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Review article

Extreme climate events in sub-Saharan Africa: A call for improving agricultural technology transfer to enhance adaptive capacity

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A R T I C L E I N F O

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A B S T R A C T

This study seeks to provide a critical overview of the existing evidence on extreme climate events and the adaptation options of the affected population in order to help scholars navigate the field. The study examined the recent extreme climate events that occurred in Sub-Saharan Africa (SSA), the climate change adaptation options mentioned in the literature, and the need for international technological transfer in SSA. 181 peer-reviewed publications were evaluated on the following topics: 1) the impacts of climate extremes in SSA; 2) the adaptation options discussed in the literature for the region; 3) the analysis of the needs and the gaps of the international technology transfer in SSA, and 4) the various impact areas of the technology transfer on the adaptive capacity in SSA. The major finding from this study is that the impacts of climate change have been observed in the region, with many extreme events leading to reductions in crop yield qualities and quantities, with much greater impacts on the smallholder farmers' livelihoods in SSA countries. Based on these findings climate change conceptual framework is proposed which summarises the observed impacts of climate change on agriculture and food systems in SSA countries. The study concluded that there are new adaptation options that SSA countries can adopt from developed countries, and that much greater agricultural technological transfer is needed to facilitate better adaptation to climate change in SSA.

1. Introduction

Climate change impacts are becoming more intense and frequent than ever, as the observed impacts of climate extremes on sub-Saharan Africa (SSA) have increased. This is reinforcing poverty, affecting more than 40 % of the region's 360 million people (Trisos et al., 2022). Several studies have reported severe consequences of climate extreme events on the agricultural sector, which is the main source of livelihood for many people in SSA (Ajetomobi, 2016; Ficchi et al., 2021; Fuller et al., 2018; Humphries et al., 2020; Wainwright et al., 2021b). The observed impacts of climate change on yields of most widely produced crops in sub-Saharan Africa (millet, maize, sorghum, and rice) have been reported by many studies (Amouzou et al., 2019, FAO and UNICEF, 2019, Atiah et al., 2022, Hadebe et al., 2017, Nyamekye et al., 2021, Oluwaranti et al., 2020). The observed impacts of extreme climate events have intensified in recent years, including prolonged dry spells, abnormal rainfall patterns, consequent shortage of water, and heat stress. (Chikoore and Jury, 2021, Thoithi et al., 2021, Wainwright et al., 2021a). These are not only affecting human activities but also the livelihoods of many people, with SSA being regarded as the region most vulnerable to climate change (Cuthbert et al., 2019). This is because key livelihoods depend on rainfall, as nearly 80 % of the agricultural land and crop production in this part of the world is rain-fed (Gérardeaux et al., 2018, Sarr et al., 2021). From 1970 up until recent years, nearly 14 % and 22 % of the East and West African populations respectively have been affected by extreme climate events such as windstorms, and

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multiple effects of drought including extreme temperatures (Diakite et al., 2020, Ekwezuo and Ezeh, 2020, Gebrechorkos et al., 2020). Other recent studies have established a warming trend through extreme heat events, with changes in patterns and amounts of rainfall (Ongoma et al., 2018, Rahimi et al., 2021, Marcotullio et al., 2021, Iyakaremye et al., 2022). In many SSA regions, the number of warm days and nights, the length of warm spells, and maximum temperatures have all increased considerably in comparison to the last three decades of the twentieth century (Trisos et al., 2022). It is clear from the literature that climate change is likely to have both direct and indirect impacts on the socio-economic sectors of SSA. For example, Arndt and Thurlow (2015) estimated climate change impacts on Mozambique's economy, with about 13 % reduction in GDP by 2050. Similar results were obtained in three southern African countries such as Namibia, Angola, Malawi, Mozambique, and Zambia (Arndt et al., 2019, Manuel et al., 2021, Luetkemeier and Liehr, 2019).

Recurrent climate extremes are indicators of change in the patterns, timing, and amount of precipitation, and are major drivers of vulnerability in many agro-ecological zones of SSA, as these may lead to changes in crop yields and higher food prices. Numerous impacts of climate change on agro-ecological zones in SSA have been reported in many scientific studies. Such impacts include reductions in crop yields, quality of crops (Cohn et al., 2016, Mpakairi and Muvengwi, 2019, Apraku et al., 2021), and the drying up of some streams and rivers (Payne et al., 2020, Jin et al., 2021), increases in urban temperature (Ayanlade, 2016, Ayanlade, 2017, Mpakairi and Muvengwi, 2019, Payne et al., 2020) and heat fluxes (Ayanlade and Howard, 2019, Adhikari et al., 2015), loss of pastureland (Ayanlade and Ojebisi, 2020, Thornton and Herrero, 2015); loss of vegetation and biodiversity, and destruction of wildlife ecosystems (Abrams et al., 2018, Mpakairi et al., 2020, Ayanlade et al., 2020); decreasing household incomes of farmers (Ayanlade et al., 2018a), and other societal impacts (Serdeczny et al., 2017). Agro-ecological zones in SSA are mainly determined by climatic elements that differ from one ecological system to the next. As a result, climate change has a significant impact on the region's agroecological system. Moreover, the latest Intergovernmental Panel on Climate Change (IPCC) report further stated, with high levels of confidence, that extreme weather events resulting from climate change are likely to have negative impacts on yields of major cereal crops in the SSA region (IPCC, 2021). As agricultural livelihoods in the SSA region become riskier due to extreme events, the rate of rural–urban migration may be expected to grow, adding to the already significant urbanization trend in the region (Serdeczny et al., 2017). This is because extreme events affect the rainfed agricultural systems on which the livelihoods of a large proportion of the region's population currently depend (Araro et al., 2020, Kogo et al., 2021). The mobility of people due to climate change, especially mobility to informal settlements, may expose them to a variety of risks with impacts which may be much more serious than those faced in their respective places of origin. Indirect impacts on people's mobility due to climate change are likely to amplify the overall impacts across sectors, and there is little understanding of how severe such impacts may be in the future (Adger et al., 2015). These scientific pieces of evidence suggest that climate change has not only led to shifts in average climatic conditions but also to much more frequent extreme weather events, which pose threats to agricultural production in the SSA, as well as to urban settlements (Serdeczny et al., 2017, Stuch et al., 2021, Mulungu and Ng'ombe, 2019). Managing the multiple risks of extreme climatic events and disasters in different agro-ecological zones ought to be a research priority in SSA regions, because rural farmers already facing hunger and food insecurity (Mbatha et al., 2021) will be at even greater risk. Therefore, this study reviewed recent literature on extreme climate events and climate change adaptation options, and the need for international technological transfer in sub-Saharan Africa (SSA) was examined. The study is based on the justification that climate change now presents the most serious environmental challenge in many countries in SSA. This review is centred on articles on climate change impacts and adaptation, and is based on the IPCC conceptual framework of vulnerability, exposure, and hazard in the agricultural sector. These aided the review process of this study, in explaining the spatial and temporal pattern of climate extremes and the keys risk in SSA countries.

