improved cultivar seed, their perceived yield, and farm soil fertility. Minimum tillage, on the other hand, is influenced by more than twelve factors, including AEZ, primary source of income, monthly income, experience, proportion of cultivated land, farming objectives, presence of a drainage system, other wetland land uses, allocation of agricultural income, primary crop, seed origin, and changes in past practices. All factors influenced the adoption of ridge tillage except the first five presented in **Table 4**, namely, average income, education level, household size, marital status, household head's age and gender, and finally, AEZ. Eight factors influence the adoption of row planting: AEZ, monthly income, membership in an association, and land tenure status. Four other factors included a drainage system, primary crop, cropping system, and perceived yield. AEZ, monthly income, other wetland land uses, seed source, sowing method, and cropping system were determining factors for drainage techniques.

Table 4. Logistic regression of determinants of adoption of CSA practices among sorghum farmers in South-Kivu wetlands

Factors	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
AEZ	*0.001**	*0.057ns*	*<0.01**	*0.015**	*0.992ns*	*0.016**	*<0.01**	*<0.01**	*<0.01**	*0.0989ns*	*0.01**	*0.779ns*	*<0.01**	*0.591ns*	*0.001**	*0.02**	*0.01**	*0.435ns*	*0.001**
Gender	*0.647ns*	*0.526ns*	*0.087ns*	*0.110ns*	*0.162ns*	*0.192ns*	*0.03**	*0.564ns*	*0.141ns*	*0.0604ns*	*0.046**	*0.267ns*	*0.30ns*	*0.734ns*	*0.77ns*	*0.101ns*	*0.281ns*	*0.005**	*0.13ns*
Age class	*0.219ns*	*0.124ns*	*0.668ns*	*0.339ns*	*0.297ns*	*0.152ns*	*0.738ns*	*0.875ns*	*0.565ns*	*0.630ns*	*0.536ns*	*0.2597*	*0.731ns*	*0.347ns*	*0.271ns*	*0.740ns*	*0.441ns*	*0.085ns*	*0.02**
Marital status	*0.211ns*	*0.190ns*	*0.570ns*	*0.192ns*	*0.720ns*	*0.577ns*	*0.206ns*	*0.110ns*	*0.631ns*	*0.181ns*	*0.938ns*	*0.196ns*	*0.190ns*	*0.881ns*	*0.451ns*	*0.978ns*	*0.902ns*	*0.019**	*0.04**
Family size	*0.114ns*	*0.037**	*0.599ns*	*0.657ns*	*0.249ns*	*0.254ns*	*0.082ns*	*0.751ns*	*0.527ns*	*0.137ns*	*0.491*	*0.590ns*	*0.331ns*	*0.656ns*	*0.2722*	*0.814ns*	*0.176ns*	*0.941ns*	*0.17ns*
Education level	*0.879ns*	*0.199ns*	*0.006**	*0.071ns*	*0.121ns*	*0.927ns*	*0.649ns*	*0.671ns*	*0.616ns*	*0.875ns*	*0.02**	*0.928ns*	*0.191ns*	*0.259ns*	*0.111ns*	*0.166ns*	*0.797ns*	*0.084ns*	*0.75ns*
Main income source	*0.501ns*	*0.622ns*	*0.003**	*0.494ns*	*0.101ns*	*0.897ns*	*0.946ns*	*0.498ns*	*0.218ns*	*0.646ns*	*0.155ns*	*0.905ns*	*0.049**	*0.121ns*	*0.321ns*	*0.209ns*	*0.443ns*	*0.132ns*	*0.04**
