Discover Water

Review

Water management for rice production: a key component of food security in East Africa

Denis Bwire[1,3] · Hirotaka Saito[1] · Roy C. Sidle[2] · Moses Mugisha[3]

Received: 26 August 2024 / Accepted: 29 January 2025
Published online: 01 February 2025

Abstract

Water is a valuable resource for rice production, which is an integral component of food security in East Africa (EA). Rice farming is expanding in the region, with up to 90% produced on smallholder farms using traditional flooding and rain-fed methods, vulnerable to climate change and variability. Despite EA's enormous agricultural and crop potential, the region largely depends on rice imports (> 500,000 tons annually) from Asia due to rising gaps between production and consumption. Sustainable water management practices, including alternate wetting and drying (AWD), system of rice intensification (SRI), and drip irrigation are critical for paddy and upland rice production although practiced at micro-research levels with limited adoption of such technologies by smallholder farmers. Herein, we synthesize key information on smallholder irrigation agriculture development and implications for food security in changing climates in the four EA countries (Uganda, Kenya, Tanzania and Ethiopia), based on scientific literature and reports. Several studies indicate water scarcity is a major threat to rice production, while poverty and food insecurity are linked to low agricultural productivity. Although rice production has increased since 2000 because of the slight expansion of irrigation, yields are still low due to insufficient irrigation development, climate change, and variability and poor agronomic practices. Nonetheless, climate-smart water management technologies such as AWD, SRI, and drip irrigation are less used by paddy and upland rice smallholder farmers for several reasons including limited awareness, funding, and technical knowledge. Therefore, commitments of government sectors, NGOs, farmer-based organizations, and private sectors with clear policies are needed to enhance technology transfer, action research, farmer training, and innovation development. These actions are vital to promote knowledge generation and the adoption of technologies to improve water management for increased rice yields, livelihoods, and food security in changing climates.

Article highlights

1. Water management is vital for rice farming in East Africa to boost food security, given the rising water scarcity with climate change.
2. Drip irrigation, SRI and AWD practices for rice farming improve water use efficiency, yields, and resilience to drought.
3. Policies that promote such climate-smart technologies boost rice production and support food security.

Keywords Rice Farming · Water Scarcity · Climate change · Irrigation technologies · Climate-smart agriculture

✉ Denis Bwire, bwiredenis@gmail.com; Hirotaka Saito, hiros@cc.tuat.ac.jp; Roy C. Sidle, roy.sidle@ucentralasia.org; Moses Mugisha, mugimoss@gmail.com | [1]United Graduate School of Agricultural Sciences, Tokyo University of Agriculture and Technology, 3-8-1, Harumicho, Fuchu, Tokyo 183-8538, Japan. [2]Mountain Societies Research Institute, University of Central Asia, 125/1 Toktogul Street, Bishkek, Kyrgyzstan 720001. [3]Department of Water Resources Engineering, Busitema University, P. O Box. 236, Tororo, Uganda.

1 Introduction

The concept of water as a natural resource is an essential component of agricultural crop production and food security at the global scale [1]. Water can be a matter of life and death depending on how it is managed as well as an instrument for economic growth, poverty alleviation, and increased crop production [2]. While food security can be defined as food availability to meet one's nutritional requirements [3], broadly it represents whether the population has the monetary and non-monetary resources to allow everyone access to adequate quantities and quality of food [4]. Globally, the role of water in ensuring food security and well-being is underappreciated, while food security remains a crucial component of Sustainable Development Goals and government policies in East Africa (EA). Additionally, water scarcity is becoming a global concern and the number of people living in areas with insufficient water is increasing in the developed, developing, and underdeveloped parts of the world [5]. In EA, these water shortages are negatively impacting agricultural crop production with many households unable to produce or buy sufficient nutritious food.

EA is an underprivileged region vulnerable to climate change with about 80% of the population living in rural areas. The effects of climate change, ranging from extreme weather events to long-term sea level rise, impact rural and urban areas alike [6]. One farmer's excessive rainfall upstream can be another's devastating urban flood downstream. Water is the great connector between climate impacts and wider efforts to reduce vulnerability, increase irrigation acreage and crop production, and accelerate poverty reduction. Agriculture, mainly rain-fed, is the backbone of most EA economies, contributing to livelihoods and food security for most of the population [7] with climatic conditions favoring the cultivation of diverse and high-value crops. High value crop production depends on water from rainfall or poorly managed irrigation systems. These crops can be categorized into six groups [8]: (a) 'paddy rice'; (b) other cereals such as wheat and maize ('cereals'); (c) cash crops such as sugarcane and cotton ('sugar/cotton'); (d) perennial tree crops ('Orchards); (e) 'vegetables'; and (f) 'fodder'. Rice, maize, and vegetables are widely cultivated crops for food and income, as they have high market potential in the region. Maize is the staple food crop in Africa, however rice is emerging among the fast-growing food crops in the continent [9], although there are problems with pathogens and pests on major food crops in the region [10]. However, water crises and scarcity, land degradation, and climate change now pose additional threats to agriculture.

Enhancing food security and reducing rural poverty in EA has been a long-awaited goal of the Green Revolution [11]. Recently, there have been signs that an African Green Revolution has begun [12]. Three technological bases are essential to make the EA Green Revolution possible in the 21st Century, i.e., high-yielding varieties, chemical fertilizers, and irrigation [12]. Additionally, water resources and irrigation development are essential technological foundations to achieving food security in EA. Reliable water supplies are prerequisite for effective fertilizer application without which high-yielding potential seeds cannot be fully exploited. In the same context, water resource development, large or small irrigation schemes, and water management in the region have always been owned by government, farmer-led, or private sector organizations. Irrigation schemes were introduced in EA by colonial governments primarily to support export crop production. However, after independence, governments in EA have continued to develop irrigation schemes through donor funding [13]. The development and management of these schemes are driven by government political and social objectives, not well aligned with farmer interests even though much of the irrigated and rainfed agriculture in EA is conducted by smallholder farmers. Subsistence farming is characterized by rainfed smallholder agriculture; nearly all the crop cultivation is practiced and maintained by the farmer and immediate family, mainly for home consumption.

Despite the rich endowment of freshwater resources, the irrigation sector remains poorly developed [14]. Additionally, large irrigation schemes in EA have failed to deliver as expected. An assessment of the performance of 79 irrigation schemes in Africa indicated that these consistently underperform [15]. The development of water resources, rice production, and water management is still low in EA due to several factors, including poor land consolidation, limited technical skills, high initial costs, weak institutional infrastructure, poor government policies, and poor access to profitable markets [16]. Lately, the frequency and intensity of climatic events such as droughts, heavy rainstorms and floods have intensified. Drought is the major contributor to water scarcity posing threats to livelihoods, crops, changes in traditional seasons, and degrading the natural environment [17, 18]. Furthermore, coastal regions of Kenya, Tanzania, and east-central Ethiopia are experiencing long-lasting droughts [19].

As a result of these climatic events, EA has continued to experience a vicious cycle of hunger and malnutrition, mostly in rural areas. With the steady population increase and industrial development in the region, most people, especially youth, are now shifting to urban areas in search of new opportunities, thus affecting agriculture production. With the current climatic changes, increasing population, industrial development, and demands for food and water remain core issues that cannot be tackled via a narrow sectoral approach. Therefore, water resources for rice cultivation must be effectively managed to improve productivity and food security through climate-smart agricultural (CSA) technologies. Some of these technologies are being employed, including rainwater harvesting, improved rice varieties, training initiatives, and rehabilitation of irrigation schemes to enhance rice production [20]. Additionally drip irrigation, alternate wetting and drying (AWD), and system of rice intensification (SRI) are being introduced and practiced at the micro-research level representing promising initiatives for improving yields, however, farmers in EA have little knowledge of these technologies [21, 22]. Although some of these CSA technologies are becoming recognized as sustainable water management solutions in paddy fields with climate change, their promotion and adoption in EA is still low, leaving smallholder farmers exposed to adverse effects of climate change [23].

Few reviews exist that assess water management for rice production as a key component of food security in EA. Current research and reports on this topic are of limited scope in the four selected vulnerable EA countries (Uganda, Kenya, Tanzania, and Ethiopia) comprising the major rice producers in EA. Thus, to improve rice production for food security, our review aims to: (i) compile information on the climate of EA and smallholder irrigation agriculture development with emphasis on rice production systems, water polices, food security and food security strategies; (ii) present implications of climate change (drought and rainfall variability) on food security; (iii) highlight the existing climate-smart water management practices for rice production and explain why drip irrigation, SRI and AWD technologies are less practiced by farmers for rice (upland and paddy) production in EA; and (iv) discuss future trajectories of water and rice production to enhance water management and build stable food security in the region. Therefore, this paper lays a foundation for planning and promoting climate-smart water management technologies and rice production that highly depend on farmer acceptance and appropriate policies to enhance the adoption of these technologies.

2 Background and climate of East Africa

For a long time, Uganda, Tanzania, and Kenya were referred to as EA, including recent reference to these nations based on climate [24]. Similarly, other authors have used the terminology "Greater Horn of Africa" (GHA) in a broader analysis of other sectors [25]. Currently, EA primarily comprises the following countries: Kenya, Uganda, Tanzania, Ethiopia, Eritrea, Djibouti, Somalia, South Sudan, Rwanda, and Burundi. In our review, we consider four major EA nations – Uganda, Kenya, Tanzania, and Ethiopia – because they are the major rice producers in the region (Fig. 1). These four countries occupy a total area of 2.88 million ha with 0.241, 0.583, 0.945, and 1.112 million ha, respectively, in rice production.

East Africa lies within the tropical latitudes and climate varies from arid in the east to more humid conditions in the west. The distinction of climatic types is essential because most EA countries experience two rainfall seasons between March to May and September–November. Several factors influence rainfall and climate, including altitude, proximity to

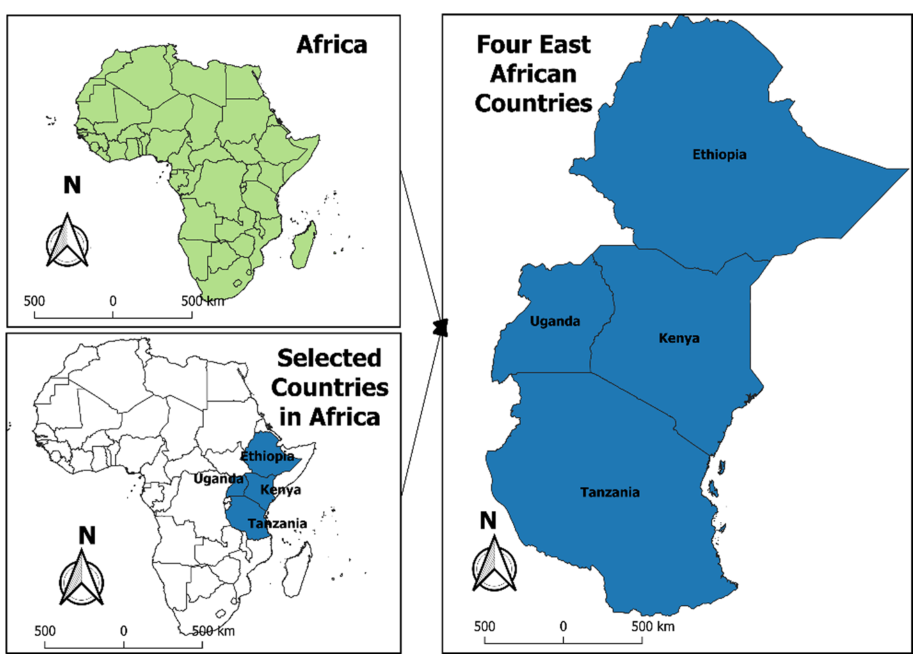

Fig. 1 Map of the four East African countries: Uganda, Kenya, Tanzania, and Ethiopia

the warm Indian Ocean, Inter-Tropical Convergence Zone (ITCZ) migration, and location of dominant atmospheric high- and low-pressure systems [26]. Climate types are described as: 1) equatorial lying 5°N and 5°S of the equator; 2) moist tropical/modified equatorial in central and western Uganda and parts of northern Uganda [24]; 3) dry tropical in several parts of EA, e.g., semiarid regions in west Karamoja, southern Nyika plateau, and parts of western Tanzania; 4) semiarid and arid in northern Kenya, e.g. the Chalbi desert, northeastern Uganda; 5) montane/alpine proximate to mountain peaks of EA; and 6) tropical monsoon in coastal regions of EA. Additionally, the equator passes through Uganda and Kenya. Regions closer to the equator typically have two rainy seasons with rainfall peaks around April and October, particularly punctuated in the most arid areas [26].

