Preprint article title: The Role of Climate Change for Transboundary Crop Pest Outbreaks in IGAD Member States – Challenges for Integrated EWS and Governance. A Review

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Preprint statement: This article is a preprint and has not been peer-reviewed.

Keywords: *transboundary crop pests, climate change, early warning systems, desert locust, fall armyworm, African armyworm, tomato leafminer, quelea birds, food security, IGAD, pest management, East Africa*

The Role of Climate Change for Transboundary Crop Pest Outbreaks in IGAD Member States – Challenges for Integrated EWS and Governance. A Review

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Abstract

This paper is based on the review of scientific literature and consultations with member states of the Intergovernmental Authority on Development (IGAD). Climate change is having a profound impact on the IGAD region, with rising temperatures and shifting rainfall patterns driving both extreme weather events and agricultural pest outbreaks. This review addresses the threat posed by five major transboundary crop pests: fall armyworm (*Spodoptera frugiperda*), African armyworm (*Spodoptera exempta*), tomato leaf miner (*Tuta absoluta*), red-billed quelea (*Quelea quelea*), and desert locust (*Schistocerca gregaria*). The lifecycle, behaviour, and economic impact of each pest are examined, with a particular focus on the role of climate change in intensifying their proliferation and spread. The paper also assesses current pest management strategies and identifies their shortcomings. It advocates for advancements in Early Warning Systems (EWS), emphasizing the need for integrating advanced technologies to prevent and manage the emergence and spread of transboundary pests. The paper calls for a holistic and integrated approach to pest management, incorporating climate services and fostering community-based interventions. It underscores the need to rethink governance to equip EWS for future challenges and stresses the importance of continuous research and international cooperation to build sustainable and resilient agricultural systems.

Contents

Abbreviations

AAW - African Armyworm

DL - Desert Locust

DLIS - Locust Information Service

EWS - Early Warning System

FAO - The Food and Agriculture Organisation of the United Nations

FAW - Fall Armyworm

GHACOF - the regional Greater Horn of Africa Climate Outlook Forum

GIS - Geographic Information Systems

ha - hectares

ICPAC - IGAD Climate Prediction and Applications Centre

IGAD - Intergovernmental Authority on Development

IOD - Indian Ocean Dipole

IPCC - Intergovernmental Panel on Climate Change

IPCC AR6 - The Sixth Assessment Report of the United Nations Intergovernmental Panel on Climate Change

IPM - integrated pest management

ITCZ - the Intertropical Convergence Zone

JJAS – June/July/August/September

MAM – March/April/May

OND – October/November/December

RAMSES - Reconnaissance and Management System of the Environment of Schistocerca

QB – Quelea bird

SSP - Shared Socioeconomic Pathways

TA – *Tuta absoluta* (the common name is tomato leaf miner)

UAV - Unmanned Aerial Vehicle

Introduction

Motivated by the escalating threat of transboundary climate-sensitive pests, this paper examines the impact of climate change in the Horn of Africa, focussing on the dynamics of crop pests in the member states of the Intergovernmental Authority on Development (IGAD) - Djibouti, Eritrea, Ethiopia, Kenya, Somalia, Sudan, South Sudan, and Uganda. This region is bearing a heavy impact of climate change effects with high levels of vulnerability for the population. The paper recognizes the interdependence of human, animal, environmental, and plant health, aligning with the principles of One Health. It explores the risks associated with shifting climate patterns and serves as a step towards advancing Early Warning Systems (EWS) through advanced technology, essential for preventing and better managing the emergence and spread of transboundary plant pests. It provides an overview of the situation in the region and lays the groundwork for developing a governance model for innovative and integrated EWS. This includes an overview of current state and initial suggestions for the necessary governance structures. To effectively manage climate-related challenges, it is crucial to integrate advanced digital technologies into the early warning and early action governance system right from the start. This will require further research and capacity development to enable practicability, usability and sustainable implementation.

Methodology

This review examines the impacts of climate change on transboundary crop pests in the Horn of Africa, with a focus on the member states of IGAD. The methodology integrates a review of relevant literature, existing climate data and expert consultations to provide an understanding of pest dynamics and their broader impacts on agriculture in the region. A key contribution of this study is a review of the current status of early warning systems (EWS) for crop pest management in the IGAD region, identifying critical gaps and offering recommendations for improvement. An extensive review of existing scientific literature, reports from international organizations (e.g., FAO, UNEP, IPCC), and regional publications was conducted. The review focused on five key transboundary pests that were identified as serious pests and recommended for research during expert consultations. The pests are Desert Locust (*Schistocerca gregaria*), Fall Armyworm (*Spodoptera frugiperda*), African Armyworm (*Spodoptera exempta*), and Tomato Leafminer (*Tuta absoluta*). The selected literature examined the relationship between climate variability—such as changes in temperature, precipitation, and extreme weather events—and pest behaviour, distribution, and impacts. Regional climate data were sourced from existing analyses provided by ICPAC and other recognized sources. Rather than conducting original analysis, this review incorporates these data to provide an understanding of the environmental context in which pest dynamics were reviewed. Consultations were held during the Greater Horn of Africa Climate Outlook Forum (GHACOF) 2024, where insights from regional climate and agriculture experts were integrated into the study. These discussions provided an understanding of the linkages between climate trends and pest dynamics. Feedback from stakeholders, including pest as well as disaster risk management professionals, was instrumental in understanding the specific climatic and agricultural challenges faced by IGAD member states. Consultative workshop was entitled “the Regional Stakeholder Consultation Workshop on Pest Early Warning Systems in the Greater Horn of Africa” and took place in Kampala, Uganda on February 22nd and 23rd, 2024. The participants included five representatives from ICPAC, two from the IGAD Disaster Risk Management team, two from TMG Research, one representative from the International Centre of

Insect Physiology and Ecology, and one from the Centre for Agriculture and Bioscience International and Plant Protection teams of the IGAD Member States, who served as focal points from the relevant ministries at the national level. A total of 27 participants attended.

Climate change and its impact on IGAD member states

This section explores the impact of climate change on IGAD member states, initially outlining key factors like rising temperatures and changes in rainfall. This provides context for our review of how climate change influences the dynamics of transboundary crop pests.

The Sixth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC AR6) echoed the increasing frequency and severity of extreme weather events, — a trend expected to intensify (IPCC, 2022). Human activities have to a large extent caused global temperatures to increase by 1.25°C (Matthews and Wynes, 2022). According to Matthews and Wynes (2022) warming is likely to exceed 1.5°C in the next 10 years if global greenhouse gas emissions are not reduced significantly. Climate patterns have already shifted in the IGAD member countries, with certain regions experiencing increases in temperature of up to 2°C.

Climate projections indicate that the IGAD region is on a trajectory towards a warmer future, markedly surpassing the global average (Choi et al., 2023; Osiima et al., 2018). Figure 1 shows projected annual temperature trend / anomalies over the Greater Horn of Africa between 1951 and 2100. As Figure 1 demonstrates, the temperature anomalies vary significantly across the different scenarios. Under the Shared Socioeconomic Pathway (SSP) 1-2.6 scenario, which assumes strong mitigation efforts, the temperature increase is more moderate. In contrast, the SSP5-8.5 scenario, which represents a high-emission future, shows a substantial rise in temperatures. Figures 2 and 3 show projected temperature change during three main seasons in the region for the years 2031-2060 and 2071-2100. Such long-term changes in climatic conditions will disrupt people's lives in various ways. Due to climate variability, the frequency and intensity of disasters such as floods, droughts, pest and disease outbreaks, will change, necessitating adaptations in agricultural practices and the migration patterns of people and animals. Local communities, state actors, businesses, and supra-national organizations all must build capacities to plan for and adapt to these changes.

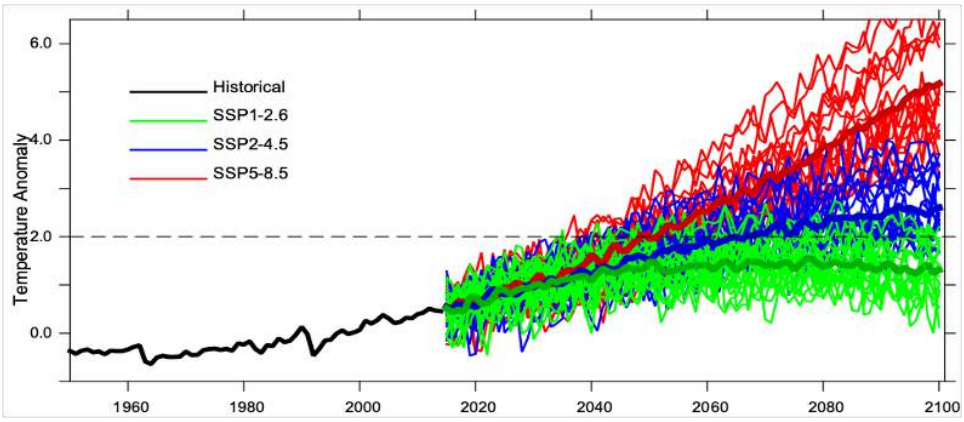


Figure 1: Projected annual temperature trend / anomalies (1951-2100) under SSP1-2.6 (green), SSP2-4.5 (blue) & SSP5-8.5 (red) averaged over the Greater Horn of Africa region (Source: ICPAC).

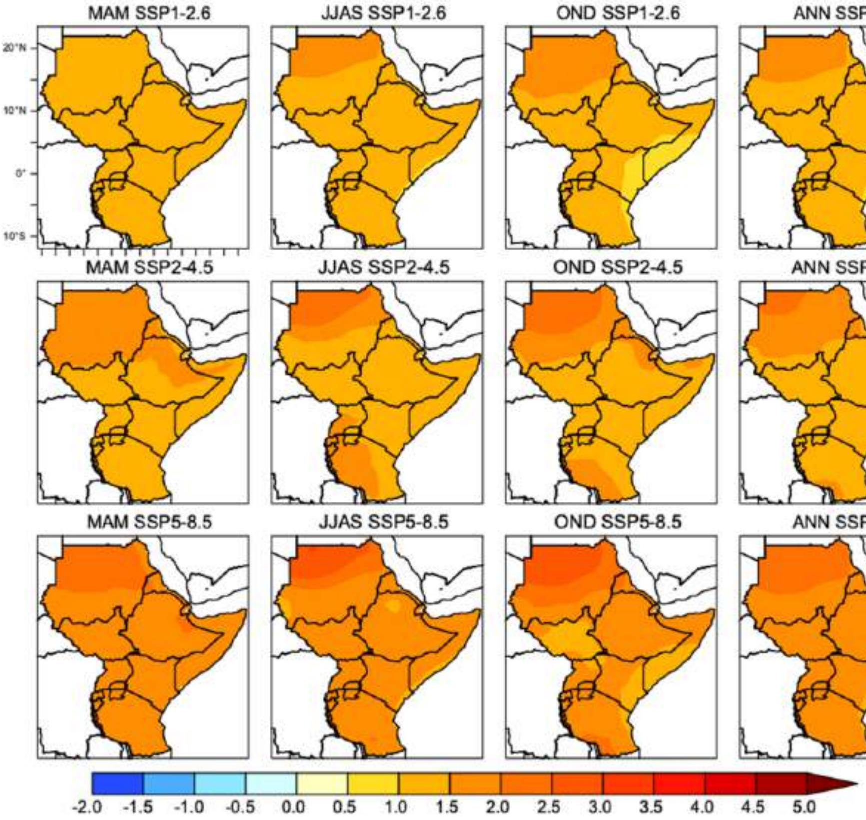


Figure 2: Projected temperature change (°C) during MAM, JJAS, OND & Annual (left-right) corresponding to SSP1-2.6, SSP2-4.5 & SSP5-8.5 (top-bottom) for 2031-2060 (Ref. Period: 1961-1990, Source: ICPAC).

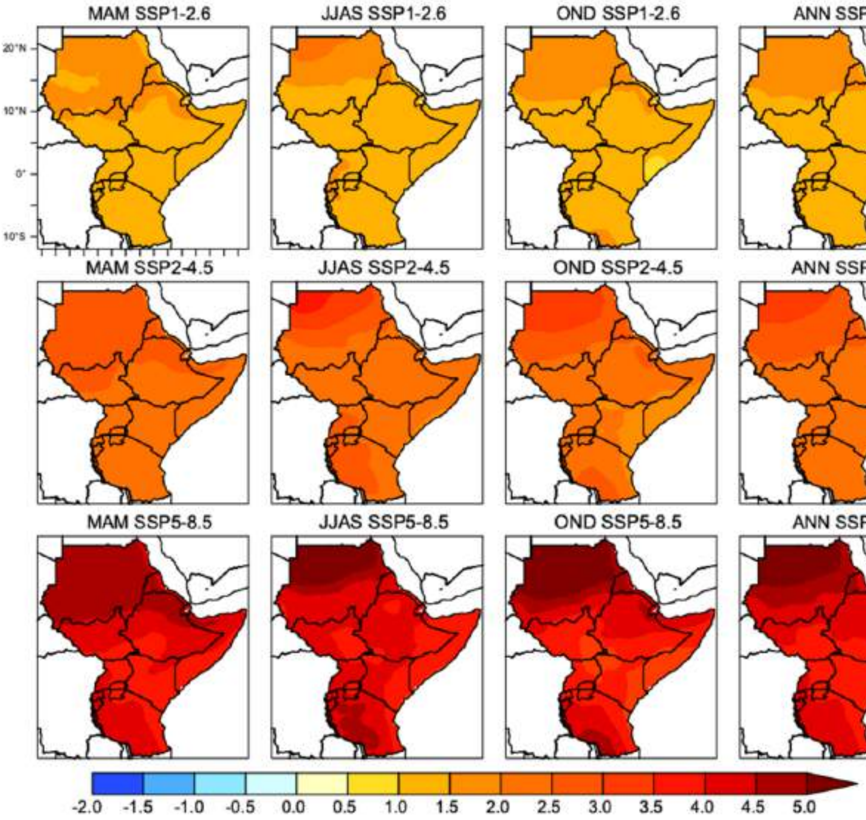


Figure 3: Projected temperature change (°C) during MAM, JJAS, OND & Annual (left-right) corresponding to SSP1-2.6, SSP2-4.5 & SSP5-8.5 (top-bottom) for 2071-2100 (Ref. Period: 1961-1990, Source: ICPAC).

Recent research highlights the complexity and diversity of future rainfall patterns in Eastern Africa (Ongoma et al., 2018; Ayugi et al., 2021). Ayugi et al. (2022) utilized the Coupled Model Intercomparison Project Phase 6 (the current global climate model data available) to understand future climate scenarios and provide insights into temperature rises, precipitation patterns, sea-level changes, and the intensity and frequency of extreme weather in the IPCC AR6 (IPCC, 2022). Ayugi et al. (2022) predicted more frequent wet events in eastern and northern Kenya, linking these occurrences to broader climate change impacts. Very wet and extremely very wet days increase, especially over Uganda and western Kenya during the mid and end of the 21st century (Ongoma et al., 2018). Figure 4 shows projected rainfall change (%) during main seasons for the years 2031-2060 and Figure 5 for the years 2071-2100, respectively.

Excessive rainfall results in floods, overwhelming run-off, erosion and degradation. Flooding has had a significant damage to crops, informal settlement, and drainage and transport infrastructure in parts of Somalia, South Sudan, Uganda, Kenya, and Ethiopia (Balikuddembe et al., 2023; Richardson et al., 2022). This is, however, not uniform. Gebrechorkos et al. (2023) reported an increase in frequency and intensity of extremes that manifest in the form of intense rainfall (floods), heat waves and prolonged drought.

The IGAD region has experienced increasing droughts, particularly noticeable during the long rainfall season (March - May), due to a significant decline in rainfall (Funk et al., 2023). Drought has affected agriculture (crops, livestock, and fisheries) and water resources in most member states of IGAD region. The prolonged drought of 2020/2023 with recorded 5 consecutive failed rainfall seasons was particularly devastating. It led to death of millions of livestock and wildlife, crop failure and decline in water availability (water stress) affecting socio-economic wellbeing of communities and economic growth in Kenya, Ethiopia and Somalia (Awange, 2022; Wanjara and Ogembo, 2023). Moreover, Haile et al. (2020) predicted that climate change is likely to result in an expansion of the drought-affected region in Eastern Africa.

According to recent studies, a combination of an increase in temperature and a decline in rainfall is associated with increasing dryness and loss of vegetation cover, which contributes to extensive and widespread wildfires (Palmer et al., 2023; Grillakis et al., 2022). Researchers suggest that these wildfires have become common particularly due to the increase in frequency, duration, and intensity of droughts in Eastern Africa linked to climate change (Palmer et al., 2023). This sequence of events underscores the interconnectedness of climate change impacts, from reduced rainfall leading to droughts and wildfires, which in turn trigger a cascade of ecological consequences, such as destruction of rangelands and forests ecosystems and biodiversity loss (Mwangi et al., 2018).

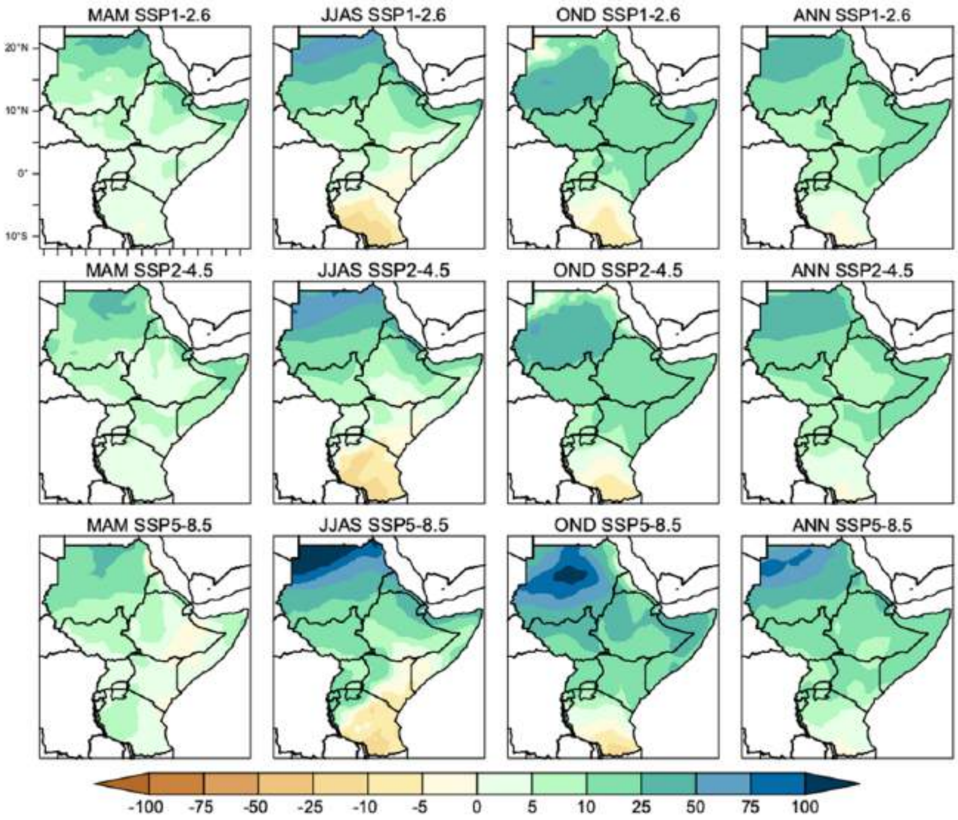


Figure 4: Projected rainfall change (%) during MAM, JJAS, OND & Annual (left-right) corresponding to SSP1-2.6, SSP2-4.5 & SSP5-8.5 (top-bottom) for 2031-2060 (Ref. Period: 1961-1990, Source: ICPAC).