2. Methodology

The systematic review methodology is based on three steps, namely searching, selecting and analysing scientific studies to provide evidence relating to extreme climate events, adaptation, and climate-change-related technological transfer, with a focus on the agricultural sector and food security. This method was adopted in order to minimize bias and maximize the practical relevance of the review across a broader spectrum of climate change and extreme-events implications in SSA countries, and the literature basis for the review was generated. The study followed the Preferred Reporting Items for Systematic Reviews and meta-Analyses (PRISMA) method. We started searching with the keywords "climate change", "climate extremes", and "technology transfer" in the three big databases: Web of Science (WoS), Scopus, and Google Scholar. A large number of results were identified based on the provided keywords, including substantial articles on climate change issues, including articles from other disciplines such as biology, medicine and medical technology transfer. To restrict the results, we add further keywords. In a subsequent phase of searching, we used "geographical keywords" (groups of names of regions and countries in SSA combined with OR) and "impacts keywords" (such as "climate change*" OR "climate extreme*" OR "extreme event*") and "agricultural technology transfer keywords" (such as ("techn*" AND "transfer") OR ("irrigat*" AND "improv*") AND ("food" OR "agric*"), as shown in Table 1. This resulted in 626 publications: including 359 in Web of Science, 216 in Scopus, and 51 in Google Scholar, from which the relevant studies were selected for this review.

The authors subsequently selected 209 published articles on the basis of their relevance to be the review and the time span/restriction of the study. Four articles were removed before the screening, as they overlapped between subgroups of topics, and a total of 205 were screened (Fig. 1). The 205 papers were screened to select the primary studies that were directly related to the objective of this study and its regional focus on SSA countries. During the screening process, 20 publications of

Table 1
Selection of articles and their inclusion and exclusion criteria.

Selection	Inclusion	Exclusion
Literature type	Journal (research articles) Chapters in the book	Book, book series, conference proceeding, Journals (review articles)
Spatial resolution	Sub-Saharan African. Any article relating to the objectives of this study from any country in sub-Saharan African	Location outside sub-Saharan African
Language	English	Non-English
Keywords	("climate change*" OR "climate extreme*" OR "extreme event*") AND (("techn*" AND "transfer") OR ("irrigat*" AND "improv*")) AND ("sub-Saharan Africa" OR "Angola" OR "Benin" OR " Botswana " OR " Burkina Faso " OR " Burundi " OR "South Africa" OR "Sudan" OR " Sierra Leone" OR "Senegal" OR "Gambia" OR " Cote d'Ivoire" OR "Togo" OR "Cameroon" OR "Congo" OR "Niger" OR "Gabon" OR "Zambia" OR "Namibia" OR "Mozambique" OR " Eritrea" OR "Zimbabwe" OR " Djibouti" OR "Rwanda" OR " Ghana " OR " Cape Verde" OR "Liberia" OR "Guinea" OR "Chad" OR "Somali*" OR "Nigeria" OR "Madagascar" OR " Ethiopia" OR " Guinea-Bissau " OR " Kenya" OR "Equatorial Guinea " OR " Malawi " OR " Mali " OR " Mauritania " OR " Tanzania " OR " Uganda " OR " Mauritius " OR " Sao Tome and Principe " OR " Central African Republic " OR "Seychelles" OR "Eswatini" OR " Lesotho ") AND ("food" OR "agric*")	