2.1 Smallholder agricultural development in East Africa

Traditional smallholder agriculture in EA is mainly rain-fed with low yields and susceptible to climate change. This has affected small-scale farmers that contribute to up to 90% of agricultural production [27, 28], rendering them vulnerable to a vicious cycle of poverty and food insecurity [29]. Nevertheless, agriculture remains the main contributor to employment; a driver of economic growth, poverty reduction, and food security; and accounts for 25–35% of GDP among the four EA nations. However, the agriculture share of EA's GDP has declined drastically since 1980 [30] from 47.2% to nearly 25% in 2001, although it is currently fluctuating within the region. Nevertheless, agriculture still accounts for about 75% of the labor force in all countries underscoring its importance in job creation and poverty reduction [27]. Given these statistics, the obvious question is, why does the region remain in this state of low production and poverty?

To describe the smallholder agriculture sector, one needs to understand who the smallholder farmer is. Smallholder agriculture generally refers to rural producers, mostly in developing countries, who mainly rely on family labor within the farm as the primary source of income [31]. However, the definitions to scale are relative to regional and national contexts, and "smallholders" in developed countries may have farms (and incomes) many times larger than those in developing countries [32].

One of the challenges limiting smallholder rice farming is low productivity emerging from limited knowledge, access to markets, credit, and technology [27]. Recently, these externalities have been affected by volatile food and energy prices and the global financial crisis. In addition, rain-fed agricultural systems remain increasingly vulnerable to climate change disruptions, especially in EA of the Sub-Saharan region, where only 6% or less of agricultural lands are irrigated [31]. The major crops include cereals and grains (e.g., maize, rice, sorghum, finger millet), root crops, banana, tea, pyrethrum, sisal, cut flowers, coffee, cotton, and tobacco. Coffee, cotton, horticulture products, and tea are the main export crops. Despite the significant potential to enhance agricultural production, the role of smallholder agriculture in food security and support of smallholder farmers to increase crop productivity amidst climate change remain major obstacles. These require knowledge and technology transfer, training, and access to agricultural inputs, but also strengthening policies that enhance access to both input and output markets [27].

2.2 Irrigation development and rice production in East Africa

Supplemental irrigation during dry periods for crop production has been used in EA. For example, spate irrigation in Kenya has been practiced for more than 500 years along River Tana and in Marakwet, Keiyo, West Pokot, and Baringo districts [34, 35]. Rice was irrigated along river valleys around Kipini, Malindi, Shimoni and Vanga in the early 19th Century. During the construction of the Kenya-Uganda railway, some irrigation activities were undertaken by Asian rail workers between 1901 and 1905 near Kibwezi and Makindu [34, 35]. In the 1930s, crop production commenced in some swampy areas in central Kenya and cash crops such as coffee, pineapple, sisal, and lucerne were introduced. This foresaw the development of public irrigation schemes under government control, including in Mwea, Hola, Perkerra, Yatta and Ishiara in Kenya [34].

Similarly, smallholder irrigation in Uganda is believed to have started in the early 1900s from Acholi, northern Uganda, where water divisions from rivers and streams were stored in trenches and applied to crops when needed [36]. Rice planting in swampy areas started in eastern Uganda before World War II, while swamp reclamation commenced in 1943 in Kigezi, southwestern Uganda [37]. The establishment of public irrigation schemes began in 1948 when diversion structures and bunds for spate irrigation, river diversions, small dams, tanks, and windmills were constructed in northeast Uganda [31]. Additionally, the development of larger government irrigation schemes, such as the Odina, Kiige, Labori, Ongom, and Atera schemes started in the 1960s. Furthermore, several public and private smallholder schemes, such as Kakira sugar estate, Olweny, Kibimba, Doho, and Agoro, were established. Recently, the Ugandan government has embarked on rehabilitation of irrigation schemes (e.g., Agoro and Olweny) to increase rice production and support the growing population [38]. Various crops are grown in these schemes using border, furrow, or sprinkler irrigation systems. Rehabilitation works were completed in 2013 in Mobuku, Doho, and Agoro public schemes [39].

Traditional irrigation systems are said to have been practiced in Tanzania hundreds of years ago characterized by temporary diversion weirs and natural canals to control water flow. The weirs washed away during heavy rains and were reconstructed after each rainy season causing extensive water losses from canals [40]. Traditional irrigation practices were mainly furrow and flood irrigation in semiarid parts of Tanzania in the 1920s [41]. However, in 1948, the Kilangali rice irrigation scheme (1000 ha) was established by the government in Morogoro Region, and more farmer-managed traditional smallholder schemes were established in the 1950s. Most irrigated areas and schemes in Tanzania use surface water; only 0.2% of irrigated areas use groundwater [42].

Evidence of past irrigation practices in Ethiopia is scarce. Formal irrigation on private farms using river diversions or motorized pumps in the Upper Awash valley is believed to have commenced in the 1950s to produce vegetables, horticultural crops, cotton, and sugarcane. This expanded to other parts of the Rift Valley region in the 1960s [43]. In the 1970s the Ethiopian government embarked on developing modern communal schemes using the diversion of streams and rivers with some employing micro-dams for water storage. Most irrigation in Ethiopia occurs in the Rift Valley, especially the Awash basin; by 2001, 62% of Ethiopia's irrigated area was in the Rift Valley region, with 39% in the Awash basin [44]. Most of the irrigation in Ethiopia uses surface water transported to fields by gravity for application via furrow irrigation, similar to other EA nations.

As a vital and increasingly popular crop in EA, rice is primarily grown by smallholder farmers using simple technologies on small landholdings (average of 2 ha). Three rice ecosystem production schemes exist: (i) rain-fed lowland; (ii) irrigated low land/paddy; and (iii) upland production systems; most are rainfed, although drip irrigation is used at the micro-research scale in Uganda [22, 45]. While agricultural development in EA is predominantly smallholder, paddy and upland rice farming is expanding and the region has significantly increased rice production area and productivity in the past 20 years (Fig. 2) with most of the production in paddy. EA has abundant croplands and irrigation potential for expansion of rice production with Tanzania, the leader of rice area and production with > 1.5 million ha and 4.5 million tons of rice yield in 2020, > 85% of the total area and yields of the other three EA nations combined. The high production and development of the rice sub-sector in Tanzania is attributed to numerous factors including the availability of suitable land for rice cultivation (21 million ha, half of all arable land); sufficient freshwater resources to support irrigation development; and increasing population and urbanization increasing food demand at local and regional levels [46]. Furthermore, EA has contributed > 10% of Africa's total rice production in the last five years (Fig. 2). The introduction and expansion of rice production in suitable areas is among the options to achieve food security and self-sufficiency within the region. Despite the growing agricultural cropland and irrigation potential in the region, agriculture crop production is still low and food insecurity persists. Low crop production is attributed to several factors including climate change (e.g., droughts and rainfall variability) and limited knowledge related to climate change adaptation [18].

2.3 Characteristics of rice production systems

Rice cultivation was introduced in EA by traders from Arabia and India approximately 2000 years ago. Crop production, especially paddy, has long been practiced in wetlands. Wetland farming in inland valleys has increased recently compared to farms in floodplains [47]. Swamps in EA highlands have been used for agricultural purposes [48], but their use increased dramatically after 2000 [49]. Additionally, small wetlands in Kenya and Tanzania cover about 12 million ha and are increasingly being converted for agricultural production and settlement [50]. Similar practices are occurring in other EA countries, such as Uganda, although there are limited guidelines for future protection or use, requiring systematic classification and characterization of wetlands. Most land units within EA wetlands are comprised of highlands and lowlands in semiarid, sub-humid, and humid zones, and occur on diverse base rock materials [50]. Although developing irrigation and drainage in upland and lowland areas increases local food production and enhances rural income, it threatens vulnerable wetlands and the ecosystem services they provide to local inhabitants [51].

Many EA countries are becoming increasingly dependent on rice imports due to the recent rising gap between production and consumption [52]. Farmers cultivate various rice varieties, such as Nerica4, Supa, Kaiso, Nerica 1&10, Sindano, and Superica in Uganda, and Nerica A-6, NericaA-15, Hibire (IRGA370-38–1-1F-B1-1), and Hiddesa in Ethiopia [53]. Two prominent varieties are grown in Uganda (Nerica 4 for upland and Supa for lowland); in Kenya the main varieties are: MWUR 4, Dourado precoce, NERICA 4, NERICA 1, NERICA 10, NERICA 11, and NERICA 2 [54].