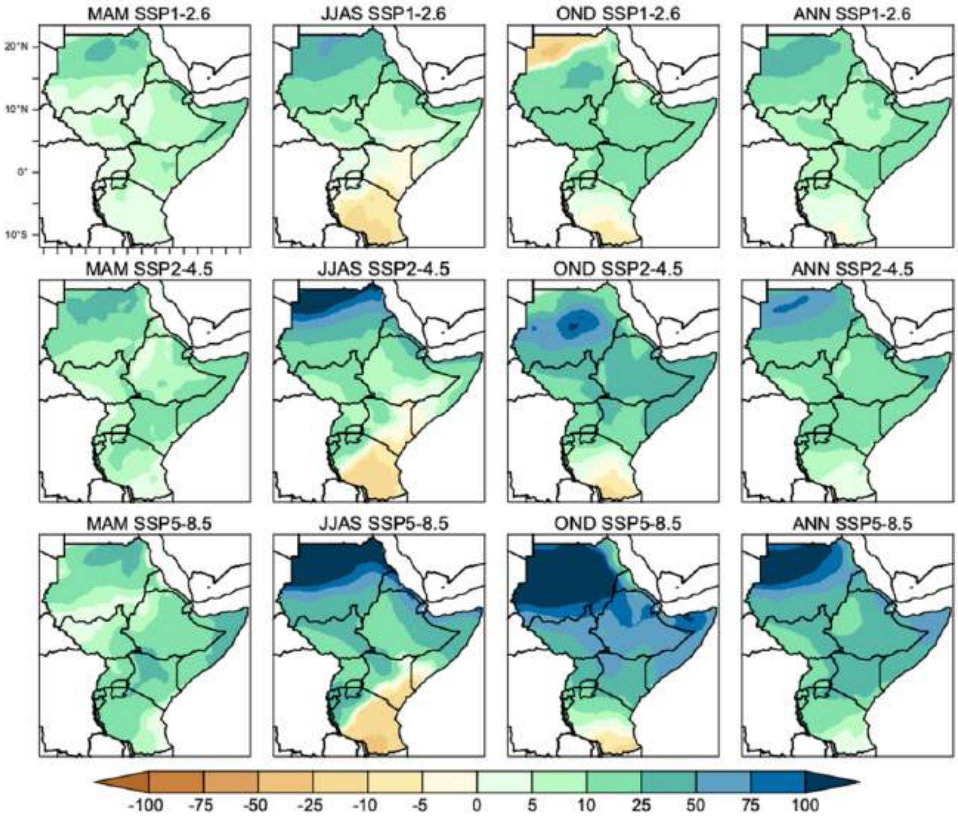


Figure 5: Projected rainfall change (%) during MAM, JJAS, OND & Annual (left-right) corresponding to SSP1-2.6, SSP2-4.5 & SSP5-8.5 (top-bottom) for 2071-2100 (Ref. Period: 1961-1990, Source: ICPAC).

A combination of rising temperatures and reduced rainfall has also resulted in the diminishing of mountain glaciers, notably on Mt. Rwenzori and Mt. Kenya (Daughty et al., 2023; Mizuno, 2022; Njoki, 2022). Mountain glaciers are a major source of fresh water that replenish key water bodies including rivers that provide hydroelectric power. For example, the Seven-Forks dam on river Tana in Kenya receives its waters from glaciers on Mt Kenya. Research has indicated that if glacial melt continues at the current rate, most mountains in Eastern Africa will lose their glaciers by 2050, resulting in the drying of several rivers (Njoki, 2022). Such a scenario would severely impact hydropower generation and fishing operations, disrupting the livelihoods of communities and the overall economic stability of the IGAD region.

Building on the discussion of climatic extremes, Finney et al. (2020) highlighted the increasing frequency in tropical cyclones in the recent years, attributed largely to increased warming, particularly in the Indian Ocean. Tropical Cyclones have in turn affected low-level wind circulation and rainfall characteristics during the critical rainfall seasons especially March – May (MAM). Tropical cyclones (depending on the position and orientation) have altered rainfall onset, caused increase in dry spells, and led to intense rainfall affecting parts of Somalia, Kenya, and Uganda (Kai et al., 2021). Late onset accompanied with early rainfall cessation (withdraw) leads to a shortened agricultural growing season and crop failures.

Following the theme of climatic disruptions, coastal regions have not been spared the consequences of climate change, as evidenced by the work of Widlansky et al. (2020). The expansion of the ocean, driven by sea level rise and intensified by stronger waves and tides, has wreaked havoc on coastal infrastructure and facilities. Sea level rise has been associated with intrusion of salty waters (salinization) that affect fresh surface and under-ground water availability along most coastal areas of Kenya, Somalia, and Djibouti (Idowu and Lasisi, 2020). The recent period has also seen fluctuation of inland lake water levels that have disrupted settlement, transport, tourism, and farming/fishing activities around major lakes (Nassali et al., 2020; Odenyo and Verdonck, 2015). Heavy storms and strong winds have also increased particularly over Lake Victoria leading to death of fishermen in the region (Thiery et al., 2017). Moreover, fishers have reported a decline in fish catch due rising lake temperatures (Outa et al., 2020).

This section has demonstrated that climate change not only manifests in clearly visible impacts such as droughts and floods, but also exerts complex, broad and less obvious effects on ecosystems and livelihoods. One critically important yet under-researched aspect of climate change—including temperature, rainfall, drought, and related events—is its impact on agricultural pests and their role in exacerbating food insecurity.

Pests have long been a major concern for farmers due to their ability to reduce crop yields, damage produce, and increase production costs. However, recently the IGAD region has witnessed an increase in activity of crop pests such as DL, FAW, AAW, TA and QB. These five pests were identified as serious agricultural threats in the IGAD region during consultations with member state representatives that took place in February 2024, on the fringes of the regional Greater Horn of Africa Climate Outlook Forum (GHACOF). In subsequent sections, we explore these pests, their lifecycles and impact on agriculture as well as factors such as temperature, rainfall, and drought that impact their proliferation and spread. For example, temperature fluctuations directly affect insect pest growth, reproduction, and survival, with rising temperatures altering the distribution of multiple pest species (Jaramillo et al., 2011; Müller et al., 2022).

Climate change has introduced both certainty and uncertainty: while it is certain that new crop pests will continue to emerge and existing ones will shift into new areas, predicting the specifics of these shifts remains challenging (CGIAR, 2022; Müller et al., 2022). Therefore, this paper also examines technological innovations for innovative pest EWS. Given the high levels of uncertainty, there is a need for adaptive, versatile systems that enable stakeholders at various governance levels and in different geographical areas to exchange information, coordinate preparedness, and strengthen response efforts. Therefore, we call for a rethinking of early warning governance so that EWS are equipped for future challenges.

Setting the scene: EWS and IGAD

The Early Warnings for All initiative aligned with the Sendai Framework for Disaster Risk Reduction 2015–2030 aims to cover every person on Earth with early warnings by 2027 (UN n.d.; UNDRR, 2015). However, despite these global goals and significant technological leaps, the situation on the ground prompts critical introspection. Since 2015, the number of people affected by disasters has surged by 80-fold, revealing often limited preparedness, response, and resilience in the face of these events (UN, 2023). Moreover, the Global Assessment Report (GAR2022), released by the United Nations Office for Disaster Risk Reduction (UNDRR, 2022) projects 560 disasters a year – or 1.5 disaster each day by 2030, underscoring the urgency for disaster risk reduction strategies. As climate extremes become the "new normal," the need for effective EWS becomes ever more evident. These systems are essential for proactively managing the multifaceted risks of climate change, including the often-overlooked issue of transboundary crop pests.

As discussed above and represented by various studies, climate change already represents a formidable challenge for the IGAD region. The region, already vulnerable due to its economies' deep reliance on climatic conditions, faces intensified risks from climate variability and extremes (Abbass et al., 2022). This vulnerability is manifested in sectors crucial for socio-economic stability, including agriculture, water resources, tourism, coastal and marine resources, transport, and forestry. Recent studies have quantified these impacts in the IGAD region pointing to evidence of worsening risks and increase losses from current variability (and extremes) and future climate change risks across sectors (Gebrechorkos et al., 2023; Mwangi et al., 2020; Ogega and Alobo, 2020; Sabiiti et al., 2018). The World Meteorological Organization (WMO) indicates damage and loss figures because of climate and water related disasters in Africa.

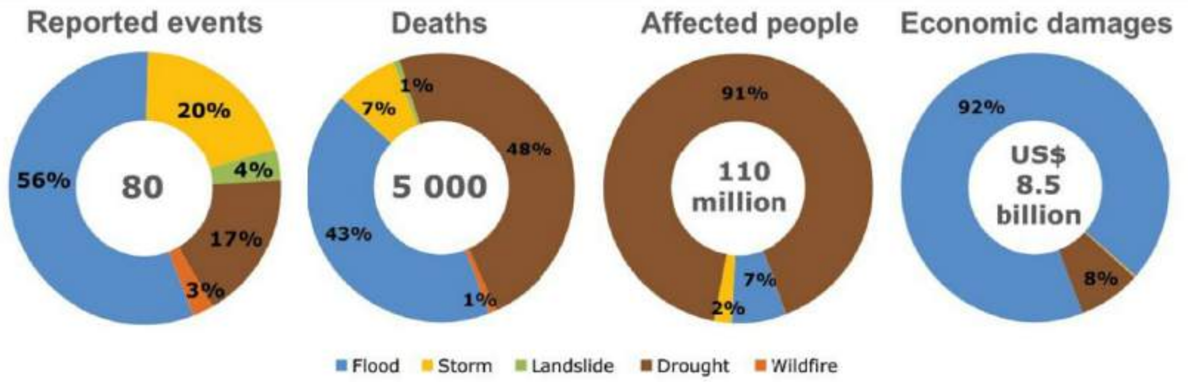


Figure 6. Weather-, climate- and water-related disasters in Africa in 2022. Note: The economic damages of some disaster occurrences are not presented in the figure due to data unavailability. Data as of June 2023 from EM-DAT. Source: WMO State of the Climate in Africa 2022; Climate-related risks and socioeconomic impacts. Pg. 16)

IGAD and its member states convene for the regional GHACOF, held three times a year, to deliberate on these impacts. This forum serves as a platform to analyze seasonal climate forecasts and possible implications and co-produce advisories for key development and humanitarian sectors of the member countries, subsequently informing the formulation of the national preparedness plans. The primary challenge lies in effectively translating these warnings into prompt action. According to ICPAC (*Pers. Comm.*), this is hindered by several factors, including limited institutional capacity to swiftly respond to early warnings, systems that are more reactive than proactive in nature, focusing on response rather than anticipation and inadequate resources allocated for anticipatory action impeding the ability to take proactive measures in anticipation of potential disasters. Addressing these challenges is crucial for enhancing disaster preparedness and resilience in the region.

Key pests: the Fall armyworm, African armyworm, tomato leaf miner, red-billed quelea birds and desert locust

Table 1 provides an overview of five major agricultural pests affecting the IGAD region: FAW, AAW, TA, QB and DL. It summarises their lifecycles, problematic stages for agriculture, affected crops, characteristics of oviposition sites, phenology, migratory behaviour, significant adaptations, economic impacts, and origins. Understanding these aspects is crucial for developing effective pest management strategies to mitigate their adverse effects on agriculture in the region.

Table 1. Overview of five major transboundary crop pests in the IGAD region

Pest	Lifecycle	Problematic Stage for Agriculture	Crops Affected	Characteristics of Oviposition Sites	Phenology	Migratory Behaviour	Significant Adaptations	Economic Impact	Origin
Fall armyworm (Day et al., 2027; CABI, 2023)	28-30 days, 6 instars	Larval stages	Maize, rice, sorghum, cotton	Near the base of plants, on leaves	Warm and humid conditions	Rapid spread across regions	Pesticide resistance, voracious feeding	Significant yield losses, increased control costs	Invasive
African armyworm (Brown 1962; Woodrow et al., 1987)	22-30 days, 6 instars	Larval stages	Sorghum, millet, wheat, rice	Grasses, cereals, edges of leaves	Breeding cycles dependent on rainfall	Localized migration influenced by wind, swarming behaviour	Rapid population growth, reduced molting stages	Complete crop failures in localized areas	Native
***Tomato leaf miner* (Desneux et al., 2010)**	30-40 days, 4 instars	Larval stages	Tomatoes, potatoes, eggplants	Underside of leaves, near veins	Linked to crop cycles, higher in warm conditions	Facilitated by human activity, short-distance migration	High fecundity, insecticide resistance	Significant crop losses, high control costs	Invasive
***Quelea birds* (Whittington-Jones 2001; (Dallimer and Jones, 2002,)**	N/A	Adult and flocking stages	Rice, millet, sorghum	Near water bodies, in tall trees or reeds	Seasonal breeding linked to rainfall	Regional migrations for food availability	Formation of massive flocks, rapid crop consumption	Severe damage to grain crops, major food security loss	Native
Desert locust (WMO and FAO 2016)	Eggs: 10-65 days, Hoppers: 24-95 days,	In gregarious stage as hopper bands and	Cereals, vegetables, pasture	Bare sandy soil, and soil moisture, permanent	Seasonal, linked to rainfall and related soil moisture	Long-distance flights, up to 150 km/day	Polyphenism, high reproductive rate	Extensive, can destroy crops	Native. Frontline countries: Sudan, Eritrea,

	Adults: 2,5-5 months	swarming adults		breeding sites are found in deserts of Africa and Arabic Peninsula	and vegetation growth			across large areas	Ethiopia, Somalia, and Djibouti. Expansion countries: Kenya, Uganda, South Sudan.

Fall armyworm’s lifecycle, behaviour, and implications for agriculture

FAW, *Spodoptera frugiperda*, native to the tropical and subtropical Americas, has quickly emerged as a significant threat to agriculture worldwide, with a pronounced impact on Eastern African nations under IGAD umbrella. First detected in West Africa in 2016 (Goergen et al., 2016), this invasive species has rapidly expanded across the continent, causing widespread devastation to croplands. This pest predominantly attacks maize, a staple in the IGAD region, but its threat spans over 80 plant species, including rice, sorghum, millet, sugarcane, vegetables, and cotton, severely affecting food security and agricultural biodiversity (Table 1) (Assefa and Ayalew, 2019; Niassy et al., 2021).

FAW's life cycle, encompassing stages from egg, larval (with several instars), pupal, to adult (moth), can conclude in approximately 30 days under optimal conditions (Navasero and Navasero, 2020). However, this duration varies across the IGAD member states due to environmental differences. The pest can produce up to 4-6 generations annually in the region's warmer climates, supported by generally favourable conditions throughout the year (Silva et al., 2017). The warm and wet seasons, typically from late March to October, are particularly conducive to FAW's rapid population growth, though the timing and severity of outbreaks can differ significantly across the varied climatic zones of the member countries (Guimapi et al., 2022; Niassy et al., 2021). Local agricultural practices, the timing of the rainy season, and the availability of control measures heavily influence the frequency of these outbreaks. Furthermore, FAW's migratory behaviour, facilitated by its ability to fly long distances with the wind, enables its swift spread across borders, complicating containment efforts (Niassy et al., 2021). Seasonal winds play a critical role in this migration, potentially introducing FAW to new areas where it can establish further populations (Overton et al., 2021; Kumar et., 2022).

In IGAD nations such as Ethiopia, Kenya, Uganda, and Somalia, FAW infestations have led to considerable economic losses, and increased food security concerns. Ethiopia and Kenya, in particular, bear the brunt of these outbreaks due to their vast areas of maize cultivation, FAW's preferred host. Severe infestations have been reported in these countries, especially in regions with optimal breeding conditions for the pest (Abro et al., 2021; Day et al., 2017; De Groote et al., 2020). Uganda has also experienced significant impacts, notably in its northern and eastern regions (Sharon et al., 2020). Somalia, despite the challenges in pest monitoring, has reported the presence of FAW in its agricultural domains (Assefa and Ayalew, 2019; Niassy et al., 2021).

The economic toll of FAW in the IGAD region is considerable. Day et al. (2017) estimate that, without the implementation of control measures, Fall Armyworm (FAW) could result in annual maize yield losses of between 8.3 and 20.6 million tonnes across 12 of Africa's maize-producing nations. This loss corresponds to 21% to 53% of the total maize production in these countries, based on an average production over a three-year period. To illustrate, In Ethiopia, FAW poses a significant risk for 9.6 million maize-producing smallholders. Current reports suggest that a quarter of the 2.9 million ha of land planted with maize is infested by FAW, resulting in a loss of more than 134,000 tons of maize production (Beemer, 2018). Such losses could have fed about 1.1 million individuals.1 In addition to yield reductions, the country has also incurred significant expenditures on insecticides and monitoring costs. For instance, in the 2017 cropping season, the country spent about US$4.6 million to purchase 277,000 litres of insecticides and equipment for surveillance work to trace and track pest infestations.

Infestations can cause yield losses of 20% to 50% in severely affected areas, with some instances of total crop failure reported where management interventions were delayed or ineffective (Abro et al., 2021; Ghimire and Bhetwal, 2021; Omwoyo et al., 2022; Overton et al., 2021). Annual crop losses in sub-Saharan Africa, particularly affecting maize, sugarcane, rice, and sorghum due to FAW, are estimated to reach around USD 13 billion (Abrahams et al., 2017). This situation places the livelihoods of millions of smallholder farmers at risk, with over 300 million people in sub-Saharan Africa potentially affected by the cascading effects of FAW on food security and agricultural productivity (Overton et al., 2021). The damage to staple crops like maize directly affects food availability and prices in local markets, exacerbating food insecurity and malnutrition issues, especially in regions where agriculture is a critical part of the economy, and communities are already facing food shortages (Abro et al., 2021).