Monthly income	*0.148ns*	*0.0191**	*0.359ns*	*0.342ns*	*0.015**	*0.599ns*	*0.209ns*	*0.172ns*	*0.017**	*0.001**	*0.320ns*	*0.034**	*0.001**	*<0.01**	*0.004**	*0.031**	*0.479ns*	*0.066ns*	*0.51ns*
Association membership	*0.007**	*0.689ns*	*0.311ns*	*0.104ns*	*0.104ns*	*0.337ns*	*0.745ns*	*0.756ns*	*0.958ns*	*0.810ns*	*0.357ns*	*0.604ns*	*0.56ns*	*<0.01**	*0.101**	*0.842ns*	*0.999ns*	*0.665ns*	*0.56ns*
Land tenure	*0.839ns*	*0.146ns*	*0.601ns*	*0.241ns*	*0.881ns*	*0.114ns*	*0.138ns*	*0.749ns*	*0.032**	*0.004**	*0.359ns*	*0.229ns*	*0.931ns*	*<0.01**	*0.031**	*0.169ns*	*0.193ns*	*0.138ns*	*0.01**
Land access	*0.001**	*0.056ns*	*0.101ns*	*0.041**	*0.667ns*	*0.060ns*	*0.023**	*0.022**	*0.794ns*	*0.546ns*	*0.345ns*	*0.978ns*	*0.371ns*	*<0.01**	*0.127ns*	*0.211ns*	*0.012**	*0.039ns*	*0.38ns*
Farm size (ha)	*0.414ns*	*0.001**	*0.068ns*	*0.143ns*	*0.920ns*	*0.911ns*	*0.261ns*	*0.008**	*0.101ns*	*0.124ns*	*0.275ns*	*0.008**	*0.461ns*	*<0.01**	*0.264ns*	*0.940ns*	*0.743ns*	*0.804ns*	*0.44ns*
Seniority (years)	*0.011**	*0.269ns*	*0.546ns*	*<0.01**	*0.693ns*	*0.113ns*	*0.315ns*	*0.755ns*	*0.271ns*	*0.367ns*	*0.844ns*	*0.209**	*0.001**	*<0.01**	*0.533ns*	*0.075ns*	*0.490ns*	*0.912ns*	*0.25ns*
Used farm proportion (%)	*0.514ns*	*0.081ns*	*0.001**	*0.528ns*	*0.534ns*	*0.770ns*	*0.321ns*	*0.009**	*0.001**	*0.001ns*	*0.288ns*	*0.018**	*0.04**	*<0.01**	*0.943ns*	*0.447ns*	*0.245ns*	*0.608ns*	*0.39ns*
Farming purpose	*0.491ns*	*0.692ns*	*0.068ns*	*0.172ns*	*0.016**	*0.606ns*	*0.01**	*0.299ns*	*0.029**	*0.011ns*	*0.314ns*	*0.386ns*	*0.01**	*<0.01**	*0.854ns*	*0.120ns*	*0.002**	*0.972ns*	*0.67ns*
Drainage system	*0.001**	*0.786ns*	*0.001**	*<0.01**	*0.780ns*	*0.904ns*	*0.099ns*	*0.391ns*	*0.112ns*	*0.618ns*	*0.023**	*0.512ns*	*0.01**	*<0.01**	*0.037**	*0.250ns*	*0.001**	*0.907ns*	*0.01**
Other uses	*0.113ns*	*0.016**	*<0.01**	*0.001**	*0.006**	*0.008**	*0.522ns*	*0.098ns*	*0.156ns*	*0.001**	*<0.01**	*0.045**	*<0.01**	*<0.01**	*0.160ns*	*0.034**	*0.097ns*	*<0.01**	*<0.01**
Income destination	*0.015**	*0.062ns*	*0.744ns*	*0.121ns*	*0.727ns*	*0.526ns*	*0.57ns*	*0.396ns*	*0.143ns*	*0.500**	*0.002**	*0.991ns*	*0.001**	*<0.01**	*0.658ns*	*0.602ns*	*0.03**	*<0.01**	*0.501ns*
Heavy rainfall	*0.001**	*0.206ns*	*0.174ns*	*0.001**	*0.714ns*	*0.131ns*	*0.201ns*	*0.861ns*	*0.167ns*	*0.032**	*0.112ns*	*0.0366**	*0.106ns*	*<0.01**	*0.449ns*	*0.148ns*	*0.280ns*	*0.258ns*	*0.121ns*
Main crop	*0.914ns*	*0.639ns*	*0.053ns*	*0.167ns*	*0.996ns*	*0.131ns*	*0.016**	*0.001**	*0.021**	*0.049**	*0.2455*	*0.613ns*	*0.001**	*<0.01**	*0.011**	*0.922ns*	*0.033**	*<0.01**	*0.453ns*
Seed origin	*0.007**	*<0.01**	*0.185ns*	*0.746ns*	*0.982ns*	*0.275ns*	*0.34ns*	*0.428ns*	*0.062ns*	*0.181ns*	*0.5718*	*0.039**	*0.01**	*<0.01**	*0.72ns*	*0.856ns*	*0.034**	*<0.01**	*0.592ns*