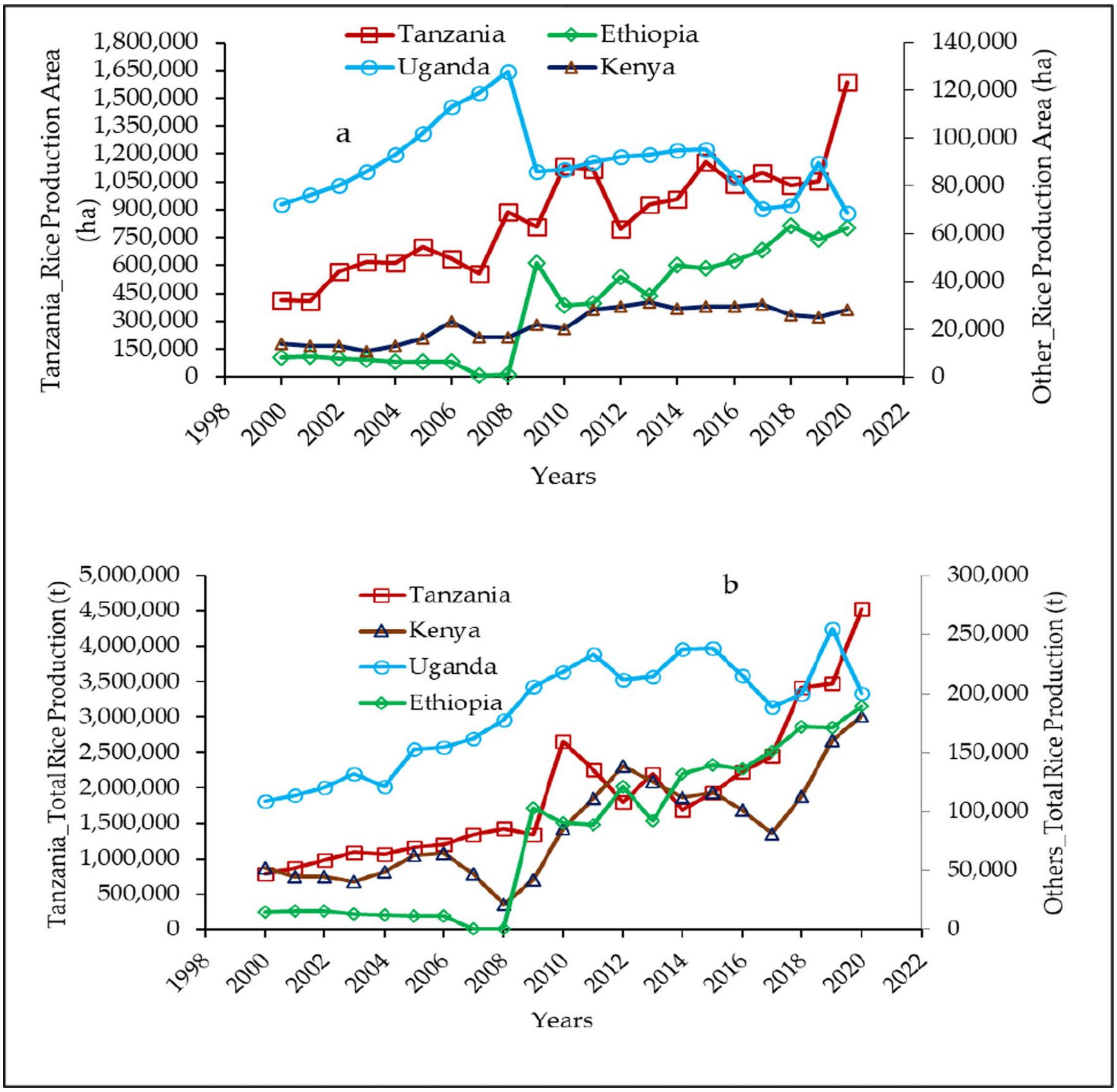

Fig. 2 Comparative changes in total rice production from 2000 to 2020: **a** area (ha) and **b** production quantity (t) of the four East African countries—Uganda, Kenya, Tanzania, and Ethiopia. Data source: [33]

Despite increases in rice production and yields in EA (Fig. 2), water availability remains the primary limiting factor in semiarid regions [55]. Limited irrigation development and water management knowledge lends agricultural systems vulnerable to rainfall variability and dry spells even during rainy seasons [56]. As such, production and yield from rainfed agricultural systems has been low; for upland rice, this is caused by uneven rain distribution across the production seasons in different areas [55]. Additionally, water availability, inefficient fertilizer use, and unsustainable subsistence and continuous farming has depleted soil nutrients, contributing to declining yields [57]. Similarly, increases in drought response to temperature variations can limit rice production if these exceed optimum ranges that induce moisture deficits [58]. Rice, both paddy and rain-fed, has an optimum growing temperature of 25 °C, and temperature increases of 1 °C above this optimum can cause a 10% yield reduction [59].

Rice production remains a growing sector in EA. Nevertheless, several environmental concerns exist, including: (1) how to fit rice production into farming systems because most paddies are in wetlands; (2) negative impacts of chemical use and disease arising from fertilizer and agrochemical applications; (3) disposal of rice wastes; (4) indiscriminate clearing of forests and wetlands for rice production; and (5) greenhouse gas emissions (e.g., methane) from paddy fields [60].

2.4 Water resources, existing policies, and regulations in East Africa

EA has ample water supplies with annual total renewable water resources (both surface and groundwater) estimated at 60, 122, 31, and 96 km^3 for Uganda, Ethiopia, Kenya, and Tanzania, respectively [61]. On average, 76% of inventoried withdrawals in these nations are used for agriculture. However, agricultural water withdrawal as a percentage of total renewable water resources is only 0.45, 4, 7, and 5% for Uganda, Ethiopia, Kenya, and Tanzania, respectively [61]. Similarly, annual total renewable groundwater resources are estimated as 3.5, 20, 29 and 30 km^3 for Kenya, Ethiopia, Uganda, and Tanzania, respectively [61]. Groundwater use for irrigation remains very low because of high well drilling costs, fluctuating and poorly accessible electricity in rural areas, and poor road infrastructure hindering market access [62]. Thus, an untapped potential exists to develop water resources for irrigation to increase irrigated land and agricultural productivity [63]. However, overuse and inefficient water management in paddy fields due to insufficient knowledge complicates regional water use. In addition, water use by individual farmers is not measured in irrigation schemes. Farmers in Uganda, Kenya and Tanzania pay only a fixed fee to the water management association, which provides no incentive for conservation [64]. As such rice, as an emerging crop in EA, exerts challenges on sustainable water management [27].

Regional policy instruments focused on rice production convinced the governments in the region to join the Coalition for African Rice Development (CARD) in 2008, with the propose of doubling rice production in sub–Saharan Africa within 10 years and increasing food security and incomes of smallholders [65]. National ministries of water and environment led the creation of water-related policies to prioritize water and preside over other sectoral policies. However, other government ministries follow established policies, ignoring outside influences [66]. For example, water ministries may preclude agriculture ministries from imposing water tariffs and permits on farmers and irrigators, which could affect their water revenues. Demands for water quality and effluent standards set by environment and water ministries may be blocked by the health ministries. Information may not be disclosed to the public or to other ministries. These are a few obstacles that must be addressed.

While Ethiopia, Tanzania, and Uganda have also made significant strides towards integrated water resource management, Kenya still leads in developing legislative and policy frameworks for this purpose [66]. Additionally, there are remain difficulties implementing policies, upholding laws, and monitoring, in the region. In EA, land use, possession, leveraging, and sales are established by the state or by custom, and rights may accrue to individuals, families, communities, or organizations [67]. Although the customary rules of land tenure are dominant in the region, these may or may not be recognized by the state [68]. This remains a major concern among smallholder farmers. Generally, the region faces key policy challenges in land tenure, water use, and enabling profitable irrigation. Additionally, irrigation schemes that have water user associations are often ineffective and lack basic institutions, such as business/operational plans [69].

3 Food security issues in East Africa

EA is among the most food-insecure regions; although there has been great improvement in global agricultural productivity and food security in recent years, EA has not followed this trend. Studies show that food insecurity has risen since 2014 manifested by the increasing food insecure population (Fig. 3) and the situation has worsened during the COVID-19 pandemic. The region generally comprises one-third of the world's undernourished population and is the only area where land and agricultural productivity has declined, especially among the smallholder farmers, during recent years [70] due to factors including declining soil fertility and precipitation variability. EA has significant untapped agricultural crop potential to achieve food self-sufficiency and increase food exports if it ceases to rely on food imports and instead intensifies farming activities [71]. Currently, more than 70 million people in the region are undernourished, including > 15% of the total population in Ethiopia and Tanzania and 10 and 14% in Uganda and Kenya, respectively (Fig. 3).

The causes of food insecurity in the region are complex and multidimensional. These are linked to several factors: drought, environmental degradation, poverty, conflict, land fragmentation, declining soil fertility, poor access to basic social services, and inadequacy of public policies [72, 73]. Food supplies in many parts of the developing world are locally derived, with much of this produced by rain-fed agriculture [73]. Therefore, changes in rainfall and temperature directly affect food supplies, cause water shortages, and heat stress limits crop growth, development, and yields.

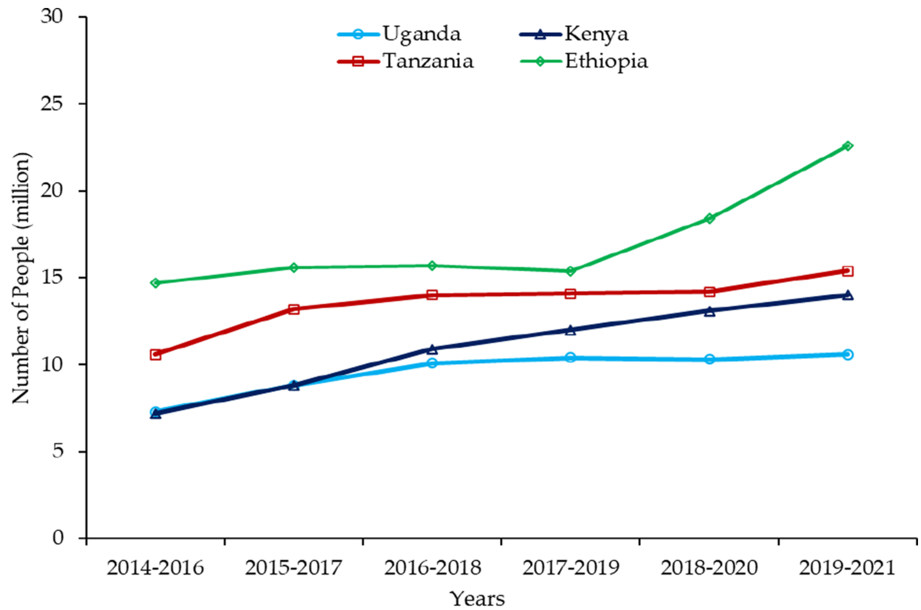

Fig.3 Prevalence of food insecure population in East Africa from 2014 to 2021. Data Source: [33]

3.1 The food security-population-poverty Nexus

Smallholder farmers, including herders and fishers, comprise the largest percentage of the region's poor inhabitants [27]. Moreover, the largest segment includes those belonging to indigenous populations living in rural areas and surviving on subsistence farming. These farmers depend largely on rain-fed agriculture, which is susceptible to droughts, floods, and shifts in markets and prices. Hence, strategies to reduce rural poverty will largely rely on improved agricultural water management, as noted in Ethiopia [74].

The EA region has the largest number of extremely poor inhabitants, which nearly doubled between 2000 and 2015. The largest population increases are those living on $1.90 to $3.20 per day and continue to suffer from low consumption levels and limited access to education and essential infrastructure services. Additionally, the poverty situation in the region is exacerbated by concurrent issues, such as recent desert locust invasions, weather-related shocks in Kenya, civil conflicts in Ethiopia, and the refugee influx and weather extremes in Uganda [75]. The World Bank (2020) noted that the 2016/2017 drought in Uganda increased the poverty rate by 1.7% from levels in 2013 to 21.4% in 2016, and multidimensional poverty incidence was estimated at 60% in 2016 [76]. In Kenya, the proportion of people living below the poverty line was estimated at 36% in 2015/16, reaching 70% in rural areas [77]. Approximately 1.3 million people in Kenya faced acute food insecurity and need assistance as of late 2019 [78].