African armyworm’s lifecycle, behaviour, and implications for agriculture

AAW, *Spodoptera exempta*, is a native pest presenting a significant concern in the IGAD region (Brown, 1962). Understanding the severity of the AAW threat requires examining its lifecycle, which includes egg, larva (with several instars), pupa, and adult (moth) stages, and its consequences for agriculture. Under favourable conditions, AAW populations can soar exponentially (Rose et al., 1995). A single female moth may lay up to 1,000 eggs during her lifetime, which can hatch in 2-3 days under optimal conditions (Aguilon and Velasco, 2015). Larvae may reach maturity in about 14-22 days, dependent on environmental factors. This rapid development enables multiple generations within a single crop growing season, leading to a swift population explosion. For instance, a single generation could potentially increase twenty-fold, escalating an initial population of 10,000 to 200,000 in under a month leading to what is known as an “outbreak generation”(Khasimuddin, 1981). This term refers to those pest population generations that result in significant crop damage, a concept distinct from the general term "generation," which encompasses any life cycle completion from egg to the end of the adult phase. Not all generations lead to an outbreak, with factors like environmental conditions and food source availability playing roles (Khasimuddin, 1981; Rose, 1975).

AAW poses a significant threat to agriculture due to its "extensive feeding habits", rapid reproduction and migratory behaviour. Larvae feed on more than 80 different plant species, including vital cereal crops and various grasses, with a single larva consuming approximately 30 square centimetres of leaf material daily (Parker and Gatehouse, 1985; Woodrow et al., 1987; Aguilon and Velasco, 2015). AAW larvae can cause total crop defoliation and substantial loss of natural vegetation, affecting pasture resources for livestock. Furthermore, ability to produce up to 13 generations annually in favourable climatic conditions such as warm temperatures and sufficient moisture, exacerbates this threat (Woodrow et al., 1987).

AAW is known for its periodic outbreaks, which are often linked to specific environmental conditions. While it is generally understood that these outbreaks occur in cycles, further research is needed to better understand the precise factors driving these patterns, particularly the influence of climatic variables such as drought and rainfall. Moreover, adult moths, emerging after pupation, exhibit migratory behaviour, forming large swarms that travel several hundred kilometres in a sequence of only a few nights, driven by wind currents (Woodrow et al., 1987). This allows them to invade new areas far from their initial breeding sites (Woodrow et al., 1987; Tucker, 1994). The swarms' ability to swiftly colonize new territories makes them a formidable force, inflicting extensive damage on crucial crops like maize, wheat, sorghum, and millet, thereby destabilizing agricultural communities (Brown et al., 2022). The Food and Agriculture Organisation of the United Nations (FAO, 2023) documented that in 2022 outbreaks of AAW impacted five of the nine Eastern African countries. The extent of agricultural impact varied depending on the growth stage of the attacked plants, with damage ranging from 9 percent for early whorl stage to a complete loss of 100 percent at the pre-tassel stage (FAO, 2023).

Tomato leaf miner’s lifecycle, behaviour, and implications for agriculture

TA, *Tuta absoluta,* commonly known as the tomato leaf miner, South American tomato moth and tomato pinworm, is a devastating transboundary pest that poses a significant threat to tomato cultivation (Desneux et al., 2010). Originating from South America, TA has spread rapidly across the globe, including to East African countries, causing extensive damage to tomato crops, one of the most important vegetables in terms of economic value and nutritional importance in the region. The pest was first reported in Europe (Spain) in 2006 and made its way to Africa shortly thereafter. Sudan reported the pest in 2010 (Mohamed et al., 2012), highlighting the pest’s rapid spread across borders. In Ethiopia, the pest was first identified in 2012. Kenya detected TA in 2014 (Tonnang et al., 2015), followed by Uganda (Tumuhaise et al., 2016) where it was reported around 2015-2016. These detection years underscore the swift movement and establishment of TA across diverse ecological zones within the IGAD countries. However, for nations like Somalia, Djibouti, South Sudan, and Eritrea, precise detection years are harder to ascertain due to limitations in data availability and agricultural monitoring systems. The reported years of detection are based on the earliest documented instances of the pest’s presence, though it is plausible that TA had established populations prior to these observations. The data on detection timelines across these countries reflects the challenges in pest surveillance and the shortfall to curb the spread of this invasive species.

TA has seen its rapid global and regional expansion facilitated notably by the global trade and transportation of agricultural products (Campos et al., 2017). The transportation of tomato products, including seedlings and fruits, plays a crucial role in this process. These items often harbour larvae and eggs, making international shipments a primary vector for the pest’s cross-border dissemination (Desneux et al., 2010). The intensive cultivation of tomatoes, particularly in controlled environments like polytunnels and greenhouses, provides an ideal habitat for TA, supporting its survival and rapid population growth. These methods, while increasing yield and extending growing seasons, also circumvent the natural climatic limitations on the pest's lifecycle (Tropea Garzia et al., 2012).

Furthermore, while TA is not as migratory as, for instance FAW, the adult moths of TA possess flight capabilities, enabling them to travel short and long distances when facilitated by winds. As detailed by Machekano et al (2018), wind patterns critically influence the spread of TA across broad regions (Table 1). Additionally, the pest's establishment in new territories is often aided by the absence of effective natural predators, a problem exacerbated by agricultural landscapes that lack biodiversity. This ecological imbalance allows TA populations to grow unchecked (Campos et al., 2017).

The lifecycle of TA, encompassing the moth, egg, larva (several instars), and pupa stages, facilitates its rapid population growth and extensive damage to tomato crops. TA larvae burrow into tomato leaves, stems, and fruits, feeding on the plant tissues and leading to direct damage (Desneux et al., 2010). While tomatoes (*Solanum lycopersicum*) are the primary and preferred host for TA, contributing significantly to its population growth due to the global importance and widespread cultivation of this crop, the pest is also known to infest other plants in the Solanaceae family. While not as preferred as tomatoes, potatoes can host TA, especially in regions where tomatoes are not available year-round (Bawin et al., 2016; Desneux et al., 2010). Similar to potatoes, eggplants can serve as an alternative host, supporting the survival and proliferation of the pest in diverse agricultural systems (Cherif and Verheggen, 2019; Desneux et al., 2010). Though less commonly infested, peppers are another potential host that can contribute to the pest's population growth (Bawin et al., 2016). Various wild relatives of cultivated Solanaceae crops can also harbour TA, serving as reservoirs for the pest between cropping seasons or in areas where agricultural hosts are not continuously available (Bawin et al., 2016). These host plants, coupled with conducive environmental conditions facilitate the rapid increase in TA populations (Table 1).

TA poses a substantial economic challenge to agricultural production due to its complex biology and behaviour. This pest's lifecycle is notably rapid, allowing it to complete multiple generations within a single tomato growing season, significantly complicating control efforts (Campos et al., 2017; Desneux et al., 2010). Female moths can lay 250-300 eggs in their lifetime, with a preference for the underside of leaves, stems, and even fruit, leading to immediate and severe damage upon egg hatch (Desneux et al., 2010) (Campos et al., 2017). The larvae, which feed internally within the plant tissue, create serpentine mines in leaves and can bore into stems and fruits, reducing the photosynthetic capacity of the plant and directly impacting crop yield and marketability (Desneux et al., 2010; Campos et al., 2017). Without effective management, losses in tomato production can range from 80% to 100% (Chidege et al., 2016). The Centre for Agriculture and Biosciences International reported mean seasonal production loss based on farmers' own estimates was 114,000 tonnes for Kenya and 10,700 tonnes for Zambia, equivalent to US$ 59.3, and US$ 8.7 million in economic losses respectively.

Red-billed quelea birds' lifecycle, behaviour, and agricultural implications

Often referred to as the "feathered locust," the red-billed quelea (*Quelea Quelea*) is considered one of the most numerous bird species on Earth and a significant transboundary pest (Mcwilliam and Cheke, 2004). Indigenous to sub-Saharan Africa, is a part of healthy ecosystem while also a formidable agricultural pest profoundly affects cereal crops, including sorghum, millet, and rice, causing severe damage (Crook and Ward, 1968). These birds' destructive behaviour is intensified by land use changes and climate variability. The extent of damage they can inflict is staggering, with their capacity to decimate entire fields of crops within an astonishingly short period. Native to the IGAD region, QB have caused periodic outbreaks in countries like Ethiopia, Kenya, and Sudan (Cheke and El Hady Sidatt, 2019; Mcwilliam and Cheke, 2004).

The lifecycle and destructive capacity of QB are intricately connected to Africa's agricultural landscape and seasonal cropping and rainfall cycles. Their breeding periods align with cereal cropping seasons, often beginning with the rainy seasons that provide plentiful food and nesting materials (Whittington-Jones, 2001). This alignment enables the QB to undergo multiple breeding cycles in a single season, a natural survival strategy that unfortunately results in catastrophic consequences for agriculture (Dallimer and Jones, 2002).

Additionally, human-induced changes to natural habitats, especially land clearing, drive these birds toward agricultural lands. Quelea's migration and breeding patterns are also increasingly influenced by human agricultural practices, particularly the advent of irrigated cropping systems. The availability of feedlots throughout the year has potentially altered the QB's traditional migration timings and extents. Understanding these patterns also offers insights into managing and predicting QB movements, allowing for the development of targeted strategies to mitigate crop damage Cheke et al., 2007).

The ability of QB to move long distances searching for food (QB can move 48–64 km in a single day), coupled with high fecundity and availability of preferred food sources, has contributed to large populations abundance in semi-arid regions of sub-Saharan Africa (Mmbaga et al., 2023). Large flocks have the capacity to consume or destroy a field of crops in a short period and then move on to the next (Cheke and El Hady Sidatt, 2019; Mcwilliam and Cheke, 2004). In extreme cases, super flocks, numbering in the millions, have devastated fields within just a few hours of arrival. For context, a single bird consumes approximately 10 grams of grain per day, meaning a flock of one million can devour about 10 metric tons of grain daily. In 2021, FAO estimated that this feeding behaviour results in significant economic losses, with annual crop losses of USD 50 million in Kenya alone (Muiruri, 2023). The frequent formation of flocks in the tens of millions highlights the vast potential for agricultural devastation and the critical need for sustainable pest management. Such remarkable feeding capabilities establish QB as one of the most destructive avian pests in Africa (Cheke et al., 2007).

Desert locust's lifecycle, behaviour, and its implications for agriculture

DL, *Schistocerca gregaria*, is one of the most dangerous transboundary crop pests worldwide (Word Ries at al., 2024). In IGAD region, the episodic outbreaks and invasions are related to favorable environmental conditions in remote breeding sites within deserts of recession areas of about 16 million km^2 from West Africa to western India (Table 1). DL exhibit a remarkable evolutionary adaptation known as phase polyphenism, which allows them to change between solitary and gregarious phases (Uvarov 1977; Pener and Simpson 2009). In solitary phase, DL densities are low, and they behave as individuals, posing no threat to agriculture and playing an important part of a food chain of a healthy ecosystem (Le Gall et al. 2019). In the gregarious phase, the nymphs form dense hopper groups and subsequently marching bands and flying swarms of adults. Highly mobile swarms can migrate from 50 to more than 100 km in a day and consuming green vegetation destroying agriculture and pasture areas. A swarm of 1 km^2 eats the same amount of food in one day as 35 000 people (WMO and FAO, 2016). Such swarms move rapidly to new breeding and feeding areas as a coherent unit and can contain millions of adult locusts, posing a major threat to crops and pastures (Word Ries et al., 2024; WMO and FAO, 2016). The observation of phase change from solitary to gregarious form is a critical early indicator of a developing outbreak and a precursor to adult swarms.

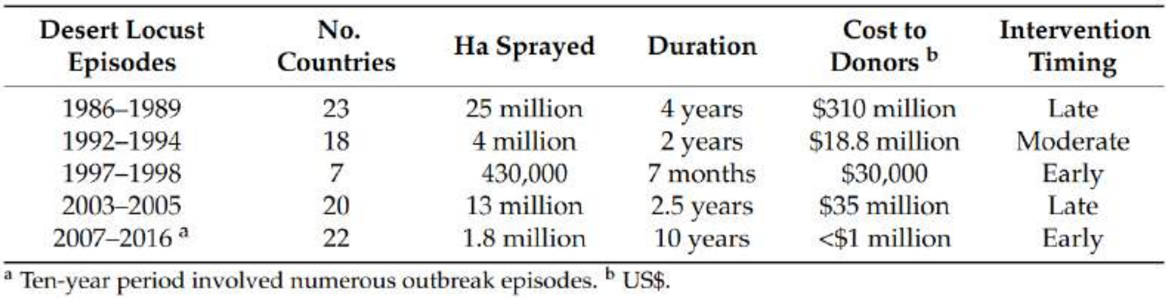
A single female locust can lay multiple egg pods containing up to 100 eggs which can hatch in about two weeks under optimal conditions or last up to 65 days (Brader et al., 2006). The entire life cycle progress depends highly on meteorological conditions and food availability (FAO, 2021). With appropriate soil moisture, the egg development is a function of soil temperature at the egg pod depth (WMO and FAO, 2016). After hatching, nymphs progress through five instars over approximately 24-95 days (36 in average) before reaching adult stage (WMO and FAO, 2016; Guillino et al., 2021). DL as a multi-voltine species can produce 2-5 generations per year (Uvarov,

1977) and its populations can soar exponentially, when environmental and climatic factors, such as rain, soil moisture and fresh green vegetation are favourable.

The gregarious phase (both hopper stage and swarming adult stage) can cause significant damage, devastating green vegetation, pastures, and crops. Furthermore, a highly polyphagous species, DL can expand its diet breadth, threatening both human and animal food security (Salih et al., 2020; Despland 2003). Moreover, DL is a highly migratory pest, with swarms capable of flying several hundred kilometers by riding high-level winds and causing damage far away from its original breeding sites (Lecoq, 1995). Swarm take off also depends on daily temperature and its direction on wind. Wind is the main transportation mechanism of locusts and concentrates them by convergence (WMO and FAO, 2016). For detailed information on thresholds and how meteorological parameters affect different life stages of DL, please refer to the study conducted by the World Meteorological Organization (WMO and FAO, 2016).

The magnitude of DL destruction and economic toll is due to exceptional gregariousness, mobility, voracity, and swarm size (Brader et al. 2006). To illustrate, in 2019, the first wave of desert locust infestations, 70,000 ha of farmland was destroyed in Somalia and Ethiopia, and 240,000 ha of pastureland in Kenya (ReliefWeb, 2020). Furthermore, the campaigns against desert locust are costly, with expenses increasing when the control operations are delayed (Müller et al., 2021; Mullié et al., 2023). Once an outbreak escalates into an upsurge or a plague, the costs skyrocket. FAO and its partners mobilized more than USD 243 million for the 2019-2021 the Horn of African and Yemen upsurge, with total costs surpassing this amount (FAO, 2021). Furthermore, extensive spray of organophosphate pesticides incurs heavy environmental costs due to their toxicity. These chemicals negatively impact non-target organisms, such as bird populations and pollinators like honeybees (Mullié et al., 2023). During the 2003-2005 upsurge, which started in the Western Africa Region, it took US$ 400 million and aerial pesticide operation on about 13 million ha to control DL in more than 20 countries (Brader et al. 2006). Around 13 million liters of insecticides were sprayed against DL nymphs and adults, of which organophosphates chlorpyrifos and malathion were the dominant products. Table 2 compares control campaigns between 1986 and 2016.

Table 2: Desert locust episodes and control related variables (duration, costs) 1986-2016 (Showler at al., 2021).



Desert Locust Episodes	No. Countries	Ha Sprayed	Duration	Cost to Donors [b]	Intervention Timing
1986–1989	23	25 million	4 years	$310 million	Late
1992–1994	18	4 million	2 years	$18.8 million	Moderate
1997–1998	7	430,000	7 months	$30,000	Early
2003–2005	20	13 million	2.5 years	$35 million	Late
2007–2016 [a]	22	1.8 million	10 years	<$1 million	Early

[a] Ten-year period involved numerous outbreak episodes. [b] US$.

Effects of climate change on FAW, AAW, TA, QB and DL

As elaborated in previous chapters, climate change - characterized by rising temperatures, altered precipitation patterns, and more frequent extreme weather events - presents profound challenges for agriculture worldwide. Its relevance to agriculture cannot be overstated, as the sector directly depends on climatic conditions for crop growth (Skendžić et al., 2021). This chapter explores the complex ways climatic changes impact FAW, AAW, TA, QB and DL.

Increasing atmospheric CO2 concentration, the primary driver of climate change, affects agricultural ecosystems by altering interactions between crops and insect pests like FAW, AAW, TA, and QB (Müller et al., 2022). These effects occur primarily through modifications in plant chemistry and habitat conditions, which in turn affect physiology and behaviour of pests (Müller et al., 2022). Elevated CO_2 levels lead to changes in plant nutrient content, particularly reducing nitrogen availability in plant tissues, which is a crucial nutrient for many pests. This can lead to compensatory feeding, where pests like FAW, AAW, and TA consume more plant material to meet their nutritional needs, potentially increasing the damage to crops (Fuhrer, 2003; Tonnang et al., 2022). The altered plant physiology under high CO_2 conditions can also affect pest development rates and reproductive cycles, potentially leading to more rapid population growth and increased insect pest pressure on crops (Fuhrer, 2003; Sokame et al., 2024; Tonnang et al., 2022).

Furthermore, climate change increases the vulnerability of agricultural crops to pest invasions, particularly under extreme weather conditions (Markov et al., 2018; Yihdego, 2017). Such stress factors reduce plant vigour and resilience, making them more susceptible to pest attacks. For instance, drought-stressed plants are more prone to pest infestations, leading to severe damage and considerable reductions in crop yield, presenting substantial challenges to pest management practices (Markov et al., 2018; Skendžić et al., 2021; Yihdego, 2017). The efficacy of conventional pest control measures may be diminished when targeting plants weakened by environmental stresses.

Climate change induced changes in temperature play a critical role for insect pests as they have specific thermal optima where they thrive. To illustrate, FAW's development is most efficient between 25°C and 28°C, significantly shortening its lifecycle and facilitating quicker population turnover, while AAW prefers a broader range of 20°C to 30°C (Niassy et al., 2021; Prasad et al., 2021; Yan et al., 2022). In the IGAD region, known for its wide array of climatic conditions from arid to humid tropical environments, both FAW and AAW are experiencing accelerated lifecycles due to increasing temperatures, especially in warmer areas. Nonetheless, there are critical thermal thresholds, often above 30°C, beyond which the growth of these pests is hindered, or their mortality rates increase, thereby impacting their fecundity and survival (Niassy et al., 2021).