Seeding method	*0.492ns*	*0.016**	*0.058ns*	*0.774ns*	*0.008**	*0.749ns*	*0.168ns*	*0.091ns*	*0.561ns*	*0.961ns*	*0.7537*	*0.998ns*	*0.21ns*	*<0.01**	*0.114ns*	*0.008**	*0.564ns*	*<0.01**	*0.641ns*
Cropping system	*0.001**	*0.143ns*	*0.093ns*	*0.053**	*0.010**	*0.088ns*	*0.048**	*0.680ns*	*0.801ns*	*0.52ns*	*0.6374*	*0.254ns*	*0.109ns*	*<0.01**	*0.001**	*0.029**	*0.003**	*<0.01**	*0.061ns*
Yield appreciation	*0.024**	*0.210ns*	*0.237ns*	*0.432ns*	*0.671ns*	*0.338ns*	*0.031**	*0.062ns*	*0.002**	*0.031**	*0.7102*	*0.025**	*0.641ns*	*<0.01**	*0.022**	*0.878ns*	*0.443ns*	*<0.01**	*0.181ns*
Soil fertility appreciation	*0.041**	*0.181ns*	*0.906ns*	*0.001**	*0.049$*	*0.516ns*	*0.001**	*0.078ns*	*<0.01**	*0.022**	*0.8579*	*0.019**	*0.881ns*	*<0.01**	*0.88ns*	*0.077ns*	*0.015**	*<0.01**	*0.671ns*
Change in practices	*0.001**	*0.061ns*	*0.599ns*	*0.601**	*0.025**	*0.041**	*0.01**	*0.026**	*<0.01**	*0.061ns*	*0.0088*	*0.91ns*	*0.001**	*<0.01**	*0.401ns*	*0.571ns*	*<0.01**	*<0.01**	*0.766ns*
-2 Log (Vraisemblance)	222.90	238.30	323.00	264.60	126.30	88.50	399.20	372.5	364.20	87.90	188.20	175.40	220.80	147.60	227.90	289.40	385.60	103.10	196.50
R^2 (McFadden)	0.61	0.46	0.49	0.57	0.58	0.59	0.38	0.41	0.38	0.82	0.45	0.50	0.61	0.71	0.46	0.35	0.35	0.60	0.51
R^2 (Cox and Snell)	0.50	0.36	0.48	0.53	0.31	0.23	0.41	0.41	0.38	0.58	0.28	0.39	0.52	0.53	0.34	0.28	0.35	0.20	0.35
R^2 (Nagelkerke)	0.73	0.58	0.65	0.72	0.66	0.64	0.54	0.57	0.53	0.89	0.55	0.67	0.74	0.81	0.57	0.46	0.49	0.60	0.61
AIC	370.90	386.40	471.00	412.60	274.60	236.50	547.20	520.50	512.20	235.90	336.20	323.40	368.80	293.60	373.90	435.40	531.60	249.10	342.50
SBC	678.80	694.30	778.90	720.90	582.10	544.50	855.20	828.40	820.20	543.90	644.10	631.30	676.90	597.20	677.50	738.90	835.30	552.80	646.10
Hosmer-Lemeshow (χ^2)	1.42	4.88	8.70	7.10	2.41	1.14	7.32	6.60	8.60	13.60	26.70	9.30	12.70	20.90	10.40	5.50	6.20	0.75	37.80

1: Intercropping, 2: crop diversification, 3: crop rotation, 4: ISFM (Integrated soil fertility management), 5: microdose, 6: mineral fertilizers, 7: organic matter, 8: compost, 9: green manure, 10: crop residues, 11: mulching, 12: improved varieties, 13: minimum tillage, 14: ridge tillage, 15: line sowing, 16: drainage, 17: irrigation, 18: conservation agriculture, 19: change in crop calendar, AEZ: agroecological zone, AIC: Akaike Information Criterion, SBS: Schwarz Bayesian Criterion.

Compared to drainage, irrigation adoption was influenced by ten factors: AEZ, land access, farming objectives, presence of a drainage system, production allocation, primary crop, seed origin, cropping system, perceived soil fertility, and finally, practice changes. The last two CSA practices—conservation agriculture and changes in planting dates or the agricultural calendar—were influenced by 11 and 7 factors, respectively. Changes in the agricultural calendar were influenced by AEZ, farmers' age, marital status, primary income source, land tenure, presence of a drainage system, and other wetland uses. The values of Beta (β) for these logistic regressions can be seen in the **Figure S1**.

3.4.5 Effectiveness of CSA practices adopted in South-Kivu wetlands

Figure 6 shows that, out of the 22 CSA practices identified, 13 were perceived as effective by wetland users. These include intercropping, drainage, manure, organic matter, ISFM, ridge tillage, liming, crop rotation, improved varieties, Zaï pits, green manure, minimum tillage, and mulching. The results indicate that only three CSA practices were highly effective: liming, manure, and compost. However, most CSA practices were moderately effective.