The region is experiencing high population growth at the rate of 1.1 million people annually (Fig. 4), with most people living in rural areas. Many youths are now moving to cities in search of employment opportunities. Annual population growth projections vary from 1.089 to 4.767 million, and the population in Uganda is projected to surpass Kenya by 2050 (Fig. 4). These population increases exert pressure on water resources and increase food demands, therefore food imports. Agriculture remains integral to the future of EA's industrialization, poverty reduction, employment opportunities, and overall food security [79]. While food security is being affected by climate change, most importantly, it depends on economic growth, changes in trade flows, and food aid policies [80].

3.2 Climate change and food security

Climate change is projected to increase temperature and precipitation variability, effectively decreasing the yields in the region whilst contributing to interannual uncertainty. Several failed rainy seasons attributed to climate change have decimated crops, contributing to a hunger crisis, and affecting food security [18, 54]. These conditions led to severe soil moisture deficits impacting agricultural and increasing wildfire hazards [19]. Additionally, about 70 million people are exposed to drought risk in EA. Climate change greatly contributes to the precipitation deficit which has

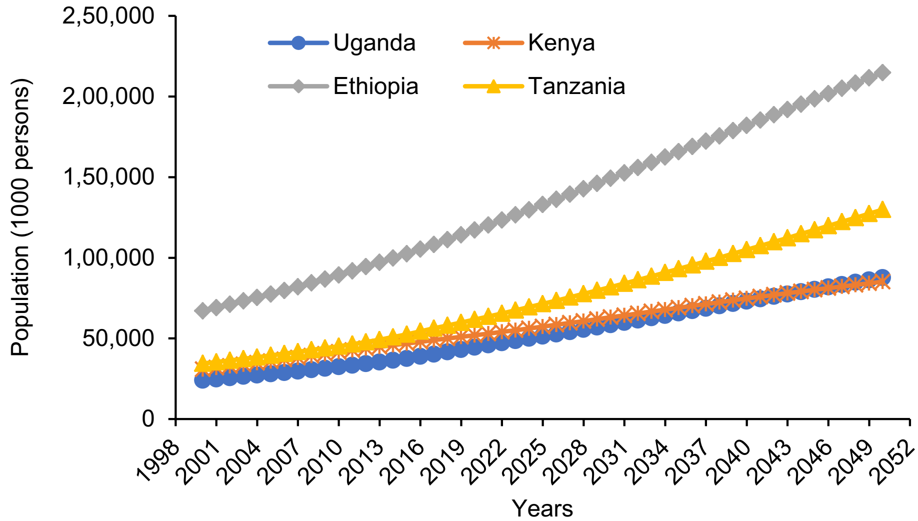

Fig. 4 Population growth projections and estimates of East Africa: Uganda, Ethiopia, Kenya, and Tanzania, from 2000–2050. Data source: [33]

worsened since November 2021. The cumulative precipitation deficit from July 2020 to June 2022 compared to the reference period 1981 to 2020 is severe across large regions in EA [19]. The driest regions in southeastern Ethiopia and eastern Kenya have deficit values up to about 50% based on CHIRPS data and even higher (up to about 70%) based on ECMWF ERA5 reanalysis. Spatial patterns are similar between the two datasets with the main differences in northern Ethiopia, southern Uganda, and northern Tanzania (deficit for ERA5, surplus for CHIRPS). The magnitude of the deficit appears uniformly more severe for ERA5 data [19].

Whereas long-term precipitation predictions are uncertain, several studies show declining rainfall between March and June and rising sea-surface temperature along coastal EA [81, 82]. These temperature increases enhance convection over the tropical Indian Ocean causing dry air to descend over EA, suppressing convection since 1980 and decreasing precipitation. In addition, rising surface temperatures in the Indian Ocean are linked to greenhouse gas emissions [81–83], which will likely continue and warm the south-central Indian Ocean, prolonging the drought trend. This in turn will exacerbate water shortages, affecting rice production in EA [82). More drought events are being reported as confirmed by the Drought Indicator (CDI) and IGAD Climate Prediction and Applications Centre-ICPAC (https://droughtwatch.icpac.net/mapviewer/) of EA, indicating drought stress related to rainfall deficits across large areas of south and east Ethiopia, Uganda, coastal regions of Kenya, and some areas in Tanzania. It is predicted that drought and precipitation deficits will persist for more than 5 years in most of EA [19]; this would cause declines in irrigated and rainfed crop production, especially rice, because it requires much water.

3.2.1 Virtual water and water footprint from imports and exports

Considering the large quantity of fresh water required for rice production and rice trade in EA with other regions, exporting countries are trading water that is virtually embedded in exported products. This water that is embodied in the production and trade of rice is referred to as 'virtual water' (VW) [84]. Additionally, water footprint (WF), a closely linked concept to VW, is an indicator of water use for all goods and services consumed per capita or on a national basis [85]. VW is a multidimensional indicator that specifies the volume of water consumed, water sources, and pollutants, and is composed of three components: green, blue, and grey water footprints [86]. Rice import and export data for 10 years obtained from the Food and Agriculture Organization (FAO) database [33], shows that EA imports a substantial amount of rice (> 500,000 tons annually) from Asia valued at approximately USD 500 million according to the Eastern African Grain Council (EAGC) [87]. Import and export statistics (Table 1) indicate that Tanzania is the largest producer and consumer of rice among the four EA countries with an annual consumption of 2,048,000 MT, followed by Kenya (370,000 MT), and Uganda (350,000 MT) [87]. Rice import among the four selected countries has increased significantly since 2011 (Table 1), attributed to low domestic rice production and growing populations. Therefore, several interventions are required to increase domestic rice production to substitute imports amidst the climate change?

Table 1 Comparative rice export and imports of East African countries during a 10-yr period

Country	Item Category	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Ethiopia	Export (Tons)	0	8	30	240	1	3	0	0	72	0
	Export (1000$)	0	4	15	11	1	2	0	0	22	0
	Import (Tons)	41,356	92,567	116,958	139,789	204,524	221,466	231,582	388,793	285,476	70,769
	Import (1000$)	25,275	50,912	72,000	88,172	138,066	124,875	127,650	184,345	114,115	34,494
Kenya	Export (Tons)	621	923	520	89	43	13	108	350	496	134
	Export (1000$)	521	500	595	93	51	11	61	712	97	69
	Import (Tons)	283,017	437,744	374,562	595,970	490,000	650,000	585,360	582,404	600,502	582,130
	Import (1000$)	156,408	200,559	146,344	300,007	187,884	228,279	243,779	245,594	242,398	240,306
Uganda	Export (Tons)	17,592	22,146	31,183	16,775	16,981	8998	12,197	5189	18,852	21,206
	Export (1000$)	8548	13,385	17,733	7983	7096	4051	6794	2766	9887	11,148
	Import (Tons)	44,123	45,106	52,114	65,385	27,732	31,714	33,175	49,257	75,396	237,767
	Import (1000$)	16,979	20,878	25,237	26,750	11,399	12,044	18,748	18,970	35,984	83,812
Tanzania	Export (Tons)	24,983	5836	21,283	8837	964	1069	243	15,518	69,695	299,688
	Export (1000$)	10,764	2326	10,159	2551	332	308	75	2491	32,207	128,100
	Import (Tons)	50,300	170,190	229,600	3513	25,559	742	857	1553	83	347
	Import (1000$)	23,800	87,200	113,000	1534	8139	597	477	1068	19	156

Data source: [33]

3.2.2 Civil unrest, migration and covid-19

Ongoing civil unrest in the region influences migration. This combined with the lingering effects of the COVID-19 pandemic has impacted food security. Food insecurity can both be a cause and a consequence of civil unrest and can fuel and drive conflict. Uganda has experienced migration and refugee influxes because of sporadic conflicts during the past decade and ongoing civil unrest in Democratic Republic of Congo and South Sudan neighboring countries. Civil unrest, widespread poverty, and food insecurity create vulnerable populations and low coping capacity in addition to the impacts of droughts and floods [19]. Additionally, recent internal conflicts in Ethiopia have disrupted agricultural food production systems, reducing access to food and income [88]. What will happen with population increases and climate change exacerbating these harsh conditions? With the recent unprecedented drought and the continuous civil conflicts within the region, particularly in Ethiopia, an estimated 1.5 million refugees are residing in rural and urban areas within and outside the country [89]. As such, the region continues to face a humanitarian crisis and migration is prevalent in areas most affected by changing climate.

Besides climate change, conflicts are the second most significant risk to food security and drivers of migration [90]. The impacts of conflict can be both direct and indirect, such as inflation, disruption of social networks and markets, forced population movements, and the devastation of food supplies and productive assets. Further, food insecurity, high food prices, and competition for available resources lead to feelings of injustice and rage. Migration has been attributed to five drivers: political, economic, social, demographic, and environmental [91]. The drivers comprise push and pull factors; push factors relate to source areas, while pull factors relate to destinations [92]. Education generally increases migration ability and aspiration, but the pre-existing cultural and social ties shape the destination [93]. In most cases, migration improves food security of urban and rural populations that rely on aid [94]. The most debatable question is the food security of migrants who sacrifice their living by providing remittances or adapt through poor nutrition habits [95].

The onset of COVID-19 in 2020 exacerbated economic and agricultural supply chain shocks, contributing to low production and damages due to border lockdowns and travel restrictions [96]. In the wake of COVID-19, civil conflicts, migration, and climate change in EA there is a need to design robust strategies that respond to the multi-layered food crisis. Such measures can stabilize crop production (e.g., rice, wheat), improve supplies, and progress towards a long-term sustainable and resilient agri-food system.

3.2.3 Gender and rice production for food security

Women continue to face barriers to access productive resources, economic opportunities, and participation in decision-making processes in many parts of the world including EA. Female farmers face several constraints in accessing agricultural inputs, services, and markets that impose barriers on relying on agriculture as a pathway out of poverty [97]. Farming systems have evolved and are affected by social norms that determine how production and consumption are organized. Men, women, and children are involved in rice production at various levels. Men are mainly engaged in land preparation (ploughing, rotavating, levelling) and transportation, whereas women and children engage in planting, weeding, bird deterrent activities, harvesting, threshing, and drying [98]. The low level of adoption of agricultural technologies has been associated with such gender-related issues in EA.

4 The past and current food security strategies

Studies have highlighted different approaches to address the overall challenge of food insecurity and strategies to evaluate multiple stressors affected by climate change [99]. These include multidisciplinary perspectives at different analytical levels holistically that display the magnitude of the problem and elucidate potential pathways for solving aspects of the crisis [100].

4.1 Diversified employment and income opportunities

Broadening the household economic base is vital to reducing food insecurity and vulnerability in arid and semi-arid areas of EA [101]. Integrated production of short-cycle livestock, such as poultry, sheep, goats, and pigs provide organic inputs for crop production, reduce production costs, and increase the efficiency of farm outputs [90]. Additionally, enhancing processing of agricultural products such as milk, meat, and hides can supplement household income. Other options for raising additional earnings in arid areas of EA include collecting non-wood forest products, such as gums and resins [101].