The development, spread and survival of FAW is highly dependent on temperature and humidity. The strongest climatic limits on FAW’s year-round distribution are the coldest annual temperature and the amount of rain in the wet season (Early et al., 2018). At present, changing precipitation patterns seemingly create favourable conditions for its expansion (Niassy et al., 2021). Increased rainfall in certain regions is considered to improve breeding habitats (Guimapi et al., 2022; Niassy et al., 2021). FAW can establish itself in almost all countries in eastern and central Africa and a large part of western Africa under the current climate. Future projections and analyses suggest that FAW invasive range will decrease from both northern and southern regions towards the equator because of increased heat stress caused by climate change (Paudel Timilsena et al., 2022). However, a large area in eastern and central Africa is projected to have an optimal climate for further persistence. These areas will remain hotspots from where FAW might migrate to the north and south during favourable seasons with some studies suggesting further expansion of suitable habitats of the pest across African countries and globally (Early et al., 2018; Fan et al., 2020; Ramasamy et al., 2022).

The Intertropical Convergence Zone (ITCZ) plays an important role as it is shaping weather patterns across the tropics (Schneider et al., 2014). This belt of low pressure, encircling the Earth near the equator, is where the northeast and southeast trade winds converge, leading to significant precipitation and, consequently, profound impacts on agriculture. Outbreaks of the AAW typically begin with the arrival of the rains, correlating with the ITCZ's movement (Harvey &

Mallya, 1995). This synchronization means that the timing of rainfall, influenced by the ITCZ, can affect the emergence and spread of armyworms, aligning pest activity with vulnerable crop stages. (Odiyo, 1984). Furthermore, the indirect effects of climate change, such as shifts in agricultural practices, can also impact AAW populations (Nayak et al., 2020; Thomson et al., 2010). For instance, changes in irrigation practices in response to altered precipitation patterns may affect AAW prevalence and the effectiveness of control measures.

Gómez-Undiano et al., 2022 present robust environment suitability for AAW in Kenya and Tanzania and conclude that a low environmental suitability coincides with arid or semi-arid areas, which may seem evident as extreme temperatures and dry conditions are not ideal for the development of its eggs and pupae. However, in Kenya and Tanzania there is not much difference in the current and future distribution because the lost habitat would be compensated by a gain, resulting in geographical shifting (Gómez-Undiano et al., 2022). In a broader context, the authors highlight the potential expansion of the species in other parts of the world.

The rise in global temperatures has also facilitated the expansion of TA beyond its native range in South America into Europe, Africa, and parts of Asia (Guimapi et al., 2016; Santana Junior et al., 2019). Warmer temperatures have allowed this moth to establish populations in areas previously too cold for its survival. This expansion is particularly notable in the Mediterranean region and parts of Africa where it has become a major threat to tomato cultivation. Researchers predicted that under the SSP2-4.5 scenario for the year 2050, the areas currently suitable for the establishment of TA will remain favorable. Additionally, an increase in suitability is expected in some regions of Africa, such as South Africa, Botswana, and Namibia (Azrag et al. 2023). On the other hand, for TA optimal development occurs around 25°C to 30°C. The pest shows lower fecundity and higher mortality rates at temperatures above 30°C. Specifically, temperatures above 30°C were found to negatively impact the pest's reproduction and survival (Satishchandra et al., 2018).

Compared to the other pests, DL is relatively well research with regards to environmental and climatic factor that affect the pest. Soil temperature is an important factor for DL development. Temperatures below 15°C are unfavourable for egg development, while extremely high temperatures, such as those above 35°C, can lead to increased egg mortality (WMO and FAO, 2016). Air temperature also plays a key role for development of DL. For nymph development the ideal air temperature range is between 24°C and 32°C. Warmer conditions lead to faster undergoing of each nymph stage. In addition, warmer conditions during the night usually favour additional movement of DL. Regarding DL swarm movement, temperature plays an important role also for take-off and resting periods. During sunny condition, the take-off of swarm occur 2-3 hours after sunrise with temperature of at least 15°C to 17°C. In case the swarms are under cloudy condition, take-off time last longer until temperature reaches 23°C - 26°C. Cooler conditions delay the take-off up to 4-6 hours (WMO and FAO, 2016).

Beyond IGAD, the study by Liu et al. (2024) on future DL distribution based on different SSPs suggests that a warming climate will lead to widespread increases in locust outbreaks with emerging hotspots in west central Asia. Liu et al. (2024) conclude that climate change with more and intense extreme events such as droughts and rainfalls, will create new breeding areas especially in previously low-temperature regions such as west central Asia. The projected new habitats are occupied by deserts and xeric shrublands and contains sandy and silty soil that serves as a precondition for locust breeding (Liu et al., 2024). The performed analyzes reveal approximately a 5% increase in locust habitat area under SSP126 scenario and 13 to 25% under SSP585 scenario. New hotspots are emerging in west India, Iran, Afghanistan, and Turkmenistan under climate change scenarios (especially under the SSP585, where locust habitats will shift northward by about 0.3° to 1.2°). Historically identified locust hotspots (i.e., the African Transition

Zone, Northwest Africa, the Horn of Africa, the Middle East, and the Indo-Pakistan area) will remain at high risk even when carbon emissions are substantially reduced in the future.

Increased air temperatures accelerate development, and unusual rainfalls create ideal conditions for consecutive generations, potentially resulting in a rapid population increase and additional locust generations within a year (FAO Locust Watch, 2024). Rainfall provides necessary moisture to soil where DL eggs are laid, and for greening vegetation growth for nymphs to feed (Showler et al., 2021). If intense rain falls in successive seasonal breeding areas, the DL will gregarize and, unless prevented by control, outbreaks and subsequently upsurges can develop. Rainfall over 25 mm in two consecutive months is enough for locust breeding and development (WMO and FAO, 2016). Therefore, rainfall (and by it affected variables soil moisture and vegetation) is the most important variable to monitor during recession periods (WMO and FAO, 2016). On the other hand, the intensity and frequency as well as timing when extreme rainfalls occur can also negatively affect the development of DL (e.g. too wet conditions over longer periods can increase egg mortality). Furthermore, although rainfall and the resulting soil moisture conditions and green vegetation it produces are critical drivers for locust outbreaks, drought can also lead to gregarization by reducing vegetation availability and promoting locust aggregation and swarming (Word Ries at al., 2024, Despland et al. 2004).

It is worth noting that the dynamics of large-scale weather patterns are important for DL outbreaks, with extreme weather events often acting as catalysts for locust proliferation. In relation to large scale weather patterns, “air brought into strong frontal systems and circulation of cyclones from the surrounding countries may collect locusts from any scattered solitarious populations, as well as survivors from multiple swarming populations. The associated widespread and scattered rains may provide suitable breeding conditions for rapid multiplication of these immigrants” (WMO and FAO, 2016, p.10). Furthermore, most DL upsurges and plagues in the past developed because of unusual meteorological conditions with heavy rains such as those associated with cyclones and other extreme weather events (Meynard et al., 2020, WMO and FAO, 2016). In 2018-2019, Indian ocean anomalies gave rise to an unprecedented number of cyclones which provided the ideal conditions for desert locust breeding (Salih et al., 2020; Müller et al., 2021). The Indian Ocean Dipole (IOD), colloquially known as the “Indian Niño, governs sea surface temperatures in the Indian Ocean. In the ‘positive phase’ the western Indian Ocean becomes warmer relative to the eastern part of the ocean, which can trigger cyclones and extreme rainfall. The IOD was in a positive phase from June to December of both 2018 and 2019. In October 2019, the dipole reached its highest positive level in 40 years (Kalakkal et al., 2021). Such extreme events are expected to occur more often and more intense due to changing climate (Li et al. 2019; Taylor et al., 2017).

For QB, rising temperatures can alter their migratory patterns and breeding seasons (Freeman et al., 2020). Warmer temperatures can lead to earlier breeding seasons, increasing the number of breeding cycles QB can complete in a year, thereby potentially increasing their population size. The breeding sites of QB are predicted in relation to rainfall (Cheke et al., 2007). QB’s breeding is closely tied to rainfall, as they prefer to nest in areas where green vegetation is available for feeding their young (Dallimer and Jones, 2002; Cheke et al., 2007). Changes in rainfall patterns, especially increased rainfall, can expand the suitable habitat for breeding, leading to population growth. Conversely, drought conditions can reduce available nesting sites and food, limiting population growth. There are documented instances where changes in rainfall patterns have led to significant shifts in QB’ breeding areas and timings. For example, variations in the onset of the rainy season in East Africa have been linked to changes in the timing and location of quelea outbreaks, affecting the severity of damage to cereal crops (Dallimer and Jones, 2002).

As noted, climate change significantly alters the timing of biological events. Rising atmospheric CO_2 levels, and changes in temperature and precipitation patterns shift plant phenology (Deka et al., 2011; Renner and Zohner, 2018) (Skendžić et al., 2021). This change influences pest dynamics, particularly for species like FAW, AAW, and TA, which have evolved to synchronize their life cycles with those of their host plants (Deka et al., 2011; Renner and Zohner, 2018; Skendžić et al., 2021). Phenological changes can disrupt the historical synchrony between insect pests like FAW, AAW, and TA and the developmental stages of their preferred host plants, potentially diminishing the pest's ability to thrive (Deka et al., 2011). For example, if host plants reach a critical growth stage earlier or later than the typical emergence of TA larvae, this can result in reduced availability of optimal food sources, thereby limiting their population (Garrett et al., 2013; Miller-Rushing et al., 2010). Conversely, research has shown that TA rapidly increased in population size following its spread from South America to other continents due to suitable conditions and host plants (Tropea Garzia et al., 2012; Campos et al., 2017).

Notably, agricultural expansion into new areas due to climate change is facilitating the spread of pests such as TA, and FAW into regions where they previously did not exist or where their life cycles are misaligned with the phenology of new host plants (Tonnang et al., 2015; Paudel Timilsena et al., 2022). Both crops and pests are shifting towards higher elevations, where conditions were previously unsuitable (Ginbo, 2022; Tonnang et al., 2022). This movement to higher elevations or latitudes in search of better growing conditions inadvertently exposes crops to pests like FAW and TA, which were previously restricted by temperature barriers (Scranton and Amarasekare, 2017). This expansion poses significant challenges for agricultural practices and pest management strategies, as regions unaccustomed to dealing with these pests must quickly adapt to their presence (Paudel Timilsena et al., 2022).

Another illustrative example is climate-induced shifts in plant phenology affecting the availability of seeds, which are the primary food source for QB. Earlier flowering and seeding of crops can lead to mismatches in the timing of food availability for bird populations, negatively affecting their breeding cycles. Conversely, if climate-induced phenological changes increase the availability of food sources over a longer period, this could support larger populations of QB, increasing the pressure on grain crops (Halupka et al., 2023). Furthermore, QB are highly adaptive, adjusting their migration and breeding in response to food availability changes (Romano et al., 2023; Ward, 1971). This could bring these birds into further conflict with agricultural interests at different times or in new regions (Romano et al., 2023). As agricultural practices and climatic conditions continue to evolve, it is crucial to develop adaptive pest management strategies that can anticipate and mitigate these dynamic interactions.

Current management strategies for FAW, AAW, TA, QB and DL: towards a holistic EWS

In agricultural pest management, EWS is structured around four foundational pillars crucial for their effectiveness (Brown et al., 2022). The first pillar, risk knowledge, entails a deep understanding of pests, including their behaviour, ecological factors, and the conditions favouring outbreaks, to anticipate and mitigate risks. The second, detection, monitoring, and forecasting, involves setting up systems for early detection of pests, ongoing monitoring of pest populations, and forecasting future outbreaks using environmental and biological data. The third pillar, warning dissemination and communication, ensures that information about potential or actual pest threats is rapidly communicated to all stakeholders, including farmers and agricultural advisors, using accessible and understandable formats. Lastly, preparedness to respond focuses on having actionable strategies and resources ready to combat pest outbreaks effectively, including training of stakeholders, stocking pest control supplies, and establishing rapid response mechanisms. Collectively, these pillars enable a proactive approach to crop pest management to safeguard livelihoods and food security (Brown et al., 2022). This section presents an overview of the current management strategies for FAW, AAW, TA, QB and DL, identifies gaps and suggests pathways towards a holistic EWS.

FAW: strategies and challenges

Research institutions and international organizations within the region are engaged in understanding the dynamics of the FAW and developing control measures, including the creation of pest-resistant crop varieties and assessing natural predators (Prasanna, 2022). Nevertheless, several gaps hinder the effectiveness of current strategies against FAW, necessitating a comprehensive approach to bridge them (Brown et al., 2022).

Effective monitoring under EWS is recognized as a vital component for proactive FAW management. However, its deployment is still in its early stages in many parts of the IGAD region. A case in point is the Fall Armyworm Monitoring and Early Warning System (FAMEWS), implemented by the FAO following the initial outbreak of FAW in Africa (Buchaillot et al., 2022). FAMEWS app includes features like user chats, Plant Village Network queries, and feedback. It provides information on natural enemies, general advice, expert images, and guidance notes under FAW IPM and a video library under Resources. These features should serve as a real-time assistance for decision making by the farmer or extension worker in the field. Nevertheless, the adoption of digital tools remains is insufficient, leading to a reactive rather than proactive management approach (Brown et al., 2022; Tonle et al., 2024). The integration of advanced technologies for pest detection and management remains limited. Although these systems hold great potential, there is a critical need to leverage the raw observational data more effectively to enhance its utility for users, ensuring timely and actionable information is available.

Extension services play a crucial role in FAW management in the IGAD region by providing farmers with information on pest identification and control methods. However, the reach and frequency of these services can be limited, affecting the timely dissemination of crucial information. Community engagement and participatory approaches to FAW management are underutilized.

Additionally, while there is a growing awareness and application of IPM practices, which combine biological controls, such as natural predators and biopesticides, with cultural practices like crop rotation and intercropping to manage FAW populations, the adoption of IPM is inconsistent, often hindered by a lack of access to resources, knowledge, and training (Assefa, 2018; Matova et al., 2020). There is also a considerable challenge in accessing necessary resources like biopesticides, compounded by an over-reliance on chemical pesticides that poses risks of resistance, environmental harm, and health issues. Furthermore, there is a notable deficiency in localized research focusing on FAW's behaviour and control measures tailored to the region's diverse agroecological zones (Tonle et al., 2024).

In the ideal FAW management scenario in the IGAD region, a holistic and integrated approach is paramount. This involves collaboration among farmers, researchers, extension services, and policymakers, leveraging advanced technologies for EWS. Integral to this scenario is the adoption of Integrated Pest Management (IPM) strategies that prioritize sustainability and environmental stewardship and combine biological, cultural, and mechanical controls, with chemical controls used only as a last resort (Brown et al., 2022; Matova et al., 2020). Addressing the existing gaps requires improved extension services, and better access to resources and technology. Collaborative research should focus on continuously enhancing FAW management tactics, such as the use of microbial pesticides and novel agronomic techniques (Brown et al., 2022). Effective extension services are critical for communicating the latest management recommendations to farmers through diverse platforms, from mobile technology to community gatherings (Brown et al., 2022; Tonle et al., 2024). Empowering farmers through participatory approaches and fostering community action groups would ensure localized decision-making and implementation of pest management strategies. Policy changes and international cooperation are vital for providing the necessary frameworks and resources for sustainable pest management and facilitating cross-border knowledge sharing. Ultimately, this comprehensive approach should build long-term resilience against pests, safeguarding crop yields, livelihoods, and food security in the face of climate change.

AAW: strategies and challenges

In Eastern African countries, the EWS for AAW management has integrated traditional surveillance methods with advanced technologies. A notable initiative in this regard is the "Emergency Support to Manage Outbreaks and Infestation by African Armyworm in Eastern Africa" project, which started in Naivasha, Kenya in June 2023 (FAO, 2023). This FAO-led project extends support across six IGAD countries: Eritrea, Ethiopia, Kenya, Somalia, South Sudan, and Uganda. It has established 2,400 monitoring sites, allocating 400 sites per country, and has trained over 1,350 individuals in monitoring, early warning, and effective management techniques for AAW (FAO, 2023). The project also provided pheromone traps (400 bucket traps, 1,600 lures, 1,600 kill strips for each country) as a pest monitoring tool. The aformentioned FAMEWS is working for both FAW and AAW. All functions are the same.

However, despite these efforts, several challenges and shortcomings could affect AAW management. Questions arise about whether the technologies are fully operational in affected countries and what might still be missing or needed. Often, the theoretical and reported success on paper or websites does not fully translate into practical effectiveness, especially given AAW has a cyclical nature. Furthermore, sustained funding and political support are crucial for the longevity and scalability of such initiatives, which might currently be lacking.

For successful management of the AAW, like the FAW, a holistic and forward-thinking strategy should be adopted, integrating cutting-edge technologies for detection and monitoring. At the heart of this approach lies the implementation of IPM techniques, combining biological controls and agricultural practices while limiting chemical treatments to specific instances to reduce environmental effects and prevent resistance development. Crucial to this framework is the establishment of robust communication networks and active community involvement, which should play essential roles in the swift sharing of information and uniting efforts against AAW challenges. This proactive stance should be reinforced by detailed contingency planning, underscored by supportive policies and international cooperation, enhancing regional readiness and resource sharing. The foundation of this desirable scenario is a dedication to continuous research and the pursuit of innovative and sustainable strategies for agricultural sector.

TA: strategies and challenges

Currently, there is no functional regional EWS for TA, in the IGAD region, a gap that must be clearly acknowledged. While there are technological capabilities for establishing an EWS, these have not yet been implemented on a regional or even national scale. EWS using remote sensing, pheromone traps, climate modelling, machine learning algorithms, and Geographic Information Systems (GIS), could predict pest outbreaks, enabling timely interventions and mitigating TA's impact on agriculture. Essential research avenues include long-term monitoring of pest and host plant phenology, modelling to predict future (mis)matches and their impacts on pest populations, and studying pests' adaptability to changing host plant and weather patterns. This research is invaluable for understanding pest population dynamics under climate change and for developing more adaptive pest management strategies. It also underscores the urgency for having EWS that integrate climate and phenological data for advanced pest outbreak predictions.