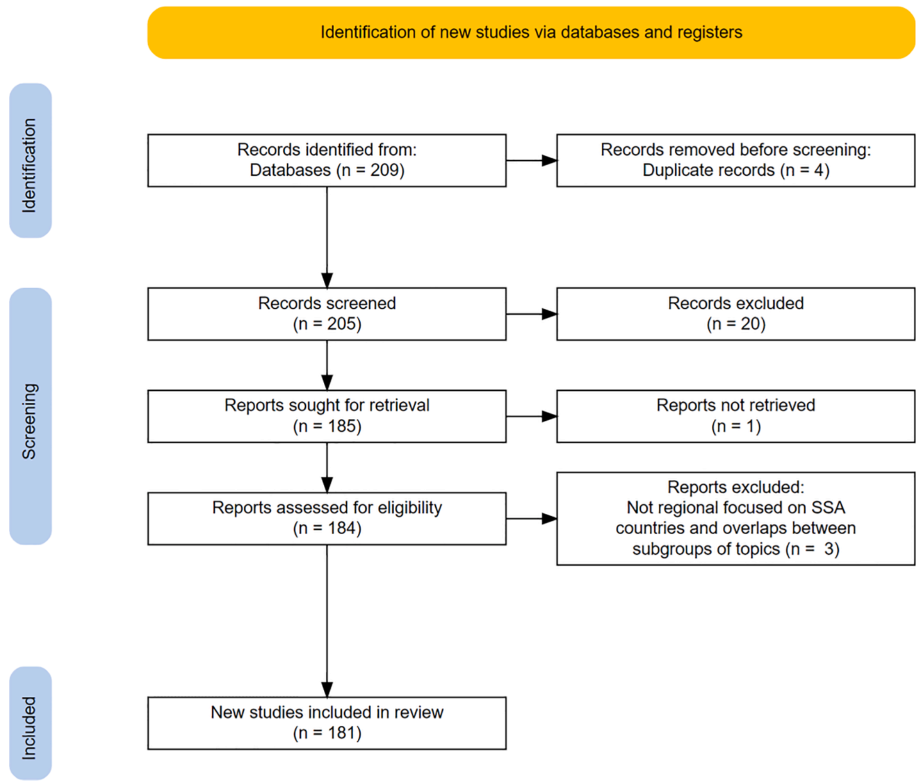

Fig. 1. The flow diagram of the study; the studies used for the systematic review process. (Developed from PRISMA 2020: https://www.prisma-statement.org/).

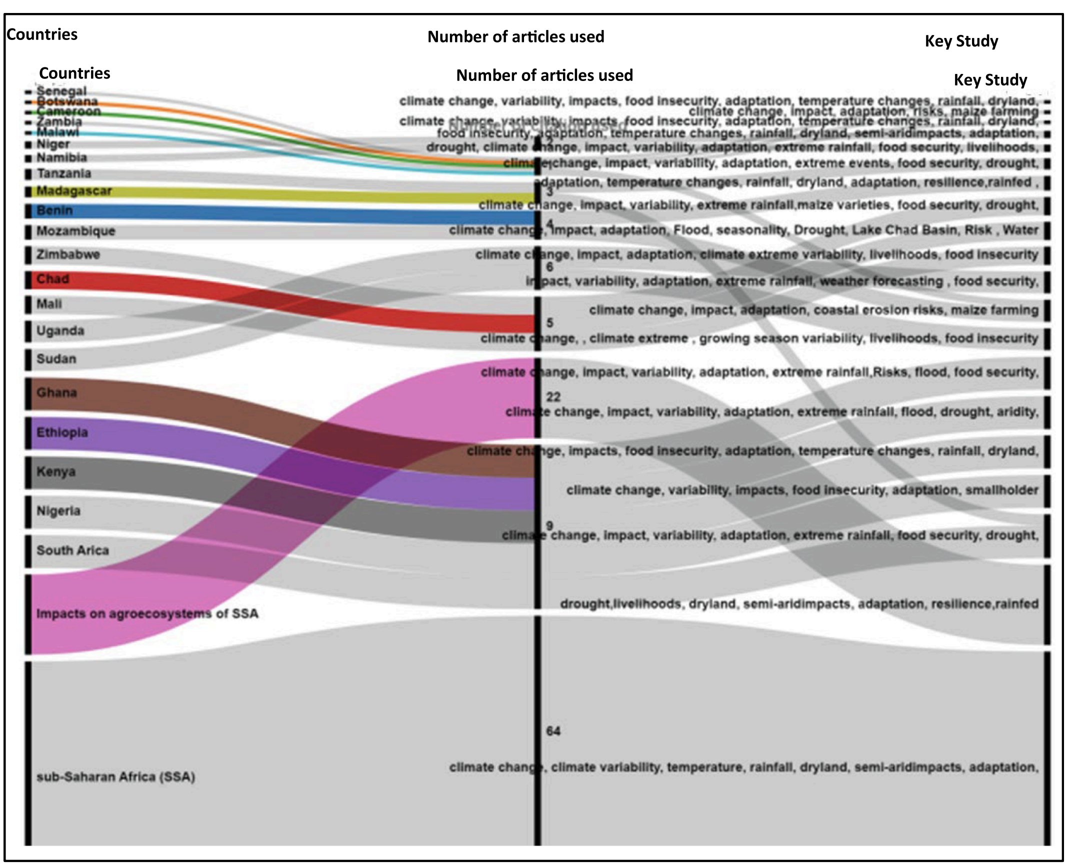

Fig. 2. Literature citation with case studies on climate extremes events in SSA.

articles were excluded as they were duplicates. The remaining 185 publications were sought for retrieval, out of which one was not retrieved. Of the remaining 184, 3 publications were excluded since they were not regionally focused on SSA countries. Thus, this study analyses the remaining 181 studies (Fig. 2). The systematic review processes are based on: (1) observed impacts of climate change on crop/livestock productivity in SSA; (2) The predicted behaviour of the climatic variables such as precipitation and temperature; (3) The implications of climate change on agro-ecosystems and livelihoods of populations in SSA (Fig. 1). In general, only literature published from 2015 to April 2022 was studied. This time frame was chosen because since 2015 there has been an increase in research output on the topic. Although some older articles and materials that were deemed important were also included, in order to explicitly highlight and supplement the literature on the impacts of climate change on the agriculture section in SSA. With these searching and selection processes (Table 1), the desired outcomes were found, since most studies focus on a single country, not on the whole SSA region (Fig. 2) and they matched the objective of this review.

3. Results

3.1. Observed indicators of climate change in SSA

There has been growing concern about climate change, and the need arises to take a critical look at the changes in the trends of climatic parameters in SSA (Pironon et al., 2019, Stuch et al., 2021). Generally, drought is one of the observed extreme weather events that affect people's livelihoods and socio-economic development in SSA (Horn and Shimelis, 2020). For example, drought disasters account for nearly 20 % of all disaster occurrences in all African regions, affecting a larger percentage of people, especially in rural communities, and contribute to malnutrition, famine and loss of livestock (Nthambi and Ijioma, 2021, Orimoloye et al., 2022, Warsame et al., 2022). Even though the occurrence and impacts of drought vary from one ecological zone of the SSA to others, a number of studies have shown that the most affected region is the Sudano-Sahelian part of SSA. Most recent studies on drought have revealed that its events and occurrence vary over different agro-ecological zones in SSA, but the Sahel and Savannah zones are highly vulnerable to severe droughts, and these have negative implications for water availability for agriculture and food security in the regions (Emmanuel, 2021, Ogolo and Matthew, 2022). It has been reported, for example, that a rainfall decrease of 29 %–49 % was observed between 1968 and 1997 compared to the 1931–1960 baseline period within the Sahel region. Prolonged declines in rainfall intensity are indicators of the droughts in many parts of SSA, the impacts of which are much more observed in the drier part of the region, where the majority are primarily

Table 2
Notable extreme climate events in sub-Saharan Africa.