4.2 Affordable gravity-fed irrigation and on-site farmer training

Smallholder gravity-fed irrigation systems may become increasingly popular in the face of climate change in EA. These efficient, low-cost technologies improve food security, farm incomes, and facilitate expansion of smallholder irrigation [102]. Decreasing costs of irrigation components such as solar kits, treadle pumps, drip kits, and small, motorized pumps are now available through dealers and promoted by several NGOs and community-based organizations. Recently, the Uganda government, supported by the Africa Development Bank and World Bank, funded the acquisition of raw materials and facilitated knowledge transfer to adopt sustainable irrigation practices [103]. Similar support has reduced poverty levels among agricultural households of Ethiopia by 22% [74].

4.3 Climate-smart water management technologies for rice production

Several factors threaten rice productivity in EA prompting studies to improve water technologies to increase rice yield in inland valleys and upland areas. Supplemental irrigation and soil conservation practices such as mulching for upland cultivation are being implemented at small scales [104]. Supplemental irrigation during dry spells of erratic rainy seasons can enhance rice productivity. In Uganda, 20 mm of supplemental sprinkler irrigation every five days during dry windows starting from the rice panicle initiation stage increased yields by 37%, fertilizer use efficiency by 54%, and profitability of rice cultivation by 32% [105]. Of the water conservation approaches advocated to enhance rice production and save water, alternate wetting and drying (AWD) irrigation is the most promising method [23]. This and other water conservation methods are summarized in Table 2. However, little research and innovative practices have been applied in the region related to climate and optimal water use; agronomic and economic performance; and determinants of climate-smart water management adoption for paddy and upland rice production [106].

Water conservation is an important component of water management, and many studies have described factors affecting the adoption of soil water conservation measures (SWC). The dimensions of farms and land ownership are important components associated with adopting conservation measures, especially for upland rice cultivation in the region. For example, research on social and economic factors affecting the adoption of SWC practices in the western

Table 2 Summary of water conservation and management technologies for rice production in East Africa

Technologies	Features	Applications	References
Contour bunds and water retention dikes	Small dikes around the rice field. Small dikes made of soil material built in the valley bottom following contour lines. Dikes constructed perpendicularly across the valley bottom	Paddy, upland	Figure 5
Supplemental irrigation	Addition of limited amounts of water to improve and stabilize yields of rain-fed crops when rainfall fails to provide sufficient moisture for normal plant growth	Rain-fed, Upland	[105, 106]
Conservation agriculture, limited tillage, zero tillage	Reduced or no-tillage of the soil in the field or mulch of crop residues and diversified crop rotation	Upland	[46, 107]
System of rice intensification	Cultivating rice with organic manure if possible, starting with young seedlings planted and widely spaced in a square pattern, including alternate wetting and irrigation	Paddy	[21, 108–110]
Alternate wetting and drying irrigation (AWD)	Use of field water tubes (piezometers) or tensiometers to monitor water levels in rice fields and irrigate when soil water drops below a threshold or a soil potential	Paddy	[109, 111]

Fig. 5 Rice management at the micro-research scale in Uganda: (a) contour bunds; (b) paddocks at NaCRRI, Namulonge; (c) SRI in paddy fields; and (d) drip irrigation for upland rice, Busitema Uni. Photos by Denis Bwire, 2023 and [22]

Uzambara Mountains of Tanzania indicates that age, gender (especially women), educational status of the heads of families, and land ownership have significant positive effects [112]. Alternatively, challenges associated with adopting SWC measures are attributed to the lack of farmer awareness of soil erosion and poor understanding of financial benefits from SWC measures [112].

Continuous flooding irrigation coupled with fertilizer application regimes is a traditional practice in paddy fields in the region. Continuous flooding enhances sufficient water and weed management by maintaining anaerobic conditions in the root zone, but such anaerobic conditions in soil during long durations of ponded water produce substantial CH_4 emissions [113].

Climate-smart approaches including systems of rice intensification (SRI), intermittent drainage, and AWD irrigation practice are being examined at experimental scales to promote sustainable water management and mitigate GHG emissions in Tanzania, Kenya, and Uganda [21, 113]. Results indicate that the interaction of rice intensification and nitrogen application significantly decrease CH_4 and CO_2 emissions in paddy fields [113], while traditional practices contribute to higher global warming potential (GWP) via GHG emissions. SRI reduced GWP, CH_4, and CO_2 by 57, 59, and 25%, respectively, compared to traditional continuous flooding [113]. Similar research from Mwea, central Kenya suggests that AWD is the best option for reducing GHG and increasing irrigation efficiency [114]. However, several reasons are attributed to why these climate-smart technologies (e.g., AWD, SRI and drip irrigation) are less practiced by smallholder farmers and only employed in small-scale experimental studies, particularly in Tanzania [109]. These reasons include limited knowledge of the use of technologies, farming experience, and limited information and awareness of climate-smart technologies among other factors [23, 115]. Additionally, the major concern related to most studies in EA is that they focus on single sites within a specific country. Research findings from these small-scale trials only involve a few farmers to access these climate-smart technologies, creating upscaling issues in the region [21].

5 Conclusion and future perspectives

Herein, key scientific literature and reports on smallholder irrigation agriculture are synthesized emphasizing rice production systems, polices, food security, and related strategies within the context of climate change in four EA countries (Uganda, Kenya, Tanzania and Ethiopia). Smallholder agriculture and rice production in the region is underperforming due to several factors including over-reliance on rain-fed production, poor water management systems, and land fragmentation. The major water-related challenges in rice production environments in the region are summarized in Table 3. While the role of smallholder agriculture in food security is less emphasized, several aspects should be considered for future research to assist in formulating potential coping measures and help smallholder farmers adapt to climate change, improve rice productivity, and support food security.

Research on the effects of climate-smart water management practices (AWD, SRI, and drip irrigation) on agricultural soil water dynamics, hydraulic properties, GHG emissions, and carbon dynamics in paddy and upland rice fields in EA is scarce. Because our review focused on factors contributing to food insecurity in four EA countries, other areas may differ due to poor coverage in the literature. Some of the stressors explored include climate change, migration, civil unrest, population growth, and diminishing land holdings. Future research on food security should consider other factors, such as poor infrastructure development, poor post-harvest handling, limited market access, and corruption, to develop a more detailed analysis of food security in the region. We therefore provide several suggestions to build robust water management systems for rice production and food security in EA.

Table 3 Summary of the major water-related challenges of rice production environments in EA

Major constraints	Causes of the constraints	Research method	Countries	Rice-growing environment	References
Droughts and Flooding	Low water-holding capacity soil, poor drainage and extended climate stress; poor rainfall distribution, low rainfall combined with increases in air temperature	Mapping and crop modelling, Review	Uganda, Ethiopia, Kenya, Tanzania	Paddy, and upland	[17, 18, 126, 127]
Poor land planning and irrigation designs, Water scarcity	Unreliable water supply, low rainfall distribution	Field surveys, interviews, environmental modelling	Uganda, Kenya, Ethiopia	Paddy	[19]
Iron toxicity, Soil salinity	Elevated iron and sodium concentrations in soil	Mapping	Africa	NA	[127]

While food security in EA is vulnerable since smallholder agriculture is rain-fed and susceptible to climate change, the region has a huge untapped potential that requires integrated applied research and innovations in water resources, soil water management, and irrigation development. Considering the vulnerability of the region to climate variability and climate extremes, such as floods and temperature increases [17, 18, 116], detailed assessments of climate variability are required at local and regional scales, in addition to access to existing data to sustainably develop agricultural water resources. Limited climate observations and gaps typify ground-based meteorological data in most of EA [117]. Therefore, a combination of available datasets from National Meteorological Agencies and remotely sensed data for sparsely covered areas must be considered. Additionally, data from reanalysis products with high accuracy (compared with ground station data) that cover large areas can be useful [117]. Furthermore, early warning systems such as drought triggering for Anticipatory Action (AA) that use weather forecasts along with risk data to identify and implement timely mitigation actions to cope with impending drought hold promise for supporting agriculture in developing nations [118].

Mitigating water stress and expanding irrigation requires developing alternative water sources through comprehensive water harvesting and storage plans at national levels. Clearly, water scarcity is a major constraint for rice production where rainfall conditions vary. Additionally, the lack of collective action on maintenance of irrigation infrastructures, declining water in reservoirs following prolonged droughts, and unreliable water supplies result in low and variable yields. The concept of water harvesting is complex and includes all methods for collecting and storing surface runoff from different sources for domestic or agricultural use [119]. Water harvesting and storage at national levels can potentially increase rainwater-fed upland rice production, thus supporting rural livelihoods [120, 121]. Similarly, runoff storage facilities such as reservoirs, ponds, and tanks are simple to construct and easily managed by groups of farmers [122]. Nevertheless, due attention needs to be given to the potential for water harvesting to impact downstream access to water and environmental flows [123], an assessment closely aligned with the concept of cumulative watershed effects [124].

The four EA nations have high potential for irrigated agriculture and expansion considering both land and water resources. Improving irrigation designs and development of large and smallholder irrigation schemes can contribute to increases in agricultural production, resilience to climate change and variability, and enhance rural economic growth [38, 125]. Generally, these countries have ample untapped water resources, albeit unevenly distributed. Water scarcity and moisture deficits due to droughts are major drivers for low rice yields. However, most of the large-irrigation and government-owned schemes have under-performed due to poor water governance, land tenure policies, mismanagement practices, market functioning, limited crop diversification opportunities, and access to credit. While managing water sources and irrigation schemes is important for improving rice productivity, most schemes in EA do not have functional irrigation infrastructure and proper water abstractions, conveyance, distribution, application structures, and canals are absent or dilapidated. Additionally, the absence of control structures such as gates makes systems inefficient, leading to water flow in fields regardless of need. Water is also lost through numerous cracks in deteriorating canals [51]. Improving irrigation structural design and integration of AWD techniques can contribute to sustainable water management in paddy fields and improve water and crop productivity [38]. Although long-term research is needed to assess how AWD affects soil hydraulic properties, soil fertility, soil salinity, carbon dynamics, GHG emissions, and weed infestation in EA, it is necessary to develop incentives for adoption of such water-saving technologies by smallholder farmers and integrate them into irrigation schemes [23].

Improving information communication technologies (ICT) and building integrated, comprehensive data platforms for smallholder farmers are other avenues to enhance productivity in EA. Our synthesis indicates that high-quality data are limited, and most data sets are not up to date (e.g., on current irrigation expansion and yield statistics), presenting huge temporal data gaps. Integrated data can support the use of weather and agricultural information at household levels, such as farmer-to-farmer exchanges, farmer field schools, and via mobile phones. Additionally, farmers can access information and guidance on field agronomic practices including on-field planning, water management techniques, and optimal application of agricultural inputs, to improve crop productivity.

Acknowledgements The authors sincerely thank the Tokyo University of Agriculture and Technology (TUAT), Institute of Global Innovation Research (GIR), and MEXT Japan for their support.

Author contributions Literature search and collection, manuscripts structuring, original draft preparation—writing, proofreading, and editing: D.B., H.S. R.C.S; proofreading and editing, M.M.

Funding No external funding.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests There is no conflict of interest among the authors.