Effectively managing TA also requires IPM that tackles pesticide resistance, a growing concern due to the frequent reliance on chemical controls. Rwomushana et al. (2019) and Desneux et al. (2010) highlighted TA's rapid development of resistance to pesticides. This situation necessitates ongoing innovation in pest control methodologies to minimize environmental impacts, protect non-target species, and sustain the effectiveness of pest management strategies (Mkonyi et al., 2020). Field sanitation practices, such as removing infested plant materials and controlling weeds, are crucial. These practices help reduce pest populations and limit the spread of infestations. Stringent quarantine measures and trade regulations are also vital to prevent the spread of TA across borders. Additionally, education and training for farmers and agricultural workers are fundamental to equip them with the skills necessary to identify infestations early and understand the range of available control options. This underscores the importance of combining various strategies to effectively control TA while maintaining ecological balance.

QB: strategies and challenges

Managing the impact of QB populations on agriculture has been a critical priority in IGAD countries, necessitating long-term monitoring and management initiatives. The challenge lies in developing strategies that are both effective and safe for the environment and human populations. Conventional control methods against QB, including the use of broad-spectrum chemicals such as the organophosphate Fenthion, fires, traps, and human bird scarers, as well as various agricultural modifications, have been widely used but come with significant drawbacks, including high costs, environmental risks, and substantial human resource demands (Elliott et al., 2014; Ruelle and Bruggers, 1982). Historically, forecasting models have been effective in predicting flocks of the Red-billed *Quelea* in Southern Africa region (Cheke et al., 2007). An operational forecasting system between 2001 and 2009 demonstrated up to 95% accuracy in its predictions but was discontinued due to financial limitations (Cheke et al., 2007). Although this system was discontinued due to financial constraints, modern technological advancements offer the potential to revitalize this EWS.

A novel approach has been developed in Namibia that utilizes a swarm of drones within an Intelligent Surveillance and Reconnaissance (ISR) system specifically targeting QB in Pearl millet crops (Dayoub et al., 2021). This system, which employs a co-design methodology involving both technology developers and end-users, emits a predator-like disruption signal. The drones produce sounds that are perceived as a significant threat by many bird species, effectively scaring them away from fields (Cheke et al., 2007; Dayoub et al., 2021). Empirical results suggest that this innovative technology offers a substantial promise for enhancing food security and sustainability in Africa by providing a more efficient and environmentally friendly solution. Given the migratory nature of QB, it is important to note that while this technology is currently implemented in Namibia, there is a strong case for further development, testing, and application across the region.

Importantly, effective and sustainable control of QB would require a multi-faceted strategy that integrates various methods to mitigate their impact. For example, physical barriers, such as netting and specialized fencing, directly prevent QB from accessing crops, while scare tactics such as the aforementioned audio deterrents help disperse flocks before they inflict significant damage. Promoting natural predators, and managing habitats, which includes the reduction of available surface water near crops and alteration of roosting sites to make them less hospitable can also contribute to prevention and control (Wallin, 1990; Mcwilliam and Cheke, 2004). As climate change alters the behaviour and population dynamics of QB, traditional pest management strategies may become less effective (Romano et al., 2023). Adjusting the timing of control measures may be necessary to match shifting migration and breeding patterns. As these birds adapt, their ability to exploit agricultural landscapes could improve, potentially leading to heightened crop damage and increased economic losses for farmers (Romano et al., 2023). Legislative measures should provide guidelines for sustainable and humane control practices, enhancing the holistic regional approach needed due to the birds' migratory nature, and balancing agricultural protection with environmental and ethical considerations. This highlights the critical need for investment in research, continuous monitoring, technological advancements, and cross-border collaboration (Cheke et al., 2007; Dayoub et al., 2021).

DL: strategies and challenges

DL recession area covers about 16 million km^2 from West Africa to western India. During upsurges and plagues the invasion area extends to 30 million km^2 (approximately four times the size of the USA (WMO and FAO, 2016). Monitoring, management and control operations over such huge territories across different countries is a mammoth task (e.g. different political and security status, different languages and cultural backgrounds, inaccessibility of certain regions).

The EWS for DL is one of the oldest, most advanced and most used pest systems across affected countries. The system is built upon 50+ years of experience and close collaboration with national agencies and international research (Word Ries et al., 2024). The Locust Information Service (DLIS) implemented by the FAO is the focal point for all DL related information which is necessary for EWS operation (Locust Watch FAO, 2024). The DLIS consist of several components with different tasks. A custom GIS called SWARMS (Schistocerca Warning and Management System) contains all geospatial datasets including ground observation data going back to 1930, remote sensing data, models to estimate DL development stages, forecast seasonal rainfall and temperature and migration trajectories. The RAMSES (Reconnaissance and Management System of the Environment of Schistocerca) has been developed for ground survey data collection by national locust officers in affected countries to manage data that is collected by their field teams during survey and control operations. National officers use RAMSES daily in the national locust centre of the country.

DLIS also integrates different models on weather forecast, path trajectories and in this way provides information basis for national locust teams as well as public dissemination via the Locust Watch homepage with regular situation updates by country as well as monthly bulletins. The website contains links to geospatial information on current threats and projections of swarm trajectories within the DLIS (https://www.fao.org/locust-watch/en.). Furthermore, datasets (locations as well as geoinformation products) are available via Locust Hub (A Geographic Information System data explorer, covering 7-day maps/datasets on Bands, Hoppers, Swarms and Ecology (including condition and density of vegetation and all-important soil moisture maps, https://locust-hub-hqfao.hub.arcgis.com/). Open access of data via the Locust Hub has been the main source of recently increased scientific investigations on DL distribution (e.g. Kimathi at al., 2020; Mullié et al., 2023; Herbillon et al., 2024; Liu et al., 2024) and demonstrates that open data policy and good dissemination stimulates new research, method and model developments based on modern data analyses and computing capacities. This is crucial for integrating of new technologies.

While the system is technologically advanced, the issue lies in the preparedness, coordination and ability of affected countries to act quickly before a crisis occurs. (Müller et al., 2021). The recent upsurge in the Horn of Africa followed a predictable trend of delayed action and excessive organophosphate pesticide use (Mullié et al., 2023). The widespread use of broad-spectrum pesticides poses serious environmental risks such as harming pollinators, which could be avoided with biopesticides (Mullié et al., 2023). Furthermore, Showler at al. (2021) discusses that “new priorities have arisen for developing outbreak prevention capability (and for enhancing proaction)”. The authors underline that there is a “salient need” for “sustainable coordination among stakeholders at national, regional, and international levels”.

Using geoinformation, remote sensing data and climate projections

As described in previous sections, transboundary pests such as DL, FAW, AAW, TA and QB affect large areas across different countries and even continents. Managing these pests is a multi-disciplinary task which requires combination of different types of datasets, information and knowledge. In this context, standardized and harmonized datasets including spatial and temporal context are indispensable. Therefore, weather forecast, geospatial information acquired from satellite remote sensing, Unmanned Aerial Vehicles (UAVs) and geolocated ground truth campaigns have become a key component of preventive pest management over the past decades (Cressman 2021). Their significance within pest management and early warning has been growing rapidly with the advance of technology (e.g. increasing spatial and temporal resolution of satellites data, open-source data policy, UAV applications, and very important the advance of computing technology which enables storage and processing of such huge amount of data) (Ochieng, 2023). The implementation of new technology is usually boosted by major upsurge events (Lecoq and Cease, 2022). Figure 7 shows the timeline of modern technology implementations for DL management by FAO. After the 2019-2020 outbreak a total of 16 innovative components have been included.

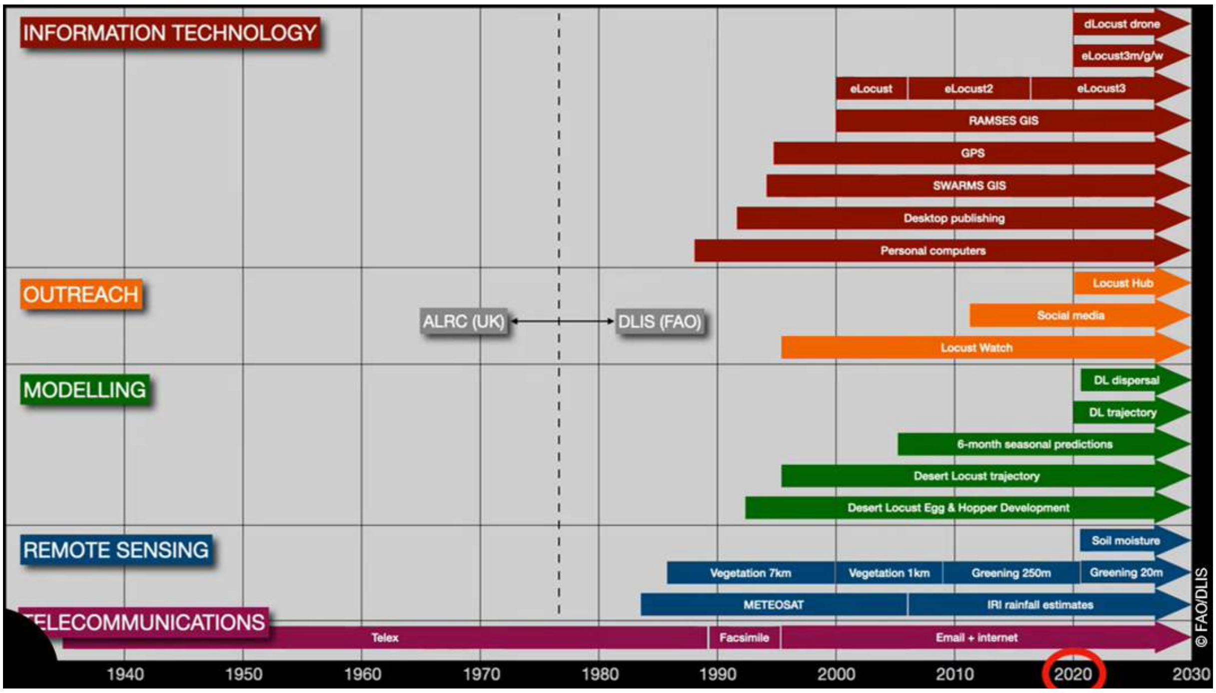


Figure 7: Development of technologies implemented for desert locust management strategies by FAO (©FAO/DLIS).

The application of geospatial datasets such as satellite remote sensing is usually tested and validated in different research projects. This process is crucial, to understand the capacity, inaccuracy and potential errors of used data sources, which must be considered for interpretation, and any made decision. For example, the usage of vegetation indices and soil moisture over desert locust habitats from satellite remote sensing were tested and analysed in different studies (Escorihuela et al., 2018; Gómez et al., 2018, 2021; Pekel et al., 2011; Piou et al., 2013, 2017, 2019; Renier et al., 2015; Waldner et al., 2015; Mongare et al., 2023). Furthermore, it is important to use the data in context of each species separately considering their unique ecological and biological characteristics as well as impact.

Apart from the regular monitoring and support for control operations, geospatial data and modelling applications can be exploited for short- and long-term forecasts as well as future projections. Especially, future projects have become essential because the impact of climate change on pests and diseases dynamics is already distinctive but still not fully understood (Lenharo, 2024; Meynard et al., 2020; Salih et al., 2020; Klein at al., 2021; Word Ries at al., 2024). Here, data archives provide enormous potential to analyze and understand past outbreak events and derive information for future modelling using climate change scenarios.

In past decades the amount of meteorological and hydrological ground stations has decreased dramatically which makes geospatial datasets and remote sensing observations the only information source (Hrachowitz et al., 2013). Despite this fact, geospatial and remote sensing dataset provides a lot of advantages for IPM. Their usage and implementation have improved our knowledge about species distribution and our capacity of monitoring, forecasting and controlling different pests. Naturally, such datasets are significant for any effective early warning and early action system for transboundary pests. Despite high potential and consistent progress there is still a lot of room to grow and improve. Especially, regarding standardization between affected countries and human capacity of using new technologies.

Governance models and early warning systems

Effective governance models and EWS are crucial in managing transboundary pests like FAW, AAW, TA, QB and DL. These systems play a pivotal role in coordinating actions across different governance levels and involve various stakeholders in the decision-making process (see Figure 7). Continuous stakeholder collaboration is essential to address challenges and meet local, regional and global needs in pest management. By combining approaches, governance models for EWS could improve crop pest management and mitigate the impact on agriculture and livelihoods:

- ***Integrated approach***: A governance model that integrates local, national, and international resources and expertise is vital for managing agricultural pests. This approach facilitates the pooling of knowledge, technology, and financial resources, enabling a coordinated response to pest outbreaks. It involves collaboration among government agencies, intergovernmental actors like IGAD, international organizations like the FAO, research institutions, NGOs, and the agricultural community.
- **One Health Approach:** Incorporating a One Health approach into governance models ensures that the interconnected health of humans, animals, and ecosystems is considered in crop pest management strategies. This holistic view helps in understanding the broader impacts of pest outbreaks and promotes integrated solutions that benefit all aspects of health.
- ***Community-based management***: Empowering local communities and farmers with knowledge and resources is essential for early detection and management of pest outbreaks. Community-based management models encourage the active participation of local stakeholders in monitoring pest populations, implementing control measures, and sharing information with broader networks.

- ***Public-private partnerships****:* Collaborations between the public sector, private companies, and non-governmental organizations can enhance the effectiveness of pest management strategies. These partnerships can facilitate access to advanced technologies, such as remote sensing and GIS for EWS, and innovative control methods, including biological control agents.
- ***Climate services:*** Effective early warning requires integrating climate services, providing stakeholders with vital, timely, and understandable information for decision-making and strategic planning. ICPAC disseminates climate information, early warnings, and advisories through platforms like East Africa Hazards Watch, the ICPAC website, MailChimp, Twitter, LinkedIn, and Facebook. In 2023, these efforts reached around 2 million users with a combined following of 155,000. Such services can be leveraged for crop pest EWS.

Building upon the four pillars of EWS, transboundary pest management consists of Disaster Risk Knowledge, Monitoring and Warning Services, Dissemination and Communication, and Response Capability. Disaster Risk Knowledge involves continuous research, sustainable strategies like biopesticides, and regular risk assessments. Monitoring and Warning Services include real-time data transmission, satellite imagery, weather data, predictive models, and IPM techniques. Dissemination and Communication focuses on information sharing, community engagement, and international cooperation. Response Capability emphasizes supportive policies, contingency planning, effective governance, and sustainable methods for environmental and health safety.

Conclusions

Increased warming has been observed across the African continent (and other regions globally) since the early 20th century, and this trend is projected to continue in all future emission scenarios (IPCC, 2021; Liu at al., 2024). The member states of the IGAD face significant challenges from climate change. As temperatures rise and extreme weather events become more frequent, climate change is driving the proliferation and expansion of transboundary crop pests such as FAW, AAW, TA, QB and DL, reflecting a global trend impacting agricultural systems beyond the IGAD region. Changes in rainfall intensity and distribution can create favorable breeding conditions for pests like the FAW and DL which thrive in wet environments. Conversely, prolonged droughts stress crops, making them more vulnerable to pest infestations.

In a broader context, regions with high latitude, such as the USA and northern Europe, will become more suitable for plant pests such as TA due to rising temperature (Santana et al. 2019; Müller et al., 2022). For Africa and Arabian Peninsula there is robust evidence that a warming climate will increase extreme precipitation (IPCC, 2021) which will elevate the risk of DL abundance, making it even more difficult to prevent and control locust outbreaks (Liu at al., 2024). Increased temperatures over breeding areas might also lead to additional locust generations within a year (FAO Locust Watch, 2024). This expansion, indicative of broader climate change effects on pest dynamics, highlights the need for enhanced regional cooperation within the IGAD region and beyond, including research, monitoring and control (Bebber, 2015; Battisti and Larsson, 2015; Scranton and Amarasekare, 2017).

Key findings highlight the critical need for continuous stakeholder collaboration and the adoption of an integrated approach that leverages local, national, and international resources. This includes the incorporation of the One Health framework, community-based management, and public-private partnerships to enhance pest management strategies. The integration of climate services into EWS is essential for providing timely and actionable information, enabling proactive measures to mitigate pest-related risks. The management of transboundary crop pests requires a science-based approach that recognizes the complexity and diversity of these threats. Each pest demands tailored strategies for EWS, developed through multidisciplinary collaboration involving technology, climate science, agronomy, plant protection, and other disciplines. Such cooperation is crucial for addressing the specific behaviours and impacts of pests. For instance, avian pests like QB pose different challenges compared to insect pests like TA. Large flocks of QB necessitate tracking migration patterns and population dynamics, while the more hidden presence of pests like TA often goes undetected until significant damage has occurred. Additionally, indigenous birds like QB have important ecological roles and require careful management due to welfare concerns. In contrast, invasive insects such FAW might be targeted with more aggressive strategies aimed at containment (Wan et al., 2021). Ultimately, pest management strategies must be precisely tailored to the unique ecological and biological characteristics of each pest.

The success of EWS for transboundary pests such as FAW, AAW, DL, TA, and QB also hinges on integrating advanced technologies, fostering cross-border collaboration, and ensuring the EWS is credible to stakeholders on the ground. Climate modelling, satellite imagery, remote sensing, GIS, and machine learning algorithms can enhance the prediction of pest outbreaks, supporting timely interventions. Meanwhile, mobile applications have the potential to enable real-time data exchange among farmers, researchers, and pest management professionals. Yet transboundary pest management requires ground based “field-level observations”. Pheromone and light traps are essential for the early detection of insect pests like AAW and FAW. For DL, ground-based monitoring is crucial for observing morphological changes and the tendency for gregarization, as no model or remote sensing method can replace this; these technologies only support more timely and precise guidance for plant protection teams across vast areas.

The effectiveness of technological applications depends on stakeholders' will, openness, and collaboration to share information transparently and accessibly. The transboundary nature of major crop pests underscores the critical need for cross-border information sharing and cooperation within regional EWS governance frameworks. This highlights the essential role of collective action, pooling resources, knowledge, and capacities from local to international levels. A broad coalition of stakeholders, including farmers, communities, NGOs, multilateral agencies, and research institutes, is needed to develop crop pest EWS that are scientifically sound, locally adapted, and capable of providing timely and actionable information.

We stress the urgency of adopting EWS to safeguard the IGAD region’s food security and livelihoods against plant pests. The absence of such a regional EWS leads to significant risks. Without timely warning and strategic guidance, farmers not only face losses but also resort to improper practices such as the indiscriminate use of pesticides, which can lead to increased pesticide resistance, as well as environmental damage. Thus, the development of a robust EWS is not only a tool for effective pest management but also a critical component for sustainable agricultural practices.