Extreme events	Observed impacts	Recent patterns	Most likely affected region of SSA	References
Drought	Likely increase in agricultural drought occurrence over many regions of SSA with heat over land areas. Likelihood of associated risk of drought becoming noticeable.	Likely to increase in many countries in SSA. Drought is likely to drive agrarian crises in many SSA countries.	Sudan, Sahel, Savanna, Eastern and Southern African highlands	Elagib (2015), Dossou-Yovo et al. (2019), Ahmed (2020), Ahmadalipour et al. (2019), Anderson et al. (2021)
Prolonged dry spell	Higher maximum temperatures are becoming very likely; high likelihood of increasing number of hot days.	Very likely to be intensified in many regions of SSA. In West Africa, there is a probability that dry-spell lengths exceed the normal limit.	Sudan, Sahel, both Northern and Southern Guinea,	Bako et al. (2020), Ayanlade et al. (2018b), Ojara et al. (2020)
Extreme rainfall	Increase in tropical cyclone peak-wind intensities. Rise in the seasonal cycle of extreme rainfall	Likely to increase in many areas in SSA. Sahelian regions are highly vulnerable to extreme rainfall Events	Southern Guinea Savanna, Sahel and forest: coastal West Africa and Central Africa	Wainwright et al. (2021b), Fotso-Nguemo et al. (2019)

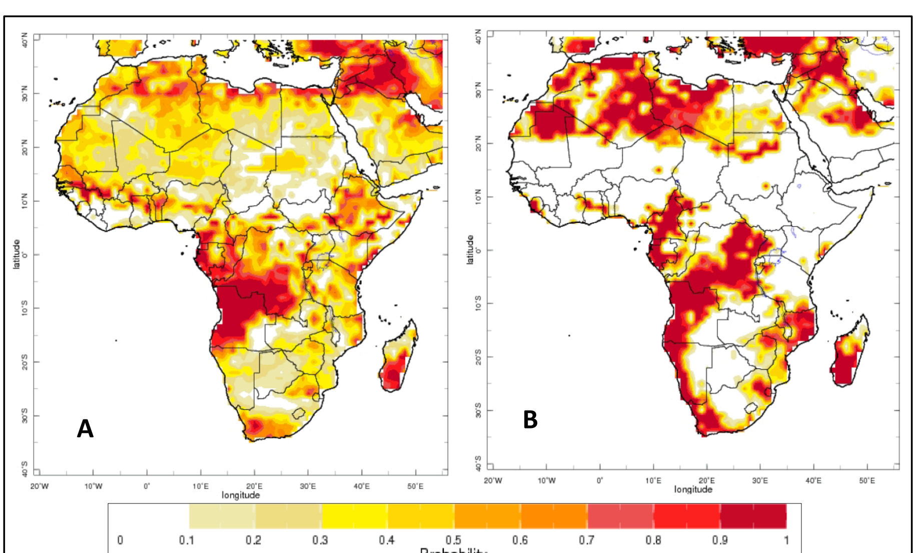

Fig. 3. Seasonal prediction of drought for SSA countries. The map shows the drought probability – on a fractional scale between 0 and 1 – the SPI in future months (A) and drought intensity (B) in long-term categories.

smallholder pastoral groups.

Increase in agricultural drought (Fig. 3B and Table 2) is likely to occur in almost all the regions of SSA, but much more so in East Africa, Central Africa and some parts of Southern Africa due to slow progress in drought-risk management. Fig. 3 presents the seasonal prediction of drought for SSA countries, using the standardized precipitation index (SPI) by International Research Institute for Climate and Society (IRI), which has worked in collaboration with the NOAA Climate Prediction Centre (CPC) to provide an accessible source of drought prediction at all regional scales. The SPI has been an effective method used for easy analysis of meteorological drought indicators. Many studies on the Sudano-Sahelian ecological zone, for example, have established that many wet regions are tending towards aridity (Jellason et al., 2021, Abrha and Hagos, 2019). Annual rainfall over the Sahel exhibited remarkable variation between 1970 and 2000 s, with a strong tendency toward drier conditions compared with earlier in the twentieth century (Biasutti, 2019). In West Africa for example, several studies have observed reductions in both annual precipitation during the last three decades. The minority of these studies concluded that recovery of precipitation in the 21st century has not been sufficient to return to pre-drought levels (Amanambu et al., 2019, Oguntunde et al., 2017, Piemontese et al., 2019). A nearly 10 % decline in mean annual rainfall has been observed in the wet tropical zone, while about a 30 % reduction was noted in Subtropical southern Africa. This has resulted in around a 40 % drop in the average discharge of major rivers in the region, leading to a sharp decrease in water availability. (Godfrey and Tunhuma, 2020, Coulibaly et al., 2018, Gebere et al., 2021).

3.2. Projected trends of precipitation, temperature and weather extremes

Future projections indicated that about 5 % to 8 % of the SSA, corresponding to nearly 60 to 90 million hectares (Trisos et al., 2022), particularly in the arid and semi-arid regions, will experience increasing drought conditions in the coming decades (Fig. 3). About 43.5 % of the agricultural land area will be characterized by dry conditions, in contrast to the world figure of 29 % (Osman, 2015). Although global climate models predict increasing temperatures and decreasing precipitation in many parts of SSA, it has been reported that the Sudano-Sahelian agro-ecological zone is already most affected by droughts, as the region is experiencing higher temperatures and lower precipitation. There are more uncertainties, though, in the spatial and temporal distribution of rainfall and surface water resources due to a significant increase in the trends of temperatures and potential evapotranspiration (Khelifa et al., 2021).