References

1. Young SL, Frongillo EA, Jamaluddine Z, Melgar-Quiñonez H, Pérez-Escamilla R, Ringler C, Rosinger AY. Perspective: the importance of water security for ensuring food security, good nutrition, and well-being. Adv Nutri. 2021;12(4):1058–73. https://doi.org/10.1093/advances/nmab003.
2. Balasubramanya S, Stifel D. Viewpoint Water, agriculture & poverty in an era of climate change Why do we know so little. J Food Policy. 2020;93:101905. https://doi.org/10.1016/j.foodpol.2020.101905.
3. Karen HM. Differentiating Between Food Security and Insecurity. MCN Am J Mat Nur. 2014;39(6):381. https://doi.org/10.1097/nmc.0000000000000080.
4. Schmidhuber J, Tubiello F. N: Global food security under climate change. Proc Natl Acad Sci. 2007;104(50):19703–8. https://doi.org/10.1073/pnas.0701976104.
5. World Economic Forum (2020). The Global Risks Report 2020, (Internet), Geneva (Switzerland), 2020. http://www3.weforum.org/docs/WEF_Global_Risk_Report_2020.pdf. Accessed 1 Feb 2023
6. Palay I. Climate, water, and poverty reduction – exploring the critical links. International Water Management Institute. Link https://www.iwmi.cgiar.org/2021/10/climate-water-and-poverty-reduction-exploring-the-critical-links/(2021). Accessed 25 Nov 2023.
7. Shimeles, A., Verdier-Chouchane, A., Boly, A.: Building a Resilient and Sustainable Agriculture in Sub-Saharan Africa 1–12. 2018. ISBN 978-3-319-76221-0 ISBN 978-3-319-76222-7 (eBook) https://doi.org/10.1007/978-3-319-76222-7.
8. Inocencio, A., Kikuchi, M., Tonosaki, M., Maruyama, A., Merrey, D. Sally, H. de Jong, I.: Costs and performance of irrigation projects: A comparison of sub-Saharan Africa and other developing regions, Report. Colombo, Sri Lanka: International Water Management Institute, pp 81. 2007. http://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/PUB109/RR109 pdf. Accessed 17 Feb 2023
9. FAO, I., UNICEF. WFP, WHO: The State of Food Security and Nutrition in the World 2018. Building climate resilience for food security and nutrition Report, Rome, FAO, 2019. https://www.fao.org/3/I9553EN/i9553en.pdf. Accessed 13 Jan 2023
10. Savary S, Willocquet L, Pethybridge SJ, Esker P, McRoberts N, Nelson A. The global burden of pathogens and pests on major food crops. Nat Ecol. 2019;3:430–9. https://doi.org/10.1038/s41559-018-0793-y.
11. Diao X, Headey D, Johnson M. Toward a green revolution in Africa: what would it achieve, and what would it require? Agric Econ. 2008;39:539–50. https://doi.org/10.1111/j.1574-0862.2008.00358.x.
12. Nakano Y, Bamba I, Diagne A, Otsuka K, Kajisa K. The possibility of a rice Green Revolution in Large-scale irrigation schemes in sub-Saharan Africa. In. An African Green Revolution: Finding ways to boost productivity on small farms, pp. 43–70. https://doi.org/10.1596/1813-9450-5560 (2012)
13. Bjornlund V, Bjornlund H. Understanding agricultural water management in a historical context using a socioeconomic and biophysical framework. Agric Water Manag. 2019;213:454–67. https://doi.org/10.1016/j.agwat.2018.10.037.
14. Hua X, Liangzhi Y, Wielgosz B, Claudia R. Estimating the potential for expanding smallholder irrigation in Sub-Saharan Africa. Agric Water Manag. 2014;131:183–93. https://doi.org/10.1016/j.agwat.2013.08.011.
15. Higginbottom TP, Adhikari R, Dimova R, Redicker S, Foster T. Performance of large-scale irrigation projects in sub-Saharan Africa. Nat Sustain. 2021;4:501–8. https://doi.org/10.1038/s41893-020-00670-7.
16. Bjornlund V, Bjornlund H, van Rooyen AF. Exploring the factors causing the poor performance of most irrigation schemes in post-independence sub-Saharan Africa. Int J Water Res Dev. 2020;36(S1):S54–101. https://doi.org/10.1080/07900627.2020.1808448.
17. Ayugi B, Eresanya OE, Onyango OA, Ogou FK, Okoro CE, Okoye OC, Anoruo MC, Dike NV, Ashiru RO, Daramola TM, Mumo R, Ongoma V. Review of meteorological drought in Africa: historical trends, impacts, mitigation measures, and prospects. Pure Appl Geophys. 2022;179:1365–86. https://doi.org/10.1007/s00024-022-02988-z.
18. Haile GG, Tanga Q, Suna S, Huanga Z, Zhanga X, Liu X. Droughts in East Africa: causes, impacts and resilience. Earth-Sci Rev. 2019;193:146–61. https://doi.org/10.1016/j.earscirev.2019.04.015.
19. Toreti A, Bavera D, Acosta Navarro J, Cammalleri C, de Jager A, Di Ciollo C, Hrast Essenfelder A, Maetens W, Magni D, Masante D, Mazzeschi M, McCormick N, Meroni M, Rembold F, Spinoni J. Drought in East Africa August 2022. GDO Anal Rep. 2022. https://doi.org/10.2760/534446.JRC130470.
20. Evans AEV, Giordano M, Clayton T. (Eds.): Investing in agricultural water management to benefit smallholder farmers in Tanzania. AgWater Solutions Project country synthesis Report. International Water Management Institute, Colombo, SriLanka, (2012). IWMI Working Paper 146, https://doi.org/10.5337/2012.208.

21. Ouma MA, Ouma LO, Ombati JM, Onyango CA. A cost benefits analysis of the adoption of system of rice intensification: Evidence from smallholder rice farmers within an innovation platform in Oluch irrigation scheme, Kenya. PLoS ONE. 2024;19(1): e0290759. https://doi.org/10.1371/journal.pone.0290759.
22. Odinga, J.A.: Assessing the impacts of supplemental drip irrigation and organic mulching on upland rice cultivation for efficient water management in Uganda. Busitema University, 2022. http://hdl.handle.net/20.500.12283/955. Accessed 12 Jul 2024
23. Bwire D, Saito H, Sidle RC, Nishiwaki J. Water management and hydrological characteristics of paddy-rice fields under alternate wetting and drying irrigation practice as climate smart practice: a review. Agronomy. 2024;14:1421. https://doi.org/10.3390/agronomy14071421.
24. Nicholson SE. Climate and climatic variability of rainfall over eastern Africa. Rev Geophys. 2017;55:590–635. https://doi.org/10.1002/2016RG000544.
25. Schreck CJ, Semazzi FHM. Variability of the recent climate of Eastern Africa. Int J Climatol. 2004;24:681–701. https://doi.org/10.1002/joc.1019.
26. Daron, J. D.: Regional Climate Messages for East Africa. Scientific report from the CARIAA Adaptation at Scale in Semi-Arid Regions (ASSAR) Project. 2014. https://idl-bnc-idrc.dspacedirect.org/handle/10625/57320. Accessed 30 Nov 2023.
27. Salami, A., Kamara, A.B., Brixiova, Z.: Smallholder Agriculture in East Africa: Trends, Constraints and Opportunities. African Development Bank, Working paper series, No 105, 2010.
28. Wiggins, S., Keats, S.: Leaping and learning: Linking smallholders to markets in Africa. Agriculture for Impact Report. 2013. https://cgspace.cgiar.org/bitstream/handle/10568/35246/L%26L%20Link%20SF%20to%20Mkt%20final%20May%202013.pdf?sequence=1&isAllowed=y. Accessed 20 Dec 2023.
29. Pablo T, Giller KE. When yield gaps are poverty traps: the paradigm of ecological intensification in African smallholder agriculture. Field Crops Res. 2013;143:76–90. https://doi.org/10.1016/j.fcr.2012.10.007.
30. Fratkin E. East African pastoralism in transition: maasai, boran, and rendille case. Afr Stud Rev. 2001;44(3):1–25. https://doi.org/10.2307/525591.
31. Nakawuka P, Langan S, Schmitter P, Barron J. A review of trends, constraints and opportunities of smallholder irrigation in East Africa. Global Food Sec. 2017;17:196–212. https://doi.org/10.1016/j.gfs.2017.10.003.
32. Morton JF. The impact of climate change on smallholder and subsistence agriculture. Agric Sci. 2007;104(50):19680–5. https://doi.org/10.1073/pnas.0701855104.
33. FAO: https://www.fao.org/faostat/en/#data. Accessed 25 Nov 2023.
34. Ngigi SN. Review of irrigation development in Kenya. In: Blank HG, Mutero CM, Murray-Rust H. (Eds.), The Changing Face of Irrigation in Kenya: Opportunities for Anticipating Change in Eastern and Southern Africa. International Water Management Institute, Colombo, Sri Lanka, pp. 35–54 (2002). https://publications.iwmi.org/pdf/H030832.pdf. Accessed 17 Feb 2023.
35. Oduori LH, Njeru T. A review paper on large scale irrigation in Kenya: a case study of maize (WPS 58/2016). Tegemeo Institute of Agricultural Policy and Development. Nairobi, Kenya. 2016. http://41.89.96.81:8080/xmlui/handle/123456789/2360. Accessed 17 Feb 2023.
36. Watson JM. The Agoro systems of irrigation. Uganda J. 1952;16(2):159–63.
37. Carruthers DI. Irrigation developments in Uganda-past experience and future prospects. East Afr Geogr Rev. 1970;1970(8):11–22. https://doi.org/10.10520/aja19376812_162.
38. Bwire D, Saito H, Okiria E. Analysis of the impacts of irrigation practices and climate change on water availability for rice production: a case in Uganda. J Arid Land Stud. 2022;32:123–7. https://doi.org/10.14976/jals.32.s_123.
39. FAO.: A data portrait of smallholder farmers. 2015b http://www.fao.org/economic/esa/esa-activities/esa-smallholders/dataportrait/farm-size/en/. Accessed 20 Dec 2023.
40. Matlock M. Water profile of Tanzania. 2008. http://www.eoearth.org/view/article/ Accessed 20 Nov 2022.
41. Tagseth M. Oral history and the development of indigenous irrigation. Methods and examples from Kilimanjaro, Tanzania. Nor Geogr Tidsskr Nor J Geogr. 2008;62(1):9–22. https://doi.org/10.1080/00291950701864898.
42. Ministry of Water and Irrigation.: Water sector status report 2009. https://www.maji.go.tz/uploads/publications/en1568462448.Water_Sector_Status_Report_2009_1_.pdf. Accessed 10 Dec 2022.
43. Girma, M, M., Awulachew, S, B.: Irrigation practices in Ethiopia: Characteristics of selected irrigation schemes. Colombo, Sri Lanka: International Water Management Institute. 80p. IWMI Working Paper 124. 2007. http://www.iwmi.cgiar.org/Publications/Working_Papers/working/WOR124.pdf. Accessed 17 Feb 2023.
44. Frenken, K.: Irrigation in Africa in figures. AQUASTAT Survey-2005. FAO water reports 29, 2005. https://digitallibrary.un.org/record/591735?ln=en. Accessed 22 Dec 2022.
45. Akongo GO, Gombya-Ssembajjwe W, Buyinza M, Namaalwa JJ. Characterization of rice production systems in northern agro-ecological zone, Uganda. J Agric Sci. 2017;10(1):272–82. https://doi.org/10.5539/jas.v10n1p272.
46. Mkonda MY, He X. Conservation agriculture in Tanzania. Part of book series on Sustainable agriculture reviews. SARV. 2017;22:309–24. https://doi.org/10.1007/978-3-319-48006-0_10.
47. Verhoeven JTA, Setter TL. Agricultural use of wetlands: opportunities and limitations. Ann Bot. 2009;105(1):155–63. https://doi.org/10.1093/aob/mcp172.
48. Wood A, Hailu A, Abbot P, Dixon A. Sustainable management of wetlands in Ethiopia: local knowledge vs. government policy. In. Proceedings, Strategies for wise use of wetlands: Best practices in participatory management, pp 81–88 (2002). https://portals.iucn.org/library/sites/library/files/documents/2002-012.pdf. Accessed 17 Feb 2023.
49. Dixon AB, Wood AP. Wetland cultivation and hydrological management in Eastern Africa: matching community and hydrological needs through sustainable wetland use. Nat Res Forum. 2003;27:117–29. https://doi.org/10.1111/1477-8947.00047.
50. Sakane N, Alvarez M, Becker M, Böhme B, Handa C, Kamir HW, Langensiepen M, Menz G, Misana S, Mogha NG, Moseler BM, Mwita EJ, Oyieke HA, Van Wijk MT. Classification, characterization, and use of small wetlands in East Africa. Wetlands. 2011;31:1103–16. https://doi.org/10.1007/s13157-011-0221-4.
51. Kosgei JR, Nasongo SA, Kipkemboi J, Kitaka N, Owuor-Okeyo JB. Land and Water Resources Planning and Management Options in Floodplain Wetlands in Nyando Basin, Kenya. J Environ Protection. 2021;12(12):1144–60. https://doi.org/10.4236/jep.2021.1212067.