The insights garnered from this paper shed light on the current state of crop pest management and pave the way for future efforts to enhance the resilience of agricultural systems. Innovations in EWS and their governance must respond to the uncertainties of a changing world, supporting sustainable food systems for IGAD member states and beyond. Looking ahead, the challenges posed by transboundary crop pests require a commitment to innovation, research, and international cooperation. Concerted effort is needed to leverage global insights to address local and regional crop pest challenges and vice versa, local knowledge and realities must inform global strategies.

References:

Abbass, K.; Qasim, M. Z.; Song, H.; Murshed, M.; Mahmood, H.; Younis, I. A Review of the Global Climate Change Impacts, Adaptation, and Sustainable Mitigation Measures. *Environ. Sci. Pollut. Res.* **2022**, *29* (28), 42539–42559.

Abrahams, P.; Bateman, M.; Beale, T.; Clottey, V.; Cock, M.; Colmenarez, Y.; Corniani, N.; et al. Fall Armyworm: Impacts and Implications for Africa; Evidence Note (2), September 2017. Unpublished Report, CABI, Wallingford, **2017**.

Abro, Z.; Kimathi, E.; Groote, H. D.; Tefera, T.; Sevgan, S.; Niassy, S.; Kassie, M. Socioeconomic and Health Impacts of Fall Armyworm in Ethiopia. *PLOS ONE* **2021**, *16*, e0257736. https://doi.org/10.1371/journal.pone.0257736.

Adhikari, U.; Nejadhashemi, A. P.; Woznicki, S. A. Climate Change and Eastern Africa: A Review of Impact on Major Crops. *Food Energy Secur.* **2015**, *4* (2), 110–132. https://doi.org/10.1002/fes3.61.

Aguilon, D. J.; Velasco, L. R. Effects of Larval Rearing Temperature and Host Plant Condition on the Development, Survival, and Coloration of African Armyworm, *Spodoptera exempta* Walker (Lepidoptera: Noctuidae). *J. Environ. Sci. Manag.* **2015**, *18*.

Assefa, F. Status of Fall Armyworm (*Spodoptera frugiperda*), Biology and Control Measures on Maize Crop in Ethiopia: A Review. *Int. J. Entomol. Res.* **2018**, *6*, 75–85. https://doi.org/10.33687/entomol.006.02.2498.

Assefa, F.; Ayalew, D. Status and Control Measures of Fall Armyworm (*Spodoptera frugiperda*) Infestations in Maize Fields in Ethiopia: A Review. *Cogent Food Agric.* **2019**, *5*, 1641902. https://doi.org/10.1080/23311932.2019.1641902.

Awange, J. Food Insecurity: Causes and Eradication. In *Food Insecurity & Hydroclimate in Greater Horn of Africa: Potential for Agriculture Amidst Extremes*; Springer International Publishing: Cham, 2022; pp. 3–27.

Ayugi, B.; Dike, V.; Ngoma, H.; Babaousmail, H.; Mumo, R.; Ongoma, V. Future Changes in Precipitation Extremes over East Africa Based on CMIP6 Models. *Water* **2021**, *13* (17), 2358.

Ayugi, B.; Jiang, Z.; Iyakaremye, V.; Ngoma, H.; Babaousmail, H.; Onyutha, C.; Dike, V. N.; Mumo, R.; Ongoma, V. East African Population Exposure to Precipitation Extremes under 1.5°C and 2.0°C Warming Levels Based on CMIP6 Models. *Environ. Res. Lett.* **2022**, *17* (4), 044051.

Azrag, A. G. A.; Obala, F.; Tonnang, H. E. Z.; Hogg, B. N.; Ndlela, S.; Mohamed, S. A. Predicting the Impact of Climate Change on the Potential Distribution of the Invasive Tomato Pinworm Phthorimaea absoluta (Meyrick) (Lepidoptera: Gelechiidae). *Sci Rep 2023*, 13, 16477. https://doi.org/10.1038/s41598-023-43564-2

Balikuddembe, J. K.; Di, B.; Reinhardt, J. D.; Wen, Z. A Haddon Matrix-Based Analysis of the Anthropogenic Drivers of Floods in 10 Eastern African Partner Countries of the Belt and Road Initiative 1990–2021. *Int. J. Disaster Risk Reduct.* **2023**, *92*, 103683.

Battisti, A.; Larsson, S. Climate Change and Insect Pest Distribution Range. *Clim. Change Insect Pests* **2015**, *7*, 1–15.

Bawin, T.; Dujeu, D.; De Backer, L.; Francis, F.; Verheggen, F. J. Ability of *Tuta absoluta* (Lepidoptera: Gelechiidae) to Develop on Alternative Host Plant Species. *Can. Entomol.* **2016**, *148*, 434–442.

BBC News. Kenyan Rice Farmers Battle Quelea Birds in Kisumu. *BBC News* **2023**, February 20. https://www.bbc.com/news/world-africa-64596927.

Bebber, D. P. Range-Expanding Pests and Pathogens in a Warming World. *Annu. Rev. Phytopathol.* **2015**, *53*, 335–356. https://doi.org/10.1146/annurev-phyto-080614-120207.

Bebber, D.P.; Ramotowski, M.A.T.; Gurr, S.J. **2013**. Crop pests and pathogens move polewards in a warming world. *Nature Clim Change*, 3, 985–988. https://doi.org/10.1038/nclimate1990.

Brader, L.; Djibo, H.; Faye, F. G.; Ghaout, S.; Lazar, M.; Luzietoso, P. N.; Babah, M. O. Towards a More Effective Response to Desert Locusts and Their Impacts on Food Security, Livelihoods and Poverty. Multilateral Evaluation of the 2003–05 Desert Locust Campaign, 2006, 49.

Brown, E. S. The African Army Worm *Spodoptera exempta* (Walker)(Lepidoptera, Nootuidae): A Review of the Literature. *Afr. Army Worm Spodoptera Exempta WalkerLepidoptera Nootuidae Rev. Lit.* **1962**.

Brown, E. S.; Odiyo, P. The Rate of Feeding of the African Army Worm *Spodoptera exempta* (Walk.) and Its Significance for Control Operations. *East Afr. Agric. For. J.* **1968**, *33*, 245–256. https://doi.org/10.1080/00128325.1968.11662207.

Brown, M. E.; Mugo, S.; Petersen, S.; Klauser, D. Designing a Pest and Disease Outbreak Warning System for Farmers, Agronomists and Agricultural Input Distributors in East Africa. *Insects* **2022**, *13*, 232. https://doi.org/10.3390/insects13030232.

Buchaillot, M. L.; Cairns, J.; Hamadziripi, E.; Wilson, K.; Hughes, D.; Chelal, J.; McCloskey, P.; Kehs, A.; Clinton, N.; Araus, J. L.; Kefauver, S. C. Regional Monitoring of Fall Armyworm (FAW) Using Early Warning Systems. *Remote Sens.* **2022**, *14*, 5003. https://doi.org/10.3390/rs14195003.

CABI. Tomato Leafminer (*Tuta absoluta*): Impacts and Coping Strategies for Africa: Evidence Note; CABI: Nairobi, Kenya, 2019.

CABI. *Spodoptera frugiperda* (fall armyworm); CABI Invasive Species Compendium, 2023. https://www.cabidigitallibrary.org/doi/10.1079/cabicompendium.29810 .

Campos, M. R.; Biondi, A.; Adiga, A.; Guedes, R. N.; Desneux, N. From the Western Palaearctic Region to Beyond: *Tuta absoluta* 10 Years after Invading Europe. *J. Pest Sci.* **2017**, *90*, 787–796.

CGIAR Research Program on Roots, Tubers and Bananas (RTB). Predicting Climate Change's Impact on Crop Pests and Diseases. January 2014. https://www.rtb.cgiar.org/news/predicting-climate-changes-impact-on-crop-pests-and-diseases/ (accessed 29 February 2024).

Cheke, R. A.; Sidatt, M. E. H. A Review of Alternatives to Fenthion for Quelea Bird Control. *Crop Prot.* **2019**, *116*, 15–23. https://doi.org/10.1016/j.cropro.2018.10.005.

Cheke, R. A.; Venn, J. F.; Jones, P. J. Forecasting Suitable Breeding Conditions for the Red-Billed Quelea *Quelea quelea* in Southern Africa. *J. Appl. Ecol.* **2007**, *44* (3), 515–526. https://doi.org/10.1111/j.1365-2664.2007.01295.x.

Cheke, R.A., Tucker, M.R. An evaluation of potential economic returns from the strategic control approach to the management of African armyworm *Spodoptera exempta* (Lepidoptera: Noctuidae) populations in eastern Africa. *Crop Prot.* **1995,** 14, 91–103.

Cherif, A.; Verheggen, F. A Review of *Tuta absoluta* (Lepidoptera: Gelechiidae) Host Plants and Their Impact on Management Strategies. *Biotechnol. Agron. Société Environ.* **2019**, *23*.

Chidege, M.; Al-Zaidi, S.; Hassan, N.; Mrema, E. First Record of Tomato Leaf Miner *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in Tanzania. *Agric. Food Secur.* **2016**, *5*, 17. https://doi.org/10.1186/s40066-016-0066-4.

Choi, Y. W.; Campbell, D. J.; Eltahir, E. A. Near-Term Regional Climate Change in East Africa. *Clim. Dyn.* **2023**, *61* (1–2), 961–978.

Cressman, K. **2021**. Technical innovations in global early warning in support of desert locust area-wide management. In *Area-wide Integrated Pest Management*; CRC Press: Boca Raton, pp. 765–778.

Crook, J. H.; Ward, P. The Quelea Problem in Africa, in *The Problems of Birds as Pests*; Proceedings of a Symposium Held at the Royal Geographical Society, London, on 28 and 29 Sept. 1967; Academic Press: New York, 1968; pp 211–229.

Dallimer, M.; Jones, P. J. Migration Orientation Behaviour of the Red-Billed Quelea *Quelea quelea*. *J. Avian Biol.* **2002**, *33*, 89–94. https://doi.org/10.1034/j.1600-048X.2002.330114.x.

Day, R.; Abrahams, P.; Bateman, M.; Beale, T.; Clottey, V.; Cock, M.; Colmenarez, Y.; Corniani, N.; Early, R.; Godwin, J.; Gomez, J.; Moreno, P. G.; Murphy, S. T.; Oppong-Mensah, B.; Phiri, N.; Pratt, C.; Silvestri, S.; Witt, A. Fall Armyworm: Impacts and Implications for Africa. *Outlooks Pest Manag.* **2017**, *28*, 196–201. https://doi.org/10.1564/v28_oct_02.

Dayoub, M.; Birech, R. J.; Haghbayan, M. H.; Angombe, S.; Sutinen, E. Co-Design in Bird Scaring Drone Systems: Potentials and Challenges in Agriculture, in: *Proceedings of the International Conference on Advanced Intelligent Systems and Informatics 2020*; Hassanien, A. E., Slowik, A., Snášel, V., El-Deeb, H., Tolba, F. M., Eds.; Springer International Publishing: Cham, 2021; pp 598–607. https://doi.org/10.1007/978-3-030-58669-0_54.

De Groote, H.; Kimenju, S. C.; Munyua, B.; Palmas, S.; Kassie, M.; Bruce, A. Spread and Impact of Fall Armyworm (*Spodoptera frugiperda* J. E. Smith) in Maize Production Areas of Kenya. *Agric. Ecosyst. Environ.* **2020**, *292*, 106804. https://doi.org/10.1016/j.agee.2019.106804.

Deka, S.; Barthakur, S.; Pandey, R.; Singh, M. P.; Khetarpal, S.; Kumar, P. Potential Effects of Climate Change on Insect Pest Dynamics. *Clim. Change Impacts Adapt. Crop Plants* New Delhi Today Tomorrow's Print. Publ. **2011**, 301–312.

Deka, S.; Byjesh, K.; Kumar, U.; Choudhary, R. Climate Change and Impacts on Crop Pests-A Critique. *ISPRS Arch.* **2010**, *48*, W3.

Desert Locust Control Organization for Eastern Africa (DLCO-EA). Quelea Birds Control Operation in Ethiopia December 2022. https://dlco-ea.org/quelea-birds-control-operation-in-ethiopia-december-2022/ (accessed 29 February 2024).

Desert Locust Control Organization for Eastern Africa (DLCO-EA). Monthly Situation Reports. https://dlco-ea.org/monthly-situation-reports/ (accessed 29 February 2024).

Desneux, N.; Wajnberg, E.; Wyckhuys, K. A.; Burgio, G.; Arpaia, S.; Narváez-Vasquez, C. A.; González-Cabrera, J.; Catalán Ruescas, D.; Tabone, E.; Frandon, J. Biological Invasion of European Tomato Crops by *Tuta absoluta*: Ecology, Geographic Expansion and Prospects for Biological Control. *J. Pest Sci.* **2010**, *83*, 197–215.

Despland, E. **2003**. Fractal index captures the role of vegetation clumping in locust swarming. *Funct Ecology*, 17, 315–322. https://doi.org/10.1046/j.1365-2435.2003.00728.x.

Despland, E.; Rosenberg, J.; Simpson, S.J. **2004**. Landscape structure and locust swarming: a satellite's eye view. *Ecography*, 27, 381–391. https://doi.org/10.1111/j.0906-7590.2004.03779.x.

Early, R.; González-Moreno, P.; Murphy, S. T.; Day, R. Forecasting the Global Extent of Invasion of the Cereal Pest *Spodoptera frugiperda*, the Fall Armyworm. *NeoBiota* **2018**, *40*, 25–50. https://doi.org/10.3897/neobiota.40.28165.

Elliott, C. C.; Mtobesya, B. N.; Cheke, R. A. Alternative Approaches to Red-Billed Quelea *Quelea quelea* Management: Mass-Capture for Food. *Ostrich* **2014**, *85*, 31–37. https://doi.org/10.2989/00306525.2014.900827.

Escorihuela, M.J.; Merlin, O.; Stefan, V.; Moyano, G.; Eweys, O.A.; Zribi, M.; Kamara, S.; Benahi, A.S.; Ebbe, M.A.B.; Chihrane, J.; Ghaout, S.; Cissé, S.; Diakité, F.; Lazar, M.; Pellarin, T.; Grippa, M.; Cressman, K.; Piou, C. **2018**. SMOS based high resolution soil moisture estimates for desert locust preventive management. *Remote Sensing Applications: Society and Environment*, 11, 140–150. https://doi.org/10.1016/j.rsase.2018.06.002.

Fan, J.; Wu, P.; Tian, T.; Ren, Q.; Haseeb, M.; Zhang, R. Potential Distribution and Niche Differentiation of *Spodoptera frugiperda* in Africa. *Insects* **2020**, *11* (6), 383. https://doi.org/10.3390/insects11060383.

FAO. Curbing the March of African Armyworm. FAO Regional Office for Africa 2023, online https://www.fao.org/africa/news/detail-news/en/c/1641969/.

FAO. Real-Time Evaluation of FAO's Response to the Desert Locust Upsurge 2020–2021: Phase III; FAO: Rome, 2021. https://openknowledge.fao.org/server/api/core/bitstreams

Freeman, M. T.; Czenze, Z. J.; Schoeman, K.; McKechnie, A. E. Extreme Hyperthermia Tolerance in the World's Most Abundant Wild Bird. *Sci. Rep.* **2020**, *10*, 13098. https://doi.org/10.1038/s41598-020-69997-7.

Fuhrer, J. Agroecosystem Responses to Combinations of Elevated CO2, Ozone, and Global Climate Change. *Agric. Ecosyst. Environ.* **2003**, *97*, 1–20.

Funk, C.; Fink, A. H.; Harrison, L.; Segele, Z.; Endris, H. S.; Galu, G.; Korecha, D.; Nicholson, S. Frequent but Predictable Droughts in East Africa Driven by a Walker Circulation Intensification. *Earth's Future* **2023**, *11* (11), e2022EF003454.

Garrett, K. A.; Dobson, A. D. M.; Kroschel, J.; Natarajan, B.; Orlandini, S.; Tonnang, H. E.; Valdivia, C. The Effects of Climate Variability and the Color of Weather Time Series on Agricultural Diseases and Pests, and on Decisions for Their Management. *Agric. For. Meteorol.* **2013**, *170*, 216–227.

Gebrechorkos, S. H.; Taye, M. T.; Birhanu, B.; Solomon, D.; Demissie, T. Future Changes in Climate and Hydroclimate Extremes in East Africa. *Earth's Future* **2023**, *11* (2), e2022EF003011.

Ghimire, P.; Bhetwal, N. FAW: An Emerging Threats to Agriculture. *Europe* **2021**, *44*, 4.

Ginbo, T. Heterogeneous Impacts of Climate Change on Crop Yields across Altitudes in Ethiopia. *Clim. Change* **2022**, *170*, 12. https://doi.org/10.1007/s10584-022-03306-1.

Goergen, G.; Kumar, P. L.; Sankung, S. B.; Togola, A.; Tamò, M. First Report of Outbreaks of the Fall Armyworm *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera, Noctuidae), a New Alien Invasive Pest in West and Central Africa. *PLOS ONE* **2016**, *11*, e0165632.

Gómez, D.; Salvador, P.; Sanz, J.; Casanova, C.; Taratiel, D.; Casanova, J.L. **2018**. Machine learning approach to locate desert locust breeding areas based on ESA CCI soil moisture. *Journal of Applied Remote Sensing*, 12, 1. https://doi.org/10.1117/1.JRS.12.036011.

Gómez, D.; Salvador, P.; Sanz, J.; Rodrigo, J.F.; Gil, J.; Casanova, J.L. **2021**. Prediction of desert locust breeding areas using machine learning methods and SMOS (MIR_SMNRT2) Near Real Time product. *Journal of Arid Environments*, 194, 104599. https://doi.org/10.1016/j.jaridenv.2021.104599.

Gómez-Undiano, I.; Musavi, F.; Mushobozi, W. L.; David, G. M.; Day, R.; Early, R.; Wilson, K. Predicting Potential Global and Future Distributions of the African Armyworm (*Spodoptera exempta*) Using Species Distribution Models. *Sci. Rep.* **2022**, *12*, 16234. https://doi.org/10.1038/s41598-022-19983-y.

Grillakis, M.; Voulgarakis, A.; Rovithakis, A.; Seiradakis, K. D.; Koutroulis, A.; Field, R. D.; Kasoar, M.; Papadopoulos, A.; Lazaridis, M. Climate Drivers of Global Wildfire Burned Area. *Environ. Res. Lett.* **2022**, *17* (4), 045021.