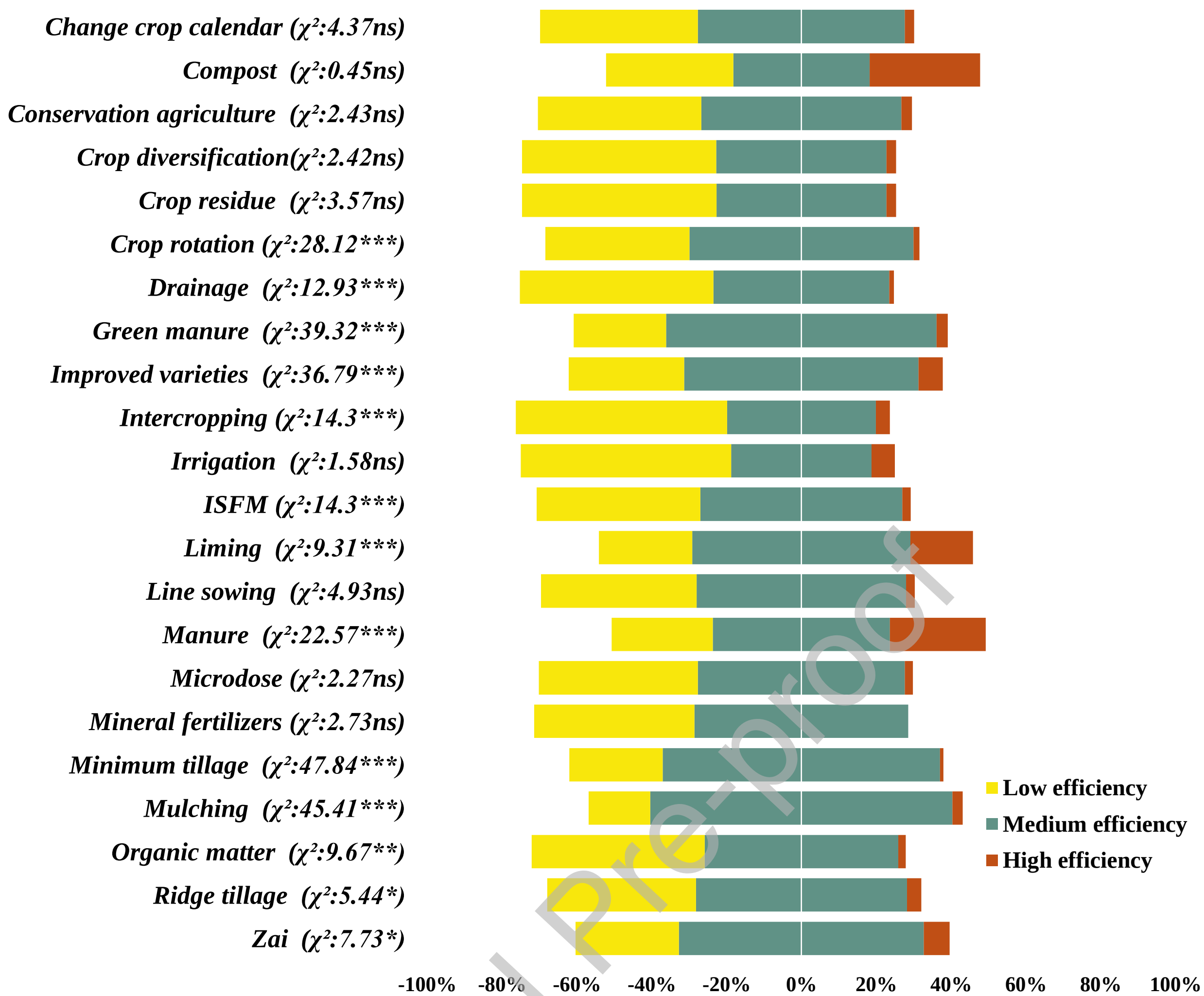


Figure 6. Effectiveness of CSA practices among sorghum farmers (b) in eastern DRC