52. Nasrin S, Bergman JL, Jirstrom M, Holmquist B, Andersson AD, Djurfeldt G. Drivers of rice production: evidence from five Sub-Saharan African countries. Agric Food Secur. 2005;4:12. https://doi.org/10.1186/s40066-015-0032-6.
53. Belayneh T, Tekle J. Review on adoption, trend, potential, and constraints of rice production to livelihood in Ethiopia. Int J Res Granta-laayah. 2017;5(6):644–58. https://doi.org/10.5281/zenodo.824116.
54. Al-Imran, D., Musila, R.N., Kamau, W.J.: Rainfed rice farming production constrains and prospects, the kenyan situation. In. Book: integrative advances in rice research, chap. (8). IntechOpen, London, United Kingdom 2021. https://doi.org/10.5772/intechopen.98389.
55. Lisa-Maria SA, R., David, M. The Nile Basin: tapping the unmet agricultural potential of Nile waters. Water Intl. 2010;35(5):623–54. https://doi.org/10.1080/02508060.2010.513091.
56. Bwire D, Watanabe F, Suzuki S. The Current Status and Issues of Irrigation Agriculture in Uganda. Proc. Japanese Assoc. of Arid Lands, Tokyo, Japan, 27th May 2017, pp. 56. https://doi.org/10.13140/rg.2.2.32998.47680.
57. Sanchez PA, Shepherd KD, Soule MJ, Place FM, Buresh RJ, Anne-Marie N Izac, Mokwunye AU, Kwesiga FR, Ndiritu CG, Woomer PL. Soil FERTILITY REPLENISHMENT IN AFRICA: AN INVESTMENT IN NATURAL RESOURCE CAPITAl. Soil Science Society of America Spec. Publ. 51. SSSA, Madison, 1–46 (1997). https://doi.org/10.2136/sssaspecpub51.c1.
58. Liu J, Steffen Fritz CFA, Wesenbeeck V, Fuchs M, You L, Obersteiner M, Yang H. A spatially explicit assessment of current and future hotspots of hunger in sub- Saharan Africa in the context of global change. Global Planet Change. 2008;64:222–35. https://doi.org/10.1016/j.gloplacha.2008.09.007.
59. Ghadirnezhad S, Seyede R, Fallah A. Temperature effect on yield and yield components of different Rice cultivars in flowering stage. Int J Agron. 2014. https://doi.org/10.1155/2014/846707.
60. Odogola R.W.: Final survey report on the status of rice production, processing, and marketing in Uganda. Japan International Cooperation Agency-JICA in collaboration. 2006. https://www.mofa.go.jp/mofaj/gaiko/oda/bunya/agriculture/pdf/uganda_report.pdf Accessed 17 Feb 2023.
61. FAO AQUASTAT database. 2015. http://www.fao.org/nr/water/aquastat/main/index.stm. Accessed 22 Dec 2022.
62. Amjath-Babu TS, Krupnik TJ, Kaechele H, Aravindakshan S, Sietz D. Transitioning to ground water irrigated intensified agriculture in Sub-Saharan Africa: an indicator-based assessment. Agric Water Manag. 2016;168:125–35. https://doi.org/10.1016/j.agwat.2016.01.016.
63. Altchenko Y, Villholth KG. Mapping irrigation potential from renewable groundwater in Africa-a quantitative hydrological approach. Hydro Earth Sys Sci Discuss. 2015;19(2):1055–67. https://doi.org/10.5194/hess-19-1055-2015.
64. Mwamakamba SN, Sibanda LM, Pittock J, Stirzaker R, Bjornlund H, Van Rooyen A, Munguambe P, Mdemu MV, Kashaigili JJ. Irrigating Africa: policy barriers and opportunities for enhanced productivity of smallholder farmers. Int J Water Res Dev. 2017;33(5):824–38. https://doi.org/10.1080/07900627.2017.1321531.
65. JICA, AGRA: Coalition for African Rice Development CARD. Thematic issues: Agriculture and rural development, Japan International Cooperation Agency-JICA. 2009. https://www.jica.go.jp/english/our_work/thematic_issues/agricultural/pdf/card_02_en.pdf. Accessed 20 Jan 2023.
66. GWP.: Integrated water resource management in East Africa: comping with complex hydrology. Technical focus paper, Global Water Partnership (GWP). 2015. https://www.gwp.org/globalassets/global/toolbox/publications/technical-focus-papers/p1238_gwp_tfp_ea_121015_web.pdf. Accessed 15 Jan 2023
67. Garvelink WJ. Land tenure, property rights, and rural economic development in Africa. Washington: Center for Strategic and International Studies; 2012.
68. Economic Commission for Africa: Land tenure systems and their impacts on food security and sustainable development in Africa, Report. 2004. https://repository.uneca.org/bitstream/handle/10855/593/bib.%209471_I.pdf?sequence=1 Accessed 16 Feb 2023
69. Mdemu MV, Mziray N, Bjornlund H, Kashaigili JJ. Barriers to and opportunities for improving productivity and profitability of the Kiwere and Magozi irrigation schemes in Tanzania. Int J Water Res Dev. 2017. https://doi.org/10.1080/07900627.2016.1188267.
70. Jessica A.: East Africa: Recommendations for Urgent Action on Productivity Growth. 2022. https://globalagriculturalproductivity.org/east-africa-recommendations-for-urgent-action-on-productivity-growth/. Accessed Apr 2024
71. Onwujekwe EC, Ezemba CC. Food security and safety: africans perspectives a review. Arch Curr Res Int. 2021;21:14–20. https://doi.org/10.9734/acri/2021/v21i830260.
72. Oluoko-Odingo AA. Vulnerability and Adaptation to Food Insecurity and Poverty in Kenya. Annals Assoc Am Geographers. 2011;101(1):1–20. https://doi.org/10.1080/00045608.2010.532739.
73. Funk C, Dettinger MD, Michaelsen JC, Verdin JP, Brown ME, Barlow M, Hoell A. Warming of the Indian Ocean threatens eastern and southern African food security but could be mitigated by agricultural development. Proc Nat Acad Sci USA. 2008;105(32):11081–6. https://doi.org/10.1073/pnas.0708196105.
74. Hagos F, Jayasinghe G, Awulachew SB, Loulseged M, Yilma AD. Agricultural water management and poverty in Ethiopia. Agri Econ. 2012;43:99–111. https://doi.org/10.1111/j.1574-0862.2012.00623.x.
75. FSIN.: Global report on food crises 2020. Food Security Information Network. https://www.fsinplatform.org/sites/default/files/resources/files/GRFC_2020_KM_200420.pdf. Accessed 13 Jan 2023
76. World Bank.: Poverty and Equity Brief: Sub Saharan Africa, Uganda. 2020. https://databankfiles.worldbank.org/public/ddpext_download/poverty/33ef03bb-9722-4ae2-abc7-aa2972d68afe/global_poveq_ssa.pdf. Accessed 27 Dec 2023
77. Monica KK, Tambo JA, Mugambi I, Bundi M, Kara A, Owuor C. COVID-19 implications on household income and food security in Kenya and Uganda: findings from a rapid assessment. World Dev. 2020;137: 105199. https://doi.org/10.1016/j.worlddev.2020.105199.
78. USAID.: Food assistance fact sheet Kenya. https://www.usaid.gov/sites/ default/files/documents/1866/FFP_Fact_Sheet_Kenya.pdf (2020). Accessed 15th Jan 2023
79. Ogalo V. What Will East Africans Eat in 2040? Who Will Produce the Food and How? Policy Brief, CUTS Africa Resource Centre, Nairobi. Prepared under "Scenario Planning for East African Community Agriculture Development and Sustainable Food Security by 2020". 2013. https://cuts-nairobi.org/pdf/What_Will_East_Africans_Eat_in_2040_Who_will_produce_the_Food_and_How.pdf Accessed 17 Feb 2023.
80. Nicol A, Langan S, Victor M, Gonsalves J. (Eds.). Water-smart agriculture in East Africa. Colombo, Sri Lanka: International Water Management Institute (IWMI). CGIAR Research Program on Water, Land and Ecosystems (WLE); Kampala, Uganda: Global Water Initiative East Africa (GWI EA). 352p. https://doi.org/10.5337/2015.203 (2015)