Recent projected spatial and temporal changes in precipitation and temperature will shift current agro-ecological zones (high confidence) in both East Africa and West Africa (Trisos et al., 2022, Sylla et al., 2016). Several other studies have projected an increase in temperature and warming trends, and an increasing number of extreme rainfall events in many parts of Western Africa (Bichet and Diedhiou, 2018, Akinsanola and Zhou, 2019, Salack et al., 2018). It has been projected that several million people in SSA are likely to be exposed to increased water stress due to climate change. As this is contributing to food insecurity and malnutrition, it is also likely to result in increased mobility of people in the region (Hadebe et al., 2017, Emeribe et al., 2021). Generally, recent projections have shown a decrease in precipitation frequency in many parts of SSA, especially over the West Sahel, East Africa, southern central Africa, and southern Africa, with the length of dry spells projected to increase over the Atlas region, over southern Africa, and the Ethiopian highlands (Dosio et al., 2021). Besides general increasing aridity has been projected over, central equatorial Africa with several implications on the Congo Basin's Cuvette Centrale peatlands (Dargie et al., 2019, Dosio et al., 2021, Tamoffo et al., 2022, Trisos et al., 2022). Spatial and temporal changes in the amount of rainfall have socio-economic implications which are associated with impacts on agriculture, human mobility and settlements, and water availability (Descheemaeker et al., 2016, Abrha and Hagos, 2019, Ayanlade et al., 2022). These have been projected to affect the livelihoods of many rural communities in the SSA, many of whom are already threatened with absolute poverty (Selormey et al., 2019, Ayanlade et al., 2018c).

The potential future impacts of changes in precipitation, temperature and weather extremes have been projected to include reductions in rangeland net primary production, a projected loss of between 42 % and 46 % for many SSA countries by 2050, under RCP 4.5 and RCP8.5 respectively (IPCC, 2021). There is a high probability of a pronounced decline in rainfall in southern Africa and an increase in East Africa (Serdeczny et al., 2017, Nicholson, 2017, Humphries et al., 2019, Humphries et al., 2020). The IPCC reports further revealed that by the end of this century, in a 4 °C warming scenario, Sub-Saharan African countries will face many challenges to their food systems (IPCC, 2021, Trisos et al., 2022). The future impact of climate change on SSA countries is predicted to differ by region, but the particular characteristics of the changes are yet unknown, and region-specific frequency and intensity estimates have a low degree of confidence (Trisos et al., 2022). Precisely because there are uncertainties in many modelling projections (Gummadi et al., 2018), therefore, lack of agreement among different climate models makes it difficult to project the future impacts and possible adaptation options in the SSA region (Vaghefi et al., 2019, Xiong et al., 2020). For example, the outputs from the Coupled Model Intercomparison Project (CMIP5) and Africa CORDEX models suggest that climate warming over North Africa is likely to be stronger in summer than winter, using the RCP4.5 and RCP8.5 scenarios, with an increase reaching up to 6 °C under RCP8.5 (Lelieveld et al., 2016, Dosio, 2017). The regional precipitation in the context of future climate change varies across CMIP5 models in both sign and magnitude of change, ranging from −9% to + 27 % %. There is high confidence that the yields of many rainfed crops are likely to fall sharply by up to 30 % over the next decade in many SSA countries (Fuller et al., 2018, Pickson and Boateng, 2022, Atiah et al., 2022) whilst for the majority of people living in climate-change-prone areas, there is a lack of alternative livelihoods other than engaging in farming activities.

1.3. Implications for agro-ecosystems and livelihoods: A conceptual framework

The SSA is ranked the second-most likely region in the world to be affected by the impacts of drought after Asia, with over 18 million sub-Sahara Africans being confronted with the challenge of insufficient food, with children being the group most vulnerable to hunger and malnutrition. Some crop failures have been observed in recent literature; this might lead to decreases in annual yields; reductions in the production of maize (−7%), millet (−9%), sorghum (−3%) and wheat (−12 %) have been projected for the regions (Parkes et al., 2018). The summary of the observed impacts of climate change on agriculture and food systems in SSA countries is presented in a conceptual framework (Fig. 4). This conceptual framework is centred on the IPCC conceptual framework of vulnerability, exposure, hazard and risk in the agricultural sector. The numbers in Fig. 4 denote the number of publications that addressed a certain issue, and the lengths of the bars are equivalent to these numbers. The conceptual framework was developed to classify the vulnerability, exposure, and hazard in the agricultural sector of SSA countries, as covered in the reviewed publications.

The observed changes in rainfall and temperature intensity and drought in most parts of SSA are hazards which potentially affect agricultural production (Fig. 4). Thus, drought conditions in this region are likely to be further intensified with several dry years and are likely to affect the countries in this region to repeated crises of famine and food insecurity, although there are uncertainties in rainfall projections over the Sahel (Klutse et al., 2018, IPCC, 2021, Trisos et al., 2022). The impacts of drought have been evidenced by increasing loss of cultivable land, socio-economic disparities, famine as well as limited capacity for infrastructural development (Serele et al., 2020). Studies have reported