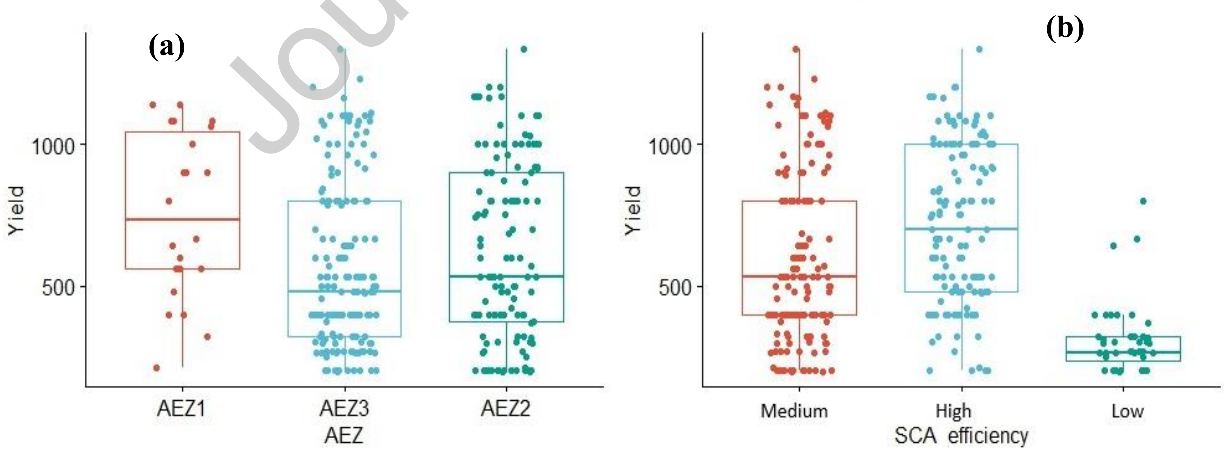


Figure 7. Variation of Sorghum yields across AEZs (a) and according to efficiency of CSA practices (b) in South-Kivu wetlands, in eastern DRC

Highest yields were observed in lowland AEZ1 farms (748 kg ha^{-1}) compared to the medium-altitude AEZ2 (630 kg ha^{-1}) and the highland AEZ3 (565 kg ha^{-1}). However, regarding efficiency, farms where CSA practices were classified as highly efficient had an average yield of 720 kg ha^{-1}, whereas those classified as moderately efficient and less efficient recorded 580 and 370 kg ha^{-1}, respectively (**Figure 7**).

Since there was a significant difference in the effectiveness among CSA practices, we assessed the yield variation across CSA practices (**Figure 8**). Yield comparisons indicate that the application of crop residues, ridge tillage, line sowing, irrigation, conservation agriculture, intercropping, crop diversification, ISFM, microdosing, and mineral fertilization did not show significant differences compared to the control plots where these practices were absent, despite some noticeable variations in certain techniques. However, some practices induced significant improvements in grain yield compared to the control plots, including manure application, compost, green manure, crop rotation, Zaï pits, drainage, minimum tillage, use of improved varieties, mulching, and liming.

For instance, liming increased sorghum grain yield from 590 to 820 kg ha^{-1}, mulching improved yield from 580 to 725 kg ha^{-1}. Using improved sorghum varieties increased yield from 560 to 680 kg ha^{-1} while minimum tillage increased yield from 570 to 710 kg ha^{-1} and the drainage application from 580 to 700 kg ha^{-1}. The Zaï pits, though rarely practiced, increased sorghum yield from 590 to 690 kg ha^{-1}. Two cases stood out as exceptions, showing a slight reduction in yield: line sowing, which decreased yield from 600 to 580 kg ha^{-1} and conservation agriculture from 650 to 580 kg ha^{-1}.