81. Funk C, Senay G, Asfaw A, Verdin J, Rowland J, Michaelsen J, Korecha D, Choularton R. Recent drought tendencies in Ethiopia and equatorial-subtropical eastern Africa. USAID Report 2015. https://pdf.usaid.gov/pdf_docs/PNADH997.pdf. Accessed 20th Dec 2022.
82. Williams AP, Funk C. A westward extension of the warm pool leads to a westward extension of the Walker circulation, drying eastern Africa. Clim Dyn. 2011;37:2417–35. https://doi.org/10.1007/s00382-010-0984-y.
83. Funk C, Eilerts G, Davenport F, Michaelsen J: A climate trend analysis of Kenya–August 2010: U.S. Geological Survey Fact Sheet 2010–3074. 2010. http://pubs.usgs.gov/fs/2010/3074/pdf/fs2010-3074.pdf. Accessed 22 Jan 2023.
84. Allan JA. Virtual water: a strategic resource global solutions to regional deficits. Groundwater. 1998;36:545–6. https://doi.org/10.1111/j.1745-6584.1998.tb02825.x.
85. Hoekstra AY. Virtual water trade. Proceedings of the International Expert Meeting on Virtual Water Trade, IHE Delft, ED: A.Y Hoekstra. Value of Water Research Report Series N°12 Delft, The Netherlands. 2003. https://sswm.info/sites/default/files/reference_attachments/HOEKSTRA%202003%20Virtual%20Water%20Trade.pdf. Accessed 17 Feb 2023
86. Karthikeyan B. Virtual water flows, water footprint and water savings from the trade of crop and livestock products of Germany. Water Environ J. 2020;34:656–68. https://doi.org/10.1111/wej.12601.
87. Kilimo Trust. Expanding rice markets in the East African community (EAC), Report, 2018. https://www.readkong.com/page/expanding-rice-markets-in-the-east-african-community-5346796. Accessed 20 Jan 2023.
88. Gatdet C. The review on the smallholder farmers' food security and conflict in Ethiopia. Sci Prog Res. 2021;1(3):191–6. https://doi.org/10.52152/spr/2021.122.
89. Terry K, Rai A. Amid record drought and food insecurity, East Africa's protracted humanitarian crisis worsens. https://www.migrationpolicy.org/article/east-africa-drought-food-insecurity-refugees/(2023). Accessed 1 Feb 2023
90. FAO.: FAOSTAT, Food Balance Sheets. 2017. http://www.fao.org/faostat/en/#data/FBS. Accessed 22 Dec 2022
91. Black R, Adger WN, Arnell NW, Dercon S, Geddes A, Thomas D. The effect of environmental change on human migration. Global Environ Change. 2011;21(S1):S3–11. https://doi.org/10.1016/j.gloenvcha.2011.10.001.
92. Warner K, Hamza M, Oliver-Smith A, Renaud F, Julca A. Climate change, environmental degradation, and migration. Nat Hazards. 2010;55(3):689–715. https://doi.org/10.1007/s11069-009-9419-7.
93. Findlay AM. Migrant destinations in an era of environmental change. Glob Environ Chang. 2011;21(S1):S50–8. https://doi.org/10.1016/j.gloenvcha.2011.09.004.
94. Zezza A, Carletto C, Davis B, Winters P. Assessing the impact of migration on food and nutrition security. Food Policy. 2011;36(1):1–6. https://doi.org/10.1016/j.foodpol.2010.11.005.
95. Crush J, Caesar M. Introduction: cultivating the migration-food security Nexus. Intern Mig. 2017;55(4):10–7. https://doi.org/10.1111/imig.12360.
96. Ayanlade A, Radeny M. COVID-19 and food security in Sub-Saharan Africa: implications of lockdown during agricultural planting seasons. Sci Food. 2020;4:13. https://doi.org/10.1038/s41538-020-00073-0.
97. Quisumbing AR, Meinzen-Dick R, Raney TL, Croppenstedt A, Behrman JA, Peterman A. Gender and agriculture: closing the knowledge gap. Book Chapter 1, 3–27 (2014). https://doi.org/10.1007/978-94-017-8616-4_1
98. Muhunyu JG. Is doubling rice production in Kenya by 2018 achievable? J Dev Sust Agric. 2011;7:46–54. https://doi.org/10.11178/jdsa.7.46.
99. UNEP-GEAS.: Food security in the Horn of Africa: the implications of a drier, hotter and more crowded future. thematic focus: ecosystem management, climate change, www.unep.org/GEAS/(2021). Accessed 15 Jan 2023
100. Hoffmann HK, Kinabo JL, Sieber S, Stuetz W, Bonatti M, Mbwana HA, Uckert GB, Matavel CE, Hafner JM, Löhr K, Rybak C. Editorial: achieving nutrition security in Tanzania by improving production, education, and economics: methods, tools and applications. Front Public Health. 2022;10:1014741. https://doi.org/10.3389/fpubh.2022.101474.
101. Lokuruka MNI. Improving food and nutrition security in kenya's arid lands, a mini review. Asian Res J Agric. 2021;14(3):45–63. https://doi.org/10.9734/arja/2021/v14i330129.
102. Bacha D, Namara R, Bogale A, Tesfaye A. Impact of small-scale irrigation on household poverty: empirical evidence from the Ambo District in Ethiopia. Irrig Drain. 2011;60:1–10. https://doi.org/10.1002/ird.550.
103. Sims, B.G., Kienzle, J., Cuevas, R., Wall, G.: Addressing the challenges facing agricultural mechanization input supply and farm product processing. Proc. FAO Workshop, CIGR World Congress on Agricultural Engineering, Bonn, German. 2006. http://haiti.countrystat.org/fileadmin/templates/inpho/documents/a1249e.pdf. Accessed 10 Feb 2023
104. Dossou-Yovoa ER, Devkota KP, Akpoti K, Danvi A, Duku C, Zwart SJ. Thirty years of water management research for rice in sub-Saharan Africa: achievement and perspectives. Field Crops Res. 2022;283: 108548. https://doi.org/10.1016/j.fcr.2022.108548.
105. Onaga, G., Kikafunda, J., Bigirwa, G., Asea, G., Mwamburi, L.A.: Rice response to nitrogen and supplemental irrigation under low phosphorus and potassium in upland production systems in East Africa. In M. A. Sutton, K. E. Mason, A. Bleeker, W. K. Hicks, C. Masso, S. Reis, M. Bekunda (Eds.), Just enough nitrogen. Perspectives on how to get there for regions with too much and too little nitrogen (Proceedings of the 6th International Nitrogen Conference). Chapter 15. Springer, 2020
106. Kipkoech AK, Tambi E, Bangali S, FARA: State of Knowledge on CSA in Africa report, Case Studies from Ethiopia, Kenya and Uganda, Forum for Agricultural Research in Africa, Accra, Ghana, 2015. https://amrh.nepad.org/sites/default/files/Nepadfiles/documents/files/kenya-ethiopia-uganda-final.pdf. Accessed 2 February 2023
107. Adamtie TF. The essentials of conservation agriculture for soil quality, crop and water productivity in Ethiopian agriculture: a review. J Nat Sci Res. 2021;9(3):16–27. https://doi.org/10.37745/gjar.2013.
108. Katambara Z, Kahimba FC, Mahoo HF, Mbungu WB, Mhenga F, Reuben P, Maugo M, Nyarubamba A. Adopting the system of rice intensification (SRI) in Tanzania: a review. Agric Sci. 2013;4(8):369–75. https://doi.org/10.4236/as.2013.48053.
109. Kahimba FC, Kombe EE, Mahoo HF. The Potential of system of rice intensification (SRI) to increase rice water productivity: a case of mkindo irrigation scheme in Morogoro Region. Tanzania Tanzania Journal of Agric Sci. 2014;12(2):10–9.
110. Materu ST, Shukla S, Sishodia RP, Tarimo A, Tumbo SD. Water use and rice productivity for irrigation management alternatives in Tanzania. Water. 2018;10(8):1018. https://doi.org/10.3390/w10081018.

111. Blango MM, Cooke RAC, Moiwo JP. Effect of soil and water management practices on crop productivity in tropical inland valley swamps. Agric Water Manag. 2019;222:82–91. https://doi.org/10.1016/j.agwat.2019.05.036.
112. Tenge AJ, De Graaff J, Hella JP. Social and economic factors affecting the adoption of soil and water conservation in West Usambara highlands, Tanzania. Land Degrad Dev. 2004;15:99–114. https://doi.org/10.1002/ldr.606.
113. Mboyerwa PA, Kibret K, Mtakwa P, Aschalew A. Greenhouse gas emissions in irrigated paddy rice as influenced by crop management practices and nitrogen fertilization rates in eastern Tanzania. Front Sustain Food Sys. 2022;6: 868479. https://doi.org/10.3389/fsufs.2022.868479.
114. Gitonga JW. Evaluation of Greenhouse Gas Emissions and Water Productivity from Rice Production as Affected by Water Management and Soil Type in Mwea, Central Kenya. Abstract, digital repository, Jomo Kenya University of Agriculture and Technology. 2020. http://ir.jkuat.ac.ke/handle/123456789/5417. Accessed 15 Jan 2023.
115. Oladele OI, Chimewah AN, Olorunfemi OD. Determinants of farmers' adoption of alternate wet and dry techniques in lowland rice production in ghana, uganda and cameroon for climate smart agriculture. J Dev Areas. 2019;53(3):169–81. https://doi.org/10.1353/jda.2019.0045.
116. Gebrechorkos SH, Hülsmann S, Bernhofer C. Changes in temperature and precipitation extremes in Ethiopia, Kenya, and Tanzania. Int J Climatol. 2018;39(1):18–30. https://doi.org/10.1002/joc.5777.
117. Gebrechorkos SH, Hülsmann S, Bernhofe KC. Statistically downscaled climate dataset for East Africa. Sci Data. 2019;6:3. https://doi.org/10.1038/s41597-019-0038-1.
118. Isaev E, Yuave N, Inape K, Jones C, Dawa L, Sidle RC. Agricultural drought-triggering for anticipatory action in Papua New Guinea. Water. 2024;16:2009. https://doi.org/10.3390/w16142009.
119. Rockstrom J. Water resources management in smallholder farms in Eastern and Southern Africa: an overview. Phys Chem Earth. 1999;25(3):275–2832000.
120. Mbowa SH, Mudahemuka W, Kaaya S, Asiimwe S. Contribution of run-off water harvesting to food production in Kyannamukaaka Sub County, Uganda. J Res Inn Impl Edu. 2020;4(3):9–18.
121. Vohland K, Barry B. A review of in situ rainwater harvesting (RWH) practices modifying landscape functions in African drylands. Agric Ecosyst Environ. 2009;131:119–27. https://doi.org/10.1016/j.agee.2009.01.010.
122. Yosef BA, Asmamaw DK. Rainwater harvesting: an option for dry land agriculture in arid and semi-arid Ethiopia. Int J Water Res Environ Eng. 2015;7(2):17–28. https://doi.org/10.5897/ijwree2014.0539.
123. Dile YT, Karlberg L, Temesgen M, Rockstrom J. The role of water harvesting to achieve sustainable agricultural intensification and resilience against water related shocks in sub-Saharan Africa. Agric Ecosyst Environ. 2013;181:69–79. https://doi.org/10.1016/j.agee.2013.09.014.
124. Sidle RC, Hornbeck JW. Cumulative effects: a broader approach to water quality research. J Soil and Water Conserv. 1991;46:268–71.
125. Amede T. Technical and institutional attributes constraining the performance of small-scale irrigation in Ethiopia. Wat Res Rural Dev. 2014;6:78–91. https://doi.org/10.1016/j.wrr.2014.10.005.
126. Haefele SM, Nelson A, Hijmans RJ. Soil quality and constraints in global rice production. Geoderma. 2014;235:250–9. https://doi.org/10.1016/j.geoderma.2014.07.019.
127. Van Oort PA, Zwart SJ. Impacts of climate change on rice production in africa and causes of simulated yield changes. Glob Change Biol. 2018;24:1029–45. https://doi.org/10.1111/gcb.13967.