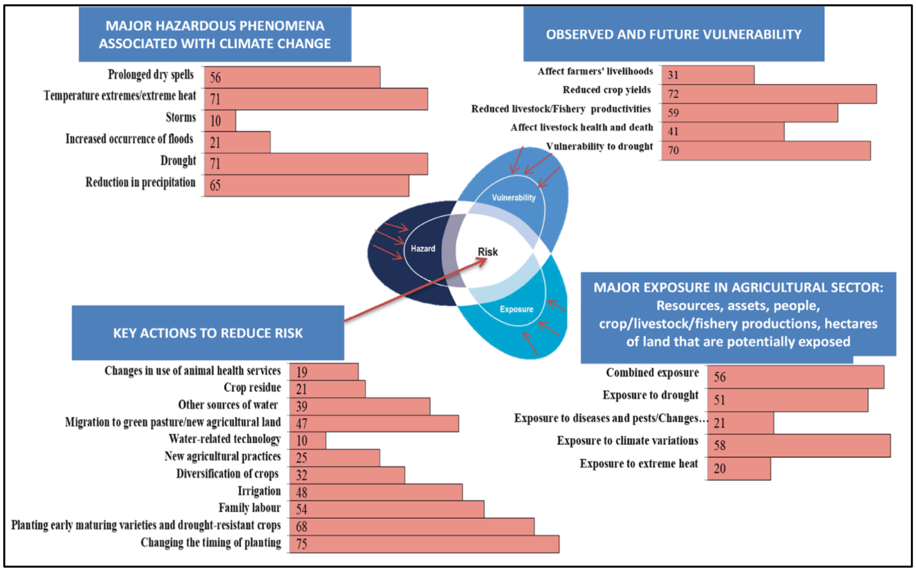

Fig. 4. Observed climate change impacts and vulnerability of agriculture and food systems in SSA countries.

that droughts have both direct and indirect consequences on human livelihoods. Crop loss and low yield for both crops and livestock are direct consequences that may lead to food insecurity and starvation, while water shortage increases the spread of disease due to lack of water for basic hygiene. (Lottering et al., 2021, Glantz, 2019, Fava and Vrieling, 2021, Hyland and Russ, 2019, Anthonj et al., 2018). In recent years, some farmers have been able to survive by selecting seed varieties based on changing conditions, but poorer farmers have not been able to adapt (Ayanlade et al., 2017).

Extreme climate events have been projected to lead to changes in various crop yields and grassland species, thus leading to a different composition of animal diets, and changing herders' capacity to manage fodder deficits, especially during prolonged dry spells and drought (Kew et al., 2021, Napogbong et al., 2021, Ayanlade and Ojebisi, 2019). Prolonged drought has also led to crop loss and the death of livestock, especially in Sudan-Sahel Zone (Ahmed, 2020, Dossou-Yovo et al., 2019), resulting in reductions in agricultural outputs and increased exposure of rural farmers, as the majority are poor and vulnerable. Reductions in agricultural outputs have triggered increases in food prices and imports, coupled with an overdependence on food aid, as well as threatened food security in the region (Ahmed, 2020, Ekpa et al., 2018). Furthermore, extreme climate events may have adverse impacts on animal health (Magiri et al., 2020) by increasing the disease burden and disease-vector capacity: rising temperatures for example contributed to the spread of tick-borne livestock diseases into high altitudes. The herders who live in remote areas with constant migration have less capacity to access veterinary services; therefore, diseases in livestock break out, increasing the mortality rate of their livestock. In addition, extreme events due to climate change may lead to a reduction in the food intake of cattle because they affect the availability of water and pasture, leading to the decline of grazing land and reduced access to water for pastoral systems (Stanzel et al., 2018, Sidibe et al., 2020) which is the major economic activity in semi-arid SSA. The majority of the pastoral people engage in transnational migration in search of water and new seasonal grazing (Bukari et al., 2019, Descheemaeker et al., 2016). In recent years, there are reported cases of conflict between pastoralists and farmers due to extreme drought conditions. Especially in West and East Africa such conflicts seem to have increased recently (Adaawen et al., 2019, Bukari et al., 2019). These may consequently affect the scale of production and diversified livestock levels (Descheemaeker et al., 2016, Rahimi et al., 2021, Bosire et al., 2022). The main findings from studies are that the multiple effects of climate change are likely to be much greater in SSA (Fig. 4), as the rainfall increases in some areas and decreases in other parts within the same region or country (Dunning et al., 2018, Barry et al., 2018, Tegegne et al., 2021, Nangombe et al., 2018).

4. Discussion

There are recent improvements in responses to the challenges of changing climate in many SSA countries. The synopses of this study are discussed in terms of three categories. (1) The response to climate change is gradually gaining momentum among people in political power, as the impacts of climate change on agriculture, water availability for humans and livestock, and the ecosystem become more evident. (2) Current and future adaptations to climate change in SSA denote all those responses that may be adopted by people to reduce risk. (3) There is a need, still, for better responses to climate change impacts in different agro-ecological zones of SSA, and the need for adaptation technology transfer is the necessary priority.

4.1. *Current and future adaptation responses: Case studies in SSA*

The necessity for adaptation to climate change and climate-related hazards has attracted the attention of researchers across different disciplines in SSA. The majority of research on climate change has focused on climate change impacts/risks and their effects on natural and human systems, mainly from a sectoral perspective (Leal Filho et al., 2021, Nyiwul, 2021, Carnohan et al., 2021, Oluwatimilehin and Ayanlade, 2021). Contemporary studies have reported that the reoccurrence of extreme events currently outweighs the adaptive options available in SSA. Many of these studies reported significant relationships between level of education, financial capabilities and incomes, and years of farming experience as the major drivers of adaptation options adopted by rural farmers in the SSA (see Table 3). These factors not only control the adoption of adaptation in agriculture but also in other sectors such as water resources and energy (Schilling et al., 2020). The major evidence from the literature is that research efforts are very much needed to develop adaptation strategies and methods that are suitable for smallholder farmers in SSA (Mashizha, 2019, Ayanlade et al., 2017), particularly in the dry zone where livestock are the predominant basis of livelihood. To achieve sustainable growth in the agricultural sector, concentrated efforts are essential to mainstream climate change adaptation into national development policies and ensure that they are

Table 3
Major determinants of adoption of climate change adaptation options in SSA, using IPCC conceptual framework of vulnerability, exposure, hazard and risk in the agricultural sector. The different colours denote percentage of use of adaptation methods and major factors determining the adoption of adaptation methods in SSA, with confidence level based on IPCC 2022 report (Trisos et al., 2022).