Guimapi, R. A.; Niassy, S.; Mudereri, B. T.; Abdel-Rahman, E. M.; Tepa-Yotto, G. T.; Subramanian, S.; Mohamed, S. A.; Thunes, K. H.; Kimathi, E.; Agboka, K. M.; Tamò, M.; Rwaburindi, J. C.; Hadi, B.; Elkahky, M.; Sæthre, M.-G.; Belayneh, Y.; Ekesi, S.; Kelemu, S.; Tonnang, H. E. Harnessing Data Science to Improve Integrated Management of Invasive Pest Species across Africa: An Application to Fall Armyworm (*Spodoptera frugiperda*) (J.E. Smith) (Lepidoptera: Noctuidae). *Glob. Ecol. Conserv.* **2022**, *35*, e02056. https://doi.org/10.1016/j.gecco.2022.e02056.

Guimapi, R. Y. A.; Mohamed, S. A.; Okeyo, G. O.; Ndjomatchoua, F. T.; Ekesi, S.; Tonnang, H. E. Modeling the Risk of Invasion and Spread of *Tuta absoluta* in Africa. *Ecol. Complex.* **2016**, *28*, 77–93. https://doi.org/10.1016/j.ecocom.2016.08.001.

Guimapi, R.A.; Niassy, S.; Mudereri, B.T.; Abdel-Rahman, E.M.; Tepa-Yotto, G.T.; Subramanian, S.; Mohamed, S.A.; Thunes, K.H.; Kimathi, E.; Agboka, K.M.; Tamò, M.; Rwaburindi, J.C.; Hadi, B.; Elkahky, M.; Sæthre, M.-G.; Belayneh, Y.; Ekesi, S.; Kelemu, S.; Tonnang, H.E.Z. **2022**. Harnessing data science to improve integrated management of invasive pest species across Africa: An application to Fall armyworm (Spodoptera frugiperda) (J.E. Smith) (Lepidoptera: Noctuidae). *Global Ecology and Conservation*, 35, e02056. https://doi.org/10.1016/j.gecco.2022.e02056.

Haile, G. G.; Tang, Q.; Hosseini-Moghari, S. M.; Liu, X.; Gebremicael, T. G.; Leng, G.; Kebede, A.; Xu, X.; Yun, X. Projected Impacts of Climate Change on Drought Patterns over East Africa. *Earth's Future* **2020**, *8* (7), e2020EF001502.

Halupka, L.; Arlt, D.; Tolvanen, J.; Millon, A.; Bize, P.; Adamík, P.; Albert, P.; Arendt, W. J.; Artemyev, A. V.; Baglione, V.; Bańbura, J.; Bańbura, M.; Barba, E.; Barrett, R. T.; Becker, P. H.; Belskii, E.; Bolton, M.; Bowers, E. K.; Bried, J.; Brouwer, L.; Bukacińska, M.; Bukaciński, D.; Bulluck, L.; Carstens, K. F.; Catry, I.; Charter, M.; Chernomorets, A.; Covas, R.; Czuchra, M.; Dearborn, D. C.;

de Lope, F.; Di Giacomo, A. S.; Dombrovski, V. C.; Drummond, H.; Dunn, M. J.; Eeva, T.; Emmerson, L. M.; Espmark, Y.; Fargallo, J. A.; Gashkov, S. I.; Golubova, E. Y.; Griesser, M.; Harris, M. P.; Hoover, J. P.; Jagiełło, Z.; Karell, P.; Kloskowski, J.; Koenig, W. D.; Kolunen, H.; Korczak-Abshire, M.; Korpimäki, E.; Krams, I.; Krist, M.; Krüger, S. C.; Kuranov, B. D.; Lambin, X.; Lombardo, M. P.; Lyakhov, A.; Marzal, A.; Møller, A. P.; Neves, V. C.; Nielsen, J. T.; Numerov, A.; Orłowska, B.; Oro, D.; Öst, M.; Phillips, R. A.; Pietiäinen, H.; Polo, V.; Porkert, J.; Potti, J.; Pöysä, H.; Printemps, T.; Prop, J.; Quillfeldt, P.; Ramos, J. A.; Ravussin, P.-A.; Rosenfield, R. N.; Roulin, A.; Rubenstein, D. R.; Samusenko, I. E.; Saunders, D. A.; Schaub, M.; Senar, J. C.; Sergio, F.; Solonen, T.; Solovyeva, D. V.; Stępniewski, J.; Thompson, P. M.; Tobolka, M.; Török, J.; van de Pol, M.; Vernooij, L.; Visser, M. E.; Westneat, D. F.; Wheelwright, N. T.; Wiącek, J.; Wiebe, K. L.; Wood, A. G.; Wysocki, D.; Zárybnická, M.; Margalida, A.; Halupka, K. The Effect of Climate Change on Avian Offspring Production: A Global Meta-Analysis. *Proc. Natl. Acad. Sci. U. S. A.* **2023**, *120*, e2208389120. https://doi.org/10.1073/pnas.2208389120.

Herbillon, F.; Piou, C.; Meynard, C.N. **2024**. An increase in management actions has compensated for past climate change effects on desert locust gregarization in western Africa. *Heliyon*, 10, e29231. https://doi.org/10.1016/j.heliyon.2024.e29231.

Hrachowitz, M.; Savenije, H.H.G.; Blöschl, G.; McDonnell, J.J.; Sivapalan, M.; Pomeroy, J.W.; Arheimer, B.; Blume, T.; Clark, M.P.; Ehret, U.; Fenicia, F.; Freer, J.E.; Gelfan, A.; Gupta, H.V.; Hughes, D.A.; Hut, R.W.; Montanari, A.; Pande, S.; Tetzlaff, D.; Troch, P.A.; Uhlenbrook, S.; Wagener, T.; Winsemius, H.C.; Woods, R.A.; Zehe, E.; Cudennec, C. **2013**. A decade of Predictions in Ungauged Basins (PUB)—a review. *Hydrological Sciences Journal*, 58, 1198–1255. https://doi.org/10.1080/02626667.2013.803183.

Idowu, T. E.; Lasisi, K. H. Seawater Intrusion in the Coastal Aquifers of East and Horn of Africa: A Review from a Regional Perspective. *Sci. Afr.* **2020**, *8*, e00402.

IGAD Climate Prediction and Applications Centre (ICPAC). Climate Change and Locust Outbreak in East Africa. *IGAD Climate Prediction and Applications Centre (ICPAC)*, February 28, 2020. https://www.icpac.net/publications/climate-change-and-locust-outbreak-east-africa/.

Intergovernmental Panel on Climate Change. *Climate Change 2022: Impacts, Adaptation and Vulnerability*; Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Pörtner, H.-O., Roberts, D. C., Tignor, M., Poloczanska, E. S., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., Rama, B., Eds.]; Cambridge University Press, 2022. https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/.

Kai, K. H.; Osima, S. E.; Ismail, M. H.; Waniha, P.; Omar, H. A. Assessment of the Impacts of Tropical Cyclones Idai to the Western Coastal Area and Hinterlands of the South Western Indian Ocean. *Atmos. Clim. Sci.* **2021**, *11* (4), 812–840.

Kalakkal, J.; Singh, A. Desert Locusts' Upsurges: A Harbinger of Emerging Climate Change-Induced Crises? **2021**. https://doi.org/10.13140/RG.2.2.18359.65441.

Kassie, M.; Wossen, T.; De Groote, H.; Tefera, T.; Sevgan, S.; Balew, S. Economic Impacts of Fall Armyworm and Its Management Strategies: Evidence from Southern Ethiopia. *Eur. Rev. Agric. Econ.* **2020**, *47*, 1473–1501. https://doi.org/10.1093/erae/jbz048.

BBC News. Kenyan Rice Farmers Battle Quelea Birds in Kisumu., February 20, 2023. https://www.bbc.com/news/world-africa-64596927.

Khasimuddin, S. Behavioural Ecology of the African Armyworm, *Spodoptera exempta* (Walker): Observations on Population Processes During a High-Density Outbreak. *Int. J. Trop. Insect Sci.* **1981**, *1*, 143–146. https://doi.org/10.1017/S1742758400000308.

Klein, I.; Oppelt, N.; Kuenzer, C. **2021**. Application of Remote Sensing Data for Locust Research and Management—A Review. *Insects*, 12, 233. https://doi.org/10.3390/insects12030233.

Kumar, R.M.; Gadratagi, B.-G.; Paramesh, V.; Kumar, P.; Madivalar, Y.; Narayanappa, N.; Ullah, F. Sustainable Management of Invasive Fall Armyworm, *Spodoptera frugiperda*. *Agronomy* **2022**, *12*, 2150. https://doi.org/10.3390/agronomy12092150

Le Gall, M.; Overson, R.; Cease, A. **2019**. A Global Review on Locusts (Orthoptera: Acrididae) and Their Interactions With Livestock Grazing Practices. *Frontiers in Ecology and Evolution*, 7, 263. https://doi.org/10.3389/fevo.2019.00263.

Lecoq, M. **1995**. Forecasting systems for migrant pests. III. Locusts and grasshoppers in West Africa and Madagascar. In *Insect Migration: Physical Factors and Physiological Mechanisms*; Drake, V. A., Gatehouse, A. G., Eds.; Cambridge University Press: Cambridge, UK, pp. 377–395.

Lecoq, M.; Cease, A. **2022**. What Have We Learned after Millennia of Locust Invasions? *Agronomy*, 12, 472. https://doi.org/10.3390/agronomy12020472.

Lenharo, M. **2024**. Brazil's record dengue surge: why a vaccine campaign is unlikely to stop it. *Nature*, 627, 250–251. https://doi.org/10.1038/d41586-024-00626-3.

Liu, X.; Zhang, D.; He, X. **2024**. Unveiling the role of climate in spatially synchronized locust outbreak risks. *Sci. Adv.*, 10, eadj1164. https://doi.org/10.1126/sciadv.adj1164.

Liu, X.; Zhang, D.; He, X. Unveiling the Role of Climate in Spatially Synchronized Locust Outbreak Risks. *Sci. Adv.* **2024**, *10* (7), eadj1164. https://doi.org/10.1126/sciadv.adj1164.

Machekano, H.; Mutamiswa, R.; Nyamukondiwa, C. Evidence of Rapid Spread and Establishment of *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in Semi-Arid Botswana. *Agric. Food Secur.* **2018**, *7*, 48. https://doi.org/10.1186/s40066-018-0201-5.

Markov, G.; Dekov, O.; Kocheva, M. Drought Impacts on Agricultural Pests. In *Drought in Bulgaria*; Routledge, 2018; pp 171–182.

Matova, P. M.; Kamutando, C. N.; Magorokosho, C.; Kutywayo, D.; Gutsa, F.; Labuschagne, M. Fall-Armyworm Invasion, Control Practices and Resistance Breeding in Sub-Saharan Africa. *Crop Sci.* **2020**, *60*, 2951–2970. https://doi.org/10.1002/csc2.20317.

Matthews, H. D.; Wynes, S. Current Global Efforts Are Insufficient to Limit Warming to 1.5°C. *Science* **2022**, *376* (6600), 1404–1409.

McWilliam, A. N.; Cheke, R. A. A Review of the Impacts of Control Operations against the Red-Billed Quelea (*Quelea quelea*) on Non-Target Organisms. *Environ. Conserv.* **2004**, *31*, 130–137. https://doi.org/10.1017/S0376892904001213.

Meynard, C.; Lecoq, M.; Chapuis, M.; Piou, C. On the Relative Role of Climate Change and Management in the Current Desert Locust Outbreak in East Africa. *Glob. Change Biol.* **2020**, *26*. https://doi.org/10.1111/gcb.15137.

Meynard, C.N.; Gay, P.-E.; Lecoq, M.; Foucart, A.; Piou, C.; Chapuis, M.-P. **2017**. Climate-driven geographic distribution of the desert locust during recession periods: Subspecies' niche differentiation and relative risks under scenarios of climate change. *Global Change Biology*, 23, 4739–4749. https://doi.org/10.1111/gcb.13739.

Meynard, C.N.; Lecoq, M.; Chapuis, M.; Piou, C. **2020**. On the relative role of climate change and management in the current desert locust outbreak in East Africa. *Global Change Biology*, 26, 3753–3755. https://doi.org/10.1111/gcb.15137.

Miller-Rushing, A. J.; Høye, T. T.; Inouye, D. W.; Post, E. The Effects of Phenological Mismatches on Demography. *Philos. Trans. R. Soc. B Biol. Sci.* **2010**, *365*, 3177–3186. https://doi.org/10.1098/rstb.2010.0148.

Mizuno, K. Geoecology I: Retreating Glaciers, Plant Succession on Mount Kenya Due to Climate Change. In *Glaciers, Nature, Water, and Local Community in Mount Kenya*; Springer Singapore: Singapore, 2022; pp 89–106.

Mkonyi, L.; Rubanga, D.; Richard, M.; Zekeya, N.; Sawahiko, S.; Maiseli, B.; Machuve, D. Early Identification of *Tuta absoluta* in Tomato Plants Using Deep Learning. *Sci. Afr.* **2020**, *10*, e00590. https://doi.org/10.1016/j.sciaf.2020.e00590.

Mmbaga, N. E.; Mongi, R. J.; Kilonzo, M. B.; Katalambula, L. K. Community Involvement in the Mass Capture of Red-Billed Queleas (*Quelea quelea*) Adjacent to Protected Areas: The Case of Chemba District, Dodoma, Tanzania. *Ostrich* **2023**, *94*, 223–227. https://doi.org/10.2989/00306525.2023.2250077.

Mohamed, E. S. I.; Mohamed, M. E.; Gamiel, S. A. First Record of the Tomato Leafminer, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) in Sudan. *EPPO Bull.* **2012**, *42*, 325–327. https://doi.org/10.1111/epp.2578.

Mongare, R.; Abdel-Rahman, E.M.; Mudereri, B.T.; Kimathi, E.; Onywere, S.; Tonnang, H.E.Z. Desert Locust (*Schistocerca gregaria*) Invasion Risk and Vegetation Damage in a Key Upsurge Area. *Earth* **2023**, *4*, 187-208. https://doi.org/10.3390/earth4020010

Muiruri, P. Kenya Declares War on Millions of Birds after They Raid Crops. *The Guardian*, January 17, 2023. https://www.theguardian.com/environment/2023/jan/17/kenya-birds-raid-crops-pesticides-quelea-raptors-aoe.

Müller, A.; Nilsson, S.; Prakash, A.; Lazutkaite, E. A Scoping Paper on the Ongoing Desert Locust Crisis 2019-2021+. *TMG Working Paper*. **2021**. https://doi.org/10.35435/2.2022.1.

Müller, A.; Prakash, A.; Lazutkaite, E.; Davis, M.; Amdihun, A.; Ouma, J. Scientific Linkages Between Climate Change and (Transboundary) Crop Pest and Disease Outbreaks. *TMG Working Paper*. **2022**. https://doi.org/10.35435/2.2022.5.

Mullié, W. C.; Prakash, A.; Müller, A.; Lazutkaite, E. Insecticide Use against Desert Locust in the Horn of Africa 2019–2021 Reveals a Pressing Need for Change. *Agronomy* **2023**, *13*, 819. https://doi.org/10.3390/agronomy13030819.

Mwangi, K.; Musili, A.; Otieno, V.; Endris, H.; Sabiiti, G.; Hassan, M.; Tsehayu, A.; Guleid, A.; Atheru, Z.; Guzha, A.; Meo, T.; Smith, N.; Makanji, D.; Kerkering, J.; Doud, B.; Kanyanya, E. Vulnerability of Kenya's Water Towers to Future Climate Change: An Assessment to Inform

Decision Making in Watershed Management. *Am. J. Clim. Change* **2020**, *9*, 317–353. https://doi.org/10.4236/ajcc.2020.93020.

Nagoshi, R.; Htain, N.; Boughton, D.; Zhang, L.; Xiao, Y.; Nagoshi, B.; Mota-Sánchez, D. Southeastern Asia Fall Armyworms Are Closely Related to Populations in Africa and India, Consistent with Common Origin and Recent Migration. *Sci. Rep.* **2020**, *10*. https://doi.org/10.1038/s41598-020-58249-3.

Nassali, J.; Yongji, Z.; Fangninou, F. F. A Systematic Review of Threats to the Sustainable Utilization of Transboundary Fresh Water Lakes: A Case Study of Lake Victoria. *Int. J. Sci. Res. Publ.* **2020**, *10* (2).

Navasero, M. M.; Navasero, M. V. Life Cycle, Morphometry and Natural Enemies of Fall Armyworm, *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae) on *Zea mays* L. in the Philippines. *J. Int. Soc. Southeast Asian Agric. Sci.* **2020**, *26*, 17–29.

Nayak, S. B.; Rao, K. S.; Ramalakshmi, V. Impact of Climate Change on Insect Pests and Their Natural Enemies. *Int. J. Ecol. Environ. Sci.* **2020**, *2*, 579–584.

Niassy, S.; Agbodzavu, M. K.; Kimathi, E.; Mutune, B.; Abdel-Rahman, E. F. M.; Salifu, D.; Hailu, G.; Belayneh, Y. T.; Felege, E.; Tonnang, H. E. Z.; Ekesi, S.; Subramanian, S. Bioecology of Fall Armyworm *Spodoptera frugiperda* (J. E. Smith), Its Management and Potential Patterns of Seasonal Spread in Africa. *PLOS ONE* **2021**, *16*, e0249042. https://doi.org/10.1371/journal.pone.0249042.

Njoki, M. The Effects of Mount Kenya Glacier Recession on Water Supply and Community Livelihoods–A Case Study of Nyeri and Laikipia Counties, Kenya (Doctoral dissertation, University of Nairobi). **2022**.

Ochieng', V.; Rwomushana, I.; Ong'amo, G.; Ndegwa, P.; Kamau, S.; Makale, F.; Chacha, D.; Gadhia, K.; Akiri, M. Optimum Flight Height for the Control of Desert Locusts Using Unmanned Aerial Vehicles (UAV). *Drones* **2023**, *7*, 233. https://doi.org/10.3390/drones7040233

Odenyo, V. A. O.; Verdonck, J. Threats to Inland Water Ecosystems in the Lake Victoria Basin–A Review in Relation to Water Resources Management Planning. *Afr. J. Educ. Sci. Technol.* **2015**, *2* (4), 291–307.

Odiyo, P. O. A Guide to Seasonal Changes in the Distribution of Armyworm Infestations in East Africa. *Int. J. Trop. Insect Sci.* **1984**, *5*, 107–119. https://doi.org/10.1017/S1742758400001764.