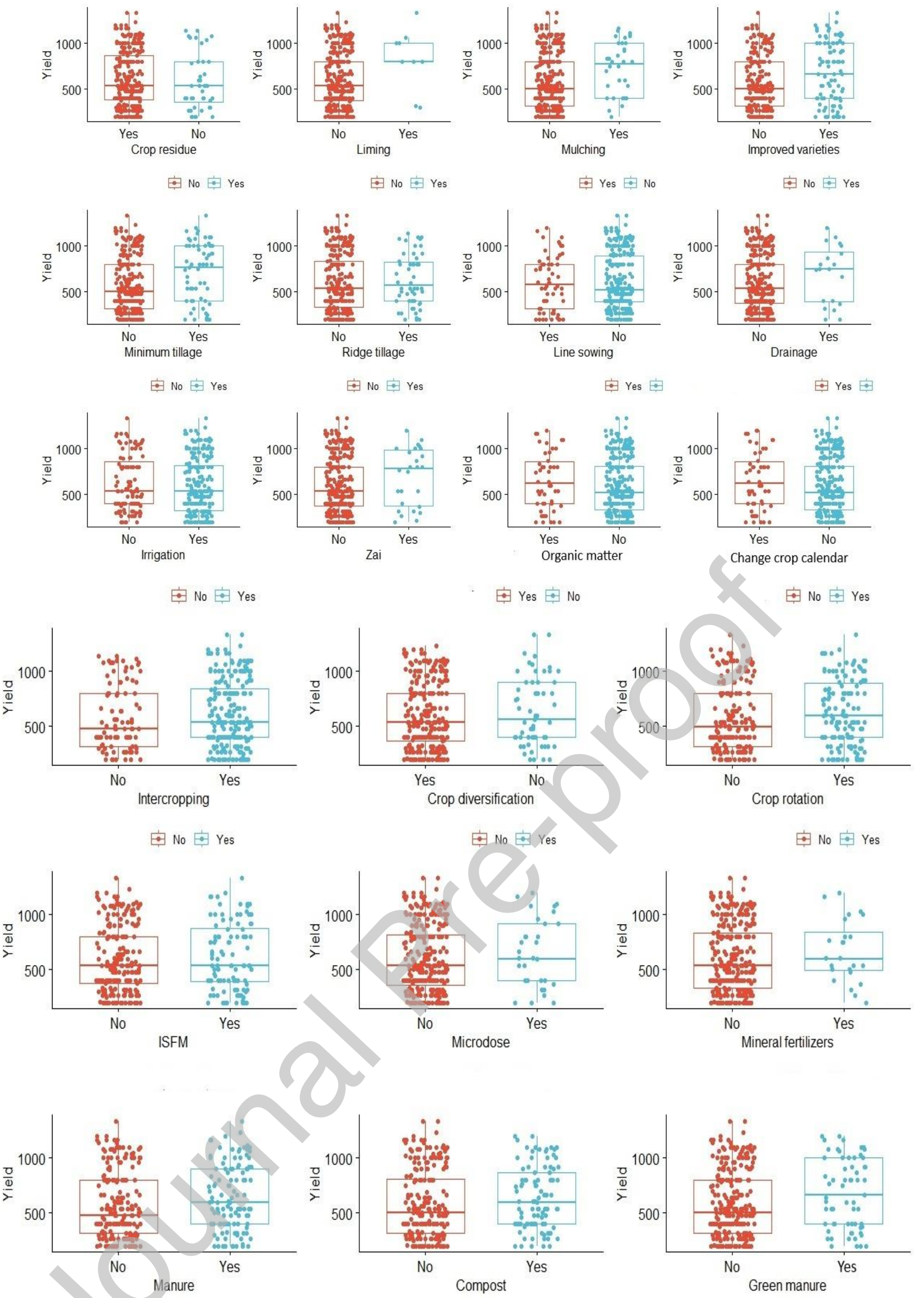


Figure 8. Mean sorghum grain yields (kg ha^{-1}) for different CSA practices in South-Kivu wetlands, in eastern DRC

4. Discussion

4.1. Farming in South-Kivu wetlands: A predominantly female activity

The findings showed that agricultural activities in South-Kivu marshlands, particularly sorghum production, is dominated by women, except in the AEZ1. These are mainly married individuals, with low education level, and earning low monthly incomes. In South-Kivu, agricultural production is primarily intended for household subsistence, except for vegetable crops such as cabbage, carrots, amaranths, and eggplants, which are mainly grown for market (Ndjadi et al., 2020; Mondo, 2024; RIKOLTO, 2025). The low-income contribution of marshland farming is explained by the fact that it is subsistence-based (60%) with limited market participation. This finding aligns with other scholars (e.g., Lambrecht et al., 2014; Mondo et al., 2019) who showed that women are predominant for subsistence crop species in eastern DRC while their men counterparts are inclined toward commercial production. Low education level and weak participation in farmer associations—where agricultural practices are disseminated and promoted—affect farmers' knowledge of CSA practices (Aryal et al., 2018; Mangaza et al., 2021; Gemtou et al., 2024). There is need to devise strategies to enhance women participation into farmer associations and promote extension tools suiting low education farmers such as visual aids and multimedia, field demonstrations, tailored communication and languages, etc. (Antwi-Agyei & Stringer, 2021). Their low income also highlights the precarious financial situation of their households, which is reflected in the small farm size, with three-quarters of farmers using less than 0.5 ha. Since marshlands are ecosystems that provide various goods and services, the uncultivated areas are used for other purposes, such as brickmaking, fodder harvesting, or as a source of fuelwood for households. In this study, more than half of the farmers (58%) reported benefiting from other wetland services, including local fishing, water supply, and fuelwood collection. Agriculture in marshlands is just one of many activities, and engaging in one activity does not necessarily exclude participation in others (Chuma et al., 2024b). Supporting wetland farmers would imply that other wetland ecosystem services are promoted at an income generating activity to diversify women farmers' income and thus strengthen their resilience to climate shocks.