Observed adaptation Options	Type of agricultural system		Most common determinant of adoption of climate change Adaptation option			References
	Crop	Livestock	INC	EDU	YFE	
Migration to green pasture/new agricultural land	**	****	***	**	****	Hassen et al. (2017), Bukari et al. (2019), Ayanlade and Ojebisi (2020)
Family labour	****	*	****	*	**	Ayanlade et al. (2017), Godde et al. (2021), Ayanlade and Ojebisi (2020)
Changes in use of animal-health services		*	**		****	Magiri et al. (2020),
Other sources of water	***	****	****	***	**	Cuthbert et al. (2019), Ayanlade et al. (2018a), Schilling et al. (2020)
Crop residue	*	**	***	**	****	Serdeczny et al. (2017)
Planting tolerant and drought-resistant crops	****		****	***	*	Hummel et al. (2018), Horn and Shimelis (2020), Oluwaranti et al. (2020)
New planting pattern	***		*	****	***	Akinseye et al. (2016), Nyagumbo et al. (2017), Mugiyo et al. (2021)
Water-related technology	***	**	**	***	****	Olawuyi (2018), Ayanlade et al. (2018a),
Irrigation	****		****	***	***	Ahmed (2020), (Mashizha, 2019), Higginbottom et al. (2021)
New agricultural practices	****	*	****	**	***	Thornton and Herrero (2015), Nyagumbo et al. (2017)

Confidence Level: Very high ****; High ***; Medium **; Low *

EDU = Level of Education; INC = Income; YFE = Years of farming experience

Adoption determinants	Low	Moderate	High	Very high
	10-40%	41-60%	61-70%	>70%

Use of adaptation option in crop and livestock system	Not Use	Percentage of use			
		10-40%	41-60%	61-70%	>70%

implemented at national, regional and local levels.

In SSA, the seasonal calendar of crop systems depends on many factors, of which the climatic dynamic is the most important for identifying appropriate sowing and harvesting dates (Mugiyo et al., 2021). Farmers have experienced a long period of adjustment to farm-management practices, including changing cropping calendars to optimize the use of available water for crop growth as well as adaptation measures to climate changes, especially increasing temperatures (Mugiyo et al., 2021). Using seasonal climate forecasts farmers in many parts of SSA could adjust their seasonal calendar to suit these changes. Changes in the seasonal calendar take account of some seasonal farming operations such as planting and harvesting time (Table 3). Arranging the seasonal calendar and crop-planting dates for better crop productivity based on information from the climate-warning system is a pressing necessity for SSA. Several climate-warning systems have been developed and used across the whole of Africa for 30 years, but linking traditional and local knowledge of climate change is crucial to maximizing optimal conditions, especially temperature and precipitation, for crop and livestock production. However, there are gaps between the information needed by farmers and that provided by the meteorological service (Nyamekye et al., 2021, Kuhl, 2021). Though various adaptation options are currently feasible in SSA to reduce climate change impacts on agricultural systems, several of the available options need significant institutional support. There is a need for policies and programmes appraisal of adaptation options in SSA, and such policies should use inclusive rights-based approaches to help to minimize maladaptation (Kuhl, 2021, Simpson et al., 2021).

4.2. A call for technological transfer – From developed nations to SSA

In recent years, many innovative climate-modelling tools and technologies have emerged, especially in developed countries. Many technological approaches, including Global Climate Modeling (GCM) and regional climate modelling tools, have been adopted in SSA countries (Kisembe et al., 2019, Shen et al., 2018, Dosio et al., 2021). Such international diffusion of technologies also includes the transfer of climate change adaptation technologies from the North to the Southern part of the globe, especially to the SSA countries. Technology transfers, North-to-South, are of particular interest in climate change discourse, as their promotion encompasses extensive policy and economic challenges because of the reluctance of industrialized countries to give away strategic intellectual assets and the difficulties developing countries may face in bearing the financial costs of developing technologies on their own (Dechezleprêtre et al., 2020). The review of the literature revealed differences in adaptation-technology options between developed nations and SSA, implying that technology transfer is required to overcome climate-related technology gaps in SSA (Olawuyi, 2018, Makate et al., 2019). This is because the developed countries have access to more sophisticated technology, while the developing countries are more vulnerable to climate change.

Despite the need for more technology transfer to SSA, the way forward should not only include policy prescriptions by African leaders; SSA countries can also proactively address current technology gaps by strengthening their domestic capacities to integrate foreign climate-related technologies (Olawuyi, 2018). The high rate of poverty in the SSA countries acts as a catalyst to increase vulnerability to climate change and the inability to generate adaptation strategies. Recently, the need for adaptation has been given more extensive recognition and has gained importance in the sixth assessment report of the IPCC (2021), in which the need for technological transfer has also been explained. Although agricultural innovation systems are spread across Africa, the IPCC report concluded that there are many more climate change adaptation options which SSA countries can adopt from developed countries, and much more work is needed with regard to technological transfer for better adaptation to climate change in SSA. Such innovation systems should include sets of actors, institutions and skills that function and interact to create conditions and mediums for innovative social, environmental and economic solutions (technologies, ideas etc.) to emerge and successfully thrive in a climate change context (Adenuga et al., 2021, Ekpa et al., 2018, Zhou, 2019).

In this study, we argue that technology transfer should entail more than just the transfer of equipment and machinery; it also requires the transfer of knowledge and skills and the development of the capacity to use and adapt the technology. Some international initiatives aim to support climate change adaptation through sustainable climate-related technology transfer in SSA. The majority of these initiatives focused on solar energy, wind energy, and bio-fuel technology. Only a few are used in agricultural and food systems technology in SSA, thus much more technology-transfer initiatives are needed in the agricultural sector. For example, Renewable Energy and Adapting to Climate Technologies Window in Africa (REACT) is one of the EU-supported projects that seek to alleviate the burden of climate change in Africa through climate-change-related technology. But REACT is part of the Africa Enterprise Challenge Fund, which funds mostly clean energy and climate-adaptation technologies through the stimulation of private-sector investments. While the focus is not solely on the agricultural sector, the fund specifically aims to support small-scale farmers with new technology in the agricultural sector. Another stakeholder in the area of climate-related technology transfer in SSA is the African Development Bank (ADB). One of ADB's projects enhances fertilizer accessibility in Tanzania. This initiative by ADB uses a credit guarantee scheme to provide farmers with access to quality fertilizer and other agricultural technologies.