Ogega, O. M.; Alobo, M. Impact of 1.5°C and 2°C Global Warming Scenarios on Malaria Transmission in East Africa. *AAS Open Res.* **2020**, *3*.

Omwoyo, C. O.; Mburu, J.; Nzuve, F.; Nderitu, J. H. Assessment of Maize Yield Losses Due to the Effect of Fall Armyworm (*Spodoptera frugiperda*) Infestation: The Case of Trans-Nzoia County, Kenya. *Int. J. Pest Manag.* **2022**, *0*, 1–10. https://doi.org/10.1080/09670874.2022.2107727.

Ongoma, V.; Chen, H.; Gao, C.; Nyongesa, A. M.; Polong, F. Future Changes in Climate Extremes over Equatorial East Africa Based on CMIP5 Multi-Model Ensemble. *Nat. Hazards* **2018**, *90*, 901–920.

Outa, N. O.; Yongo, E. O.; Keyombe, J. L. A.; Ogello, E. O.; Wanjala, D. N. A Review on the Status of Some Major Fish Species in Lake Victoria and Possible Conservation Strategies. *Lakes Reserv.* **2020**, *25* (1), 105–111.

Overton, K.; Maino, J. L.; Day, R.; Umina, P. A.; Bett, B.; Carnovale, D.; Ekesi, S.; Meagher, R.; Reynolds, O. L. Global Crop Impacts, Yield Losses and Action Thresholds for Fall Armyworm (*Spodoptera frugiperda*): A Review. *Crop Prot*. **2021**, *145*, 105641. https://doi.org/10.1016/j.cropro.2021.105641.

Palmer, P. I.; Wainwright, C. M.; Dong, B.; Maidment, R. I.; Wheeler, K. G.; Gedney, N.; Hickman, J. E.; Madani, N.; Folwell, S. S.; Abdo, G.; Allan, R. P. Drivers and Impacts of Eastern African Rainfall Variability. *Nat. Rev. Earth Environ*. **2023**, *4* (4), 254–270.

Parker, W. E.; Gatehouse, A. G. The Effect of Larval Rearing Conditions on Flight Performance in Females of the African Armyworm, *Spodoptera exempta* (Walker) (Lepidoptera: Noctuidae). *Bull. Entomol. Res*. **1985**, *75*, 35–48.

Paudel Timilsena, B.; Niassy, S.; Kimathi, E.; Abdel-Rahman, E. M.; Seidl-Adams, I.; Wamalwa, M.; Tonnang, H. E.; Ekesi, S.; Hughes, D. P.; Rajotte, E. G.; Subramanian, S. Potential Distribution of Fall Armyworm in Africa and Beyond, Considering Climate Change and Irrigation Patterns. *Sci. Rep*. **2022**, *12*, 539.

Pekel, J.-F.; Ceccato, P.; Vancutsem, C.; Cressman, K.; Vanbogaert, E.; Defourny, P. **2011**. Development and Application of Multi-Temporal Colorimetric Transformation to Monitor Vegetation in the Desert Locust Habitat. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 4, 318–326. https://doi.org/10.1109/JSTARS.2010.2052591.

Pener, M.P.; Simpson, S.J. **2009**. Locust Phase Polyphenism: An Update. In *Advances in Insect Physiology*; Elsevier, pp. 1–272. https://doi.org/10.1016/S

Prasad, T. V.; Srinivasa Rao, M.; Rao, K. V.; Bal, S. K.; Muttapa, Y.; Choudhary, J. S.; Singh, V. K. Temperature-Based Phenology Model for Predicting the Present and Future Establishment and Distribution of Recently Invasive *Spodoptera frugiperda* (J. E. Smith) in India. *Bull. Entomol. Res.* **2021**, *1*–15. https://doi.org/10.1017/S0007485321000882.

Prasanna, B. M.; Bruce, A.; Beyene, Y.; Makumbi, D.; Gowda, M.; Asim, M.; Martinelli, S.; Head, G. P.; Parimi, S. Host Plant Resistance for Fall Armyworm Management in Maize: Relevance, Status and Prospects in Africa and Asia. *Theor. Appl. Genet*. **2022**, *135* (11), 3897–3916. https://doi.org/10.1007/s00122-022-04073-4.

Ramasamy, M.; Das, B.; Ramesh, R. Predicting Climate Change Impacts on Potential Worldwide Distribution of Fall Armyworm Based on CMIP6 Projections. *J. Pest Sci*. **2022**, *95* (2), 841–854. https://doi.org/10.1007/s10340-021-01411-1.

ReliefWeb. Horn of Africa: Humanitarian Snapshot (October 2019). *ReliefWeb*, October 2019. https://reliefweb.int/sites/reliefweb.int/files/resources/ROSEA_20191016_HOA_Humanitarian_Snapshot_October2019.pdf.

ReliefWeb. Regional Humanitarian Snapshot - June 2019. *ReliefWeb*, June 2019. https://reliefweb.int/sites/reliefweb.int/files/resources/Regional%20Humanitarian%20Snapshot%20-%20June%202019%20-%20EN.pdf.

Renner, S. S.; Zohner, C. M. Climate Change and Phenological Mismatch in Trophic Interactions Among Plants, Insects, and Vertebrates. *Annu. Rev. Ecol. Evol. Syst*. **2018**, *49*, 165–182. https://doi.org/10.1146/annurev-ecolsys-110617-062535.

Richardson, K.; Calow, R.; Pichon, F.; New, S.; Osborne, R. Climate Risk Report for the East Africa Region. *Met Office, ODI, FCDO: UK* **2022**.

Romano, A.; Garamszegi, L. Z.; Rubolini, D.; Ambrosini, R. Temporal Shifts in Avian Phenology Across the Circannual Cycle in a Rapidly Changing Climate: A Global Meta-Analysis. *Ecol. Monogr.* **2023**, *93*, e1552. https://doi.org/10.1002/ecm.1552.

Rose, D. J. W. Field Development and Quality Changes in Successive Generations of *Spodoptera exempta* Wlk., the African Armyworm. *J. Appl. Ecol.* **1975**, *12*, 727–739. https://doi.org/10.2307/2402085.

Rose, D. J. W.; Dewhurst, C. F.; Page, W. W. The Bionomics of the African Armyworm *Spodoptera exempta* in Relation to Its Status as a Migrant Pest. *Integr. Pest Manag. Rev.* **1995**, *1*, 49–64. https://doi.org/10.1007/BF00140333.

Rwomushana, I. *Spodoptera frugiperda* (Fall Armyworm). In *CABI Compendium*; CABI: Wallingford, UK, **2020**. https://doi.org/10.1079/cpc.29810.20210102715.

Sabiiti, G.; Ininda, J. M.; Ogallo, L. A.; Ouma, J.; Artan, G.; Basalirwa, C.; Opijah, F.; Nimusiima, A.; Ddumba, S. D.; Mwesigwa, J. B.; Otieno, G. Adapting Agriculture to Climate Change: Suitability of Banana Crop Production to Future Climate Change Over Uganda. *Limits to Climate Change Adaptation* **2018**, pp. 175–190.

Salih, A. A.; Baraibar, M.; Mwangi, K. K.; Artan, G. Climate Change and Locust Outbreak in East Africa. *Nature Clim. Change* **2020**, *10* (7), 584–585.

Santana Júnior, P.; Kumar, L.; Silva, R.; Picanço, M. Global Geographic Distribution of *Tuta absoluta* as Affected by Climate Change. *J. Pest Sci.* **2019**, *92* (1), 1–13. https://doi.org/10.1007/s10340-018-1057-y.

Satishchandra, N.K.; Vaddi, S.; Naik, S.O.; Chakravarthy, A.; Atlıhan, R. Effect of Temperature and CO2 on Population Growth of South American Tomato Moth, Tuta absoluta (Meyrick) (Lepidoptera: Gelechiidae) on Tomato. *J. Econ. Entomol.* **2018**, *111*, 1614-1624. https://doi.org/10.1093/jee/toy143.

Schneider, L.; Rebetez, M.; Rasmann, S. The Effect of Climate Change on Invasive Crop Pests Across Biomes. *Curr. Opin. Insect Sci.* **2022**, *50*, 100895. https://doi.org/10.1016/j.cois.2022.100895.

Schneider, T.; Bischoff, T.; Haug, G. H. Migrations and Dynamics of the Intertropical Convergence Zone. *Nature* **2014**, *513*, 45–53. https://doi.org/10.1038/nature13636.

Scranton, K.; Amarasekare, P. Predicting Phenological Shifts in a Changing Climate. *Proc. Natl. Acad. Sci. U. S. A.* **2017**, *114*, 13212–13217. https://doi.org/10.1073/pnas.1711221114.

Gullino, M. L.; Albajes, R.; Al-Jboory, I.; Angelotti, F.; Chakraborty, S.; Garrett, K. A.; Hurley, B. P.; Juroszek, P.; Makkouk, K. Scientific Review of the Impact of Climate Change on Plant Pests. *FAO on behalf of the IPPC Secretariat*. **2021**.

Sharon, B.; Michael, M.; Bwayo, M. F. Severity and Prevalence of the Destructive Fall Armyworm on Maize in Uganda: A Case of Bulambuli District. *Afr. J. Agric. Res.* **2020**, *16*, 777–784. https://doi.org/10.5897/AJAR2019.14670.

Showler, A. T.; Ould Babah Ebbe, M. A.; Lecoq, M.; Maeno, K. O. Early Intervention Against Desert Locusts: Current Proactive Approach and the Prospect of Sustainable Outbreak Prevention. *Agronomy* **2021**, *11* (2), 312. https://doi.org/10.3390/agronomy11020312.

Silva, D. M. da; Bueno, A. de F.; Andrade, K.; Stecca, C. dos S.; Neves, P. M. O. J.; Oliveira, M. C. N. de. Biology and Nutrition of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) Fed on Different Food Sources. *Sci. Agric.* **2017**, *74*, 18–31.

Silva, D.; Bueno, A.; Andrade, K.; Stecca, C.; Neves, P.; Oliveira, M. Biology and Nutrition of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) Fed on Different Food Sources. *Scientia Agricola* **2017**, *74*, 18–31. https://doi.org/10.1590/1678-992X-2015-0160.

Skendžić, S.; Zovko, M.; Živković, I. P.; Lešić, V.; Lemić, D. The Impact of Climate Change on Agricultural Insect Pests. *Insects* **2021**, *12* (5), 440. https://doi.org/10.3390/insects12050440.

Sokame, B. M.; Tonnang, H. E.; Calatayud, P.-A.; Dubois, T. Assessing the Impact of Climate-Resilient Maize Varieties and Their Interaction with the Stem Borer *Chilo partellus* (Swinhoe) (Lepidoptera: Crambidae) in Semi-Field Conditions. *Int. J. Trop. Insect Sci.* **2024**, *44*, 297–305.

The Guardian. Human-Driven Climate Crisis Fuelling Horn of Africa Drought – Study. *The Guardian*, 2023. https://www.theguardian.com/environment/2023/jan/17/kenya-birds-raid-crops-pesticides-quelea-raptors-aoe.

The Star. Embu Farmer Narrates Disappointing Trial with Pesticide Alternatives. *The Star*, December 12, 2021. https://www.the-star.co.ke/counties/eastern/2021-12-12-embu-farmer-narrates-disappointing-trial-with-pesticide-alternatives/.

Thiery, W.; Gudmundsson, L.; Bedka, K.; Semazzi, F. H. M.; Lhermitte, S.; Willems, P.; van Lipzig, N. P. M.; Seneviratne, S. I. Early Warnings of Hazardous Thunderstorms Over Lake Victoria. *Environ. Res. Lett.* **2017**, *12* (7), 074012.

Thomson, L. J.; Macfadyen, S.; Hoffmann, A. A. Predicting the Effects of Climate Change on Natural Enemies of Agricultural Pests. *Biol. Control* **2010**, *52*, 296–306.

Tonle, F. B. N.; Niassy, S.; Ndadji, M. M. Z.; Tchendji, M. T.; Nzeukou, A.; Mudereri, B. T.; Senagi, K.; Tonnang, H. E. Z. A Road Map for Developing Novel Decision Support System (DSS) for Disseminating Integrated Pest Management (IPM) Technologies. *Comput. Electron. Agric.* **2024**, *217*, 108526. https://doi.org/10.1016/j.compag.2023.108526.

Tonnang, H. E.; Mohamed, S. F.; Khamis, F.; Ekesi, S. Identification and Risk Assessment for Worldwide Invasion and Spread of *Tuta absoluta* with a Focus on Sub-Saharan Africa: Implications for Phytosanitary Measures and Management. *PLoS ONE* **2015**, *10*, e0135283.

Tonnang, H. E.; Sokame, B. M.; Abdel-Rahman, E. M.; Dubois, T. Measuring and Modelling Crop Yield Losses Due to Invasive Insect Pests Under Climate Change. *Curr. Opin. Insect Sci.* **2022**, *50*, 100873.

Tropea Garzia, G.; Siscaro, G.; Biondi, A.; Zappalà, L. *Tuta absoluta*, a South American Pest of Tomato Now in the EPPO Region: Biology, Distribution and Damage. *EPPO Bull.* **2012**, *42*, 205–210. https://doi.org/10.1111/epp.2556.

Tucker, M. R. Inter- and Intra-Seasonal Variation in Outbreak Distribution of the Armyworm, *Spodoptera exempta* (Lepidoptera: Noctuidae), in Eastern Africa. *Bull. Entomol. Res.* **1994**, *84*, 275–287. https://doi.org/10.1017/S0007485300039791.

Tumuhaise, V.; Khamis, F. M.; Agona, A.; Sseruwu, G.; Mohamed, S. A. First Record of *Tuta absoluta* (Lepidoptera: Gelechiidae) in Uganda. *Int. J. Trop. Insect Sci.* **2016**, *36*, 135–139. https://doi.org/10.1017/S1742758416000035.

United Nations Office for Disaster Risk Reduction (UNDRR). Humanity's Broken Risk Perception Reversing Global Progress, Spiral of Self-Destruction. *UNDRR*, April 2022. https://www.undrr.org/news/humanitys-broken-risk-perception-reversing-global-progress-spiral-self-destruction-finds-new.

United Nations Office for Disaster Risk Reduction. Sendai Framework for Disaster Risk Reduction 2015-2030. *UNDRR*, **2015**. https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030.

Uvarov, B. P. Grasshoppers and Locusts: A Handbook of General Acridology, Volume 2: Behaviour, Ecology, Biogeography, Population Dynamics; Centre for Overseas Pest Research: London, 1977.

Wallin, D. O. Habitat Dynamics for an African Weaver-Bird: The Red-Billed Quelea (*Quelea quelea*). Ph.D. Thesis, University of Virginia, 1990.

Wan, J.; Huang, C.; Li, C.; Zhou, H.; Ren, Y.; Li, Z.; Xing, L.; Zhang, B.; Qiao, X.; Liu, B.; Liu, C.; Xi, Y.; Liu, W.; Wang, W.; Qian, W.; McKirdy, S.; Wan, F. Biology, Invasion and Management of the Agricultural Invader: Fall Armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae). *J. Integr. Agric.* **2021**, *20*, 646–663. https://doi.org/10.1016/S2095-3119(20)63367-6.

Wang, L.; Zhuo, W.; Pei, Z.; Tong, X.; Han, W.; Fang, S. Using Long-Term Earth Observation Data to Reveal the Factors Contributing to the Early 2020 Desert Locust Upsurge and the Resulting Vegetation Loss. *Remote Sens.* **2021**, *13* (4), 680. https://doi.org/10.3390/rs13040680.

Wanjara, A. O.; Ogembo, P. O. Impact of Climate Change on Health and Livelihoods of Pastoral Communities in Kenya: A Case of North Eastern Region. *Indones. J. Soc. Environ. Issues* **2023**, *4* (3), 299–315.

Ward, P. The Migration Patterns of *Quelea quelea* in Africa. *Ibis* **1971**, *113*, 275–297. https://doi.org/10.1111/j.1474-919X.1971.tb05158.x.

Whittington-Jones, C. A. The Ecology of the Red-Billed Quelea *Quelea quelea* (Linnaeus) and Other Granivorous Birds at Eastern Cape Feedlots. Ph.D. Thesis, Rhodes University, **2001**.

Widlansky, M. J.; Long, X.; Schloesser, F. Increase in Sea Level Variability with Ocean Warming Associated with the Nonlinear Thermal Expansion of Seawater. *Commun. Earth Environ.* **2020**, *1*, 9.

World Meteorological Organization (WMO). State of the Climate in Africa 2022. WMO-No. 1330, Geneva,**2023**. State of the Climate in Africa 2022 (wmo.int).

Woodrow, K. P.; Gatehouse, A. G.; Davies, D. A. The Effect of Larval Phase on Flight Performance of African Armyworm Moths, *Spodoptera exempta* (Walker) (Lepidoptera: Noctuidae). *Bull. Entomol. Res.* **1987**, *77*, 113–122. https://doi.org/10.1017/S0007485300011597.

Word Ries, M.; Adriaansen, C.; Aldobai, S.; Berry, K.; Bal, A. B.; Catenaccio, M. C.; Cigliano, M. M.; Cullen, D. A.; Deveson, T.; Diongue, A.; Foquet, B.; Hadrich, J.; Hunter, D.; Johnson, D. L.; Karnatz, J. P.; Lange, C. E.; Lawton, D.; Lazar, M.; Latchininsky, A. V.; Lecoq, M.; Le Gall, M.; Lockwood, J.; Manneh, B.; Overson, R.; Peterson, B. F.; Piou, C.; Poot-Pech, M. A.; Robinson, B. E.; Rogers, S. M.; Song, H.; Springate, S.; Therville, C.; Trumper, E.; Waters, C.; Woller, D. A.; Youngblood, J. P.;

Zhang, L.; Cease, A. Global Perspectives and Transdisciplinary Opportunities for Locust and Grasshopper Pest Management and Research. *J. Orthoptera Res*. **2024**, *33* (2), 169-216. https://doi.org/10.3897/jor.33.112803.

World Meteorological Organization. State of the Climate in Africa 2022; WMO-No. 1293; World Meteorological Organization: Geneva, Switzerland, **2023**. https://library.wmo.int/records/item/67761-state-of-the-climate-in-africa-2022.

Yan, X.-R.; Wang, Z.-Y.; Feng, S.-Q.; Zhao, Z.-H.; Li, Z.-H. Impact of Temperature Change on the Fall Armyworm, *Spodoptera frugiperda* under Global Climate Change. *Insects* **2022**, *13*, 981.

Yihdego, Y. Drought and Pest Management. In *Handbook of Drought and Water Scarcity*; CRC Press, **2017**; pp 261–274.