The predominance of women in agricultural activities, particularly in marshlands, is well documented (e.g., Carney, 1993, 2017; Nabahungu & Visser, 2013; Nyirenda, 2021). Overall, the significant contribution of marshland production highlights the crucial role of these ecosystems in the regional food security. Whether in vegetable production (Nabahungu & Visser, 2011; Balasha et al., 2024) or other forms of land use, marshlands play an essential role in income generation (Chuma et al., 2021; 2024b). Based on the findings, it is evident that sorghum cultivation in marshlands is primarily for household consumption, except in low-altitude areas (AEZ1) where it is grown mainly by men for sale and thus generates high incomes. Women in highland AEZs should be encouraged to form cooperatives, trained in marketing techniques and value addition options, and connected to formal markets to increase their income from sorghum production and trade, as it is the case for their male counterpart in the AEZ1 (Mondo, 2024).

A significant portion of the sorghum produced is mainly consumed by elderly individuals, people with diabetes, and young children in the form of porridge and, most notably, for brewing the local alcoholic beverage known as *Kasiksi* (Sawadogo-Lingani et al., 2021, 2025; Kazige et al., 2022; Mondo, 2024) Although this study did not specifically analyze the impact of sorghum sales or processing on income improvement, it is clear that such uses could significantly increase household income. Several other factors explain why people are drawn to farming in marshlands (Chuma et al., 2021; 2024b; Balasha et al., 2024). These include water availability year-round and the perceived fertility of marshland soils, which more than half of the farmers classified as "fertile." In light of ongoing climate disruptions and the increasing degradation of upland soils, many farmers are migrating to lowlands for agricultural activities (Chuma et al., 2024a).

4.2. CSA in South-Kivu marshlands: more awareness but limited implementation

The results showed that sorghum farmers in marshlands are aware of CSA practices. More than 22 CSA practices are known, and most are used, though their adoption levels vary depending on the practice. However, it is noteworthy that the most well-known CSA practices are not necessarily widely adopted or perceived as the most effective by farmers. Some practices, such as liming, mineral fertilization, Zaï pits, and drainage, are well known but rarely implemented (Karume et al., 2022). Their effectiveness is acknowledged, yet they remain underutilized. This low adoption rate is mainly due to a lack of knowledge regarding their practical implementation, prompting a need for effective extension strategies based on practical and hands-on approaches such as field demonstrations of practices directly on farmers' plots, group training sessions, workshops, and field days to facilitate learning and knowledge sharing (Antwi-Agyei & Stringer, 2021). Farmers perceive a high risk in adopting techniques they do not fully understand, especially when no local actor can promote them. These techniques are often introduced through experimental research institutions but have not yet been widely disseminated (Karume et al., 2022). Some techniques more suited to tropical conditions, such as fertilizer micro-dosing, ISFM, crop rotation, and diversification, are poorly known. Others, such as organic matter application and mineral fertilization, are rarely applied in marshlands. This is partly due to farmers' poverty, who cannot afford these inputs, and partly due to a lack of knowledge about their correct application (Chuma et al., 2022; Karume et al., 2022). For instance, mineral fertilizer application requires knowledge of the right dosage, the right place, and the right time, knowledge that is often beyond the reach of small-scale farmers. Organic matter application also requires large quantities (measured in tens of tons per ha) that most farmers cannot access. Only livestock farming can easily integrate organic matter into their fields. As a result, farmers tend to prefer practices that they are more familiar with, and that are less costly for their households. They also favor easily applicable practices, such as burying crop residue, crop diversification, intercropping, and green manure application, as they require less labor and are easier to implement. This is confirmed by the significant role that household members play in implementing these practices (**Figure 4**). In addition to effective extension strategies to raise awareness on CSA practices and their right implementation among local farmers, there is need for financial incentives to enhance the adoption rates of effective, yet labor- and resource-demanding CSA practices.