In the past decades, farmers in Africa have been adopting adaptation strategies such as irrigating with traditional technologies, but what they need now is to improve water efficiency. For example, farmers in the arid region of SSA urgently need techniques, technologies and investments that will increase water-management efficiency and access to irrigation, or find ways to increase their incomes in the face of less secure and more variable water availability. This is because Africa only irrigates 6 % (13.6 million hectares) of its arable land, in contrast to 20 % worldwide (Trisos et al., 2022). Water availability is projected to decline steeply given the rate of population growth in the next several decades across Eat Africa, Central and southern Africa (Mashizha, 2019, Godfrey and Tunhuma, 2020, Trisos et al., 2022). Thus, studies have reported that irrigation expansion through efficient water-resource management is a key ingredient for reaching the agricultural growth targets of many SSA countries (Ahmed, 2020, Mashizha, 2019, Higginbottom et al., 2021). Improved irrigated production can buffer the impacts of drought and lead to enhanced crop production (Higginbottom et al., 2021). These kinds of coping strategies should be determined by the rural farmers' preferences and what best suits the rural farming communities. Despite these efforts, the need for improvement in various aspects of climate action in SSA should be a priority deliberation, to aid strong technological innovations, institutional innovations and policy innovations for successful climate action for better agricultural production (Higginbottom et al., 2021, Ahmed, 2020, Stenzel et al., 2021).

5. Conclusion

The key findings from the literature reviewed in this study are that extreme weather events resulting from climate change have a direct impact on agricultural production (Mashizha, 2019), because of the climate-dependent nature of agricultural systems. Agriculture is the major occupation in SSA countries; this makes them more vulnerable to climate change, especially so with regard to the livelihoods of both farmers and herders (Apraku et al., 2021, Eleblu et al., 2020). The impacts of drought are particularly significant in many SSA countries, where agriculture constitutes employment and the main source of income for the majority of the population. Extreme events pose a danger to people's lives, livestock and the ecosystem. Such events may perhaps trigger more of the already high rates of under-nutrition and infectious disease in the region. Assessment of relevant literature and climate change projections for SSA countries points to warmer temperature trends with frequent occurrence of extreme heat events, decline in rainfall, and increased aridity in the southern and eastern regions. A reduction of land suitable for agriculture has been projected in the next few decades, as many lands with high agricultural potential in SSA are becoming arid. Extreme events have been predicted to occur more often in Africa in the next century as a result of climate change. Drought is a major extreme weather event which threatens livestock sustainability in SSA, as climate determines the composition of pasture which in turn determines the level of fodder self-sufficiency and its sustainability. What is obvious from the literature is that the analysis of climate extremes such as drought is complex and is affected strongly by the balance between precipitation and evapotranspiration and the concomitant effect on soil moisture. The regional drought record has been observed to be driven by increased temperatures combined with low precipitation and reduced soil moisture. Studies have reported the impacts of drought on both crop and livestock production in many parts of SSA. The majority of these studies have noted ways by which extreme climatic events can affect agricultural productivity, but patterns of vulnerability, exposure, hazard and risk vary among countries and within different agro-ecological zones of SSA. With the increase in temperature and precipitation erratically distributed across sub-Saharan Africa, agricultural production has been declining within recent decades, particularly wherever drought events are frequent. There is a high likelihood that the hydro-climatological patterns of different ecological zones in SSA would be altered as a result of climate change, with consequences for the availability of water resources for the agricultural sector (The Ministry of Environment of the Federal Republic of Nigeria, 2003). All of these combine to affect water resources, including groundwater and surface water, in specific ways (Carrière et al., 2021, Ayanlade et al., 2022). It is clear from the present study that SSA is one of the most vulnerable regions to extreme climate events, as the livelihoods of the majority of the population depend on rainfed agriculture, yet many smallholder farmers lack adequate technology to adapt to extreme climate events. Thus, the vulnerability of SSA countries to climate change is high, because of their low capacity to adapt to climate change. Adaptive capacities of farmers to climatic change are higher in the developed countries than the developing countries because of their access to more technology. There is a need for effective technology transfer from the Global North to the South, to encourage building resilience and enhance adaptive capacity in SSA countries.

Technological transfer is a fundamental process to facilitate access to adaptation and mitigation technologies in SSA. The distribution of these technologies from Global North to South will be necessary for the mitigation of and adaptation to climate change. Climate-change-related technology should be made available to developing countries through technological transfer guided by patents and licensing (Zhou, 2019, Olawuyi, 2018). Such technology transfer from developed countries to SSA countries is vital for the attainment of sustainable development in the latter. There is an urgent need for policy interventions to increase the adaptive capacities of the farmers and herders (Cuni-Sanchez et al., 2018). Another approach that can be recommended for decision-makers and partners to adopt as policy strategy is "putting the vulnerable first". This has to do with recognition of the need for adaptation that is mostly embraced by and acceptable to the present impact-driven sectorial adaptation that research and programmes presently support. Most importantly, this idea of "putting the small holder farmers' vulnerable first" demands a much stronger focus on resilience and adaptive capacity as well as ability.

Declaration of Competing Interest

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.

Data availability

Data will be made available on request.

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Author contributions

A.A., A.O., and O.S.A. conceived and designed the study. A.A., M.B., P.S., and H.S, contributed to methods development, conducted the analysis and interpretation. O.S.A., M.O.J., L.F.W. and A.F.O.A. contributed to data/literature collection, and the manuscript preparation. All authors contributed to the manuscript preparation and write-up.

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