4.3. CSA practices' adoption is linked to ease of application, long experience, family labor, and results in contrasting efficiency

The findings indicate that the efficiency of CSA practices varies with their applicability, farmers' knowledge, practical experience, and the type of labor available. The results also showed that farmers do not widely appreciate practices requiring large areas (*i.e*, irrigation, ridge tillage, and Zaï pits) and those demanding significant time investment (such as crop rotation and composting). The hydrographic conditions of marshlands make it challenging to implement crop rotation, as it limits crops that can be rotated. For instance, soil reshaping techniques are challenging to maintain over time for cassava, maize, and cabbage. These practices are, therefore, mainly used by small-scale farmers with limited land or within the framework of local organizational support and experimental projects. Nevertheless, some of these practices significantly improve sorghum yields. Firstly, sorghum cultivation is more profitable in low-altitude zones (AEZ1) than in the other two AEZs though their effectiveness varies with used CSA practices. Yield variations across AEZs are linked to the water and soil management techniques adopted, the natural soil fertility, and, most importantly, the biophysical conditions favorable for cereal production, particularly sorghum. Indeed, cereal productivity is strongly correlated with local climatic conditions. High temperatures and well distributed precipitation that characterize the AEZ1 could explain good sorghum performance, while high-altitude zones with lower temperatures and depleted soils extend the crop cycle and reduce yields. Site specific interventions are, therefore, necessary to tailor policies or interventions to local socioeconomic and biophysical conditions to better support sorghum farmers in improving their livelihoods through CSA adoption.

In a global perspective, to enhance the adoption of CSA practices, it is crucial to strengthen agricultural extension services to provide farmers with both practical and support trainings. In a region with limited land access, securing land particularly for low-income women could encourage long-term investments in CSA practices. Additionally, improving access to inputs and financial resources, such as microloans or subsidies, will help smallholders afford CSA technologies. Encouraging farmer-to-farmer knowledge exchange through demonstration farms can further promote adoption. Finally, integrating CSA into local agricultural policies and development programs will provide institutional backing and long-term sustainability for climate-resilient farming. Access to finance through banks or cooperatives could also improve household conditions by enabling the purchase of tools, pay labor, or any other resources that can contribute to the adoption of CSA practices.

5. Conclusion and recommendations

This study examined CSA practices known and used by sorghum farmers in South-Kivu wetlands, in eastern DRC. It helps bridge the knowledge gap by documenting factors driving CSA practices' adoption and effectiveness in improving sorghum yields. The findings reveal that around 22 CSA practices are known, but only eight seemed most effective in rising sorghum grain yields in wetlands. Liming, improved varieties, and minimum tillage significantly increased sorghum yields compared to control plots where no such practices were applied. However, some CSA techniques did not improve yields at the farm level, indicating the need for adjustments or adaptations to unlock their potential. Several constraints persist regarding the use of these practices, mainly related to knowledge gap, applicability, and labor availability for their implementation since sorghum farming is predominantly a women-led and subsistence-oriented activity. There is need to enhance the dissemination and promotion of CSA knowledge while improving marshland land access to help resource-poor farmers adapt to future climate conditions. This implies promoting effective extension strategies based on practical and hands-on approaches and financial incentives to improve CSA practices uptake among predominantly resource-poor low educated sorghum farmers in eastern DRC. Farmer support structures should encourage women farmers to form cooperatives, train them in marketing techniques and value addition options, and connect them with formal markets to increase their incomes from sorghum production. Additionally, further research should evaluate factors associated with inefficiency of some widely practiced CSA techniques and promoting efficient practices that are still underutilized in the region. Potential future research directions should also consider assessing the long-term impact of CSA adoption on household income and food security.

Author contributions

J.M.M. and G.C.B. designed the study. L.K., G.C.B., B.M. and J.M.M. performed data collection. G.C.B. performed data analysis and drafted the manuscript with inputs from J.M.M. J.-G.M.M., K.K. and C.K. supervised the research and revised the manuscript. J.-G.M.M. and K.K. participated in resource mobilization. All the authors have read the last version and approved its submission.

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Conflict of interest

No conflict of interest

Ethical approval

The study protocol was approved by the Interdisciplinary Centre of Ethical Research (CIRE) of the Université Evangélique en Afrique (UEA), Ref: CNES 036/DPSK/322PP/2024. We obtained verbal informed consent from all resource-persons and farmers prior interviews after ensuring the confidentiality in use of data collected and explaining the study objectives, as approved and directed by the above Institutional Review Board.

Abbreviations

AEZ: Agro-ecological zone
DRC: Democratic Republic of Congo
CSA: Climate-smart agriculture
SSA: Sub-Saharan Africa
ISFM: Integrated soil fertility management
FAO: Food and Agriculture Organization
GHG: Greenhouse gas

Availability of data and materials

The database and the complete tables of all the regressions are in the supplementary materials

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Declaration of interests

☐ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☒ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Jean M. Mondo reports financial support was provided by Regional Universities Forum for Capacity Building in Agriculture. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.