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Special Section:
Multi-Sector Dynamics: Advancing Complex Adaptive Human-Earth Systems Science in a World of Interconnected Risks

Key Points:

- In Eastern Africa, desert locusts swarm in vast numbers, devouring crops, and vegetation, causing crop production losses ranging from 42% to 69%
- The system dynamics model was employed for a comprehensive analysis of the impacts, scenarios, and policy options for mitigating desert locust effects
- Desert locusts hinder farming, reduce food production, spur urbanization, and heighten food insecurity across affected Eastern African countries

Supporting Information:

Supporting Information may be found in the online version of this article.

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An Integrated Assessment Approach for Socio-Economic Implications of the Desert Locust in Eastern Africa

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Abstract Desert locust (*Schistocerca gregaria*) infestations cause significant damage to crops and pastureland, impeding food security and livelihoods globally. In recent years, some East African countries have suffered severe desert locust outbreaks, causing significant harm to agriculture and local communities. To comprehensively understand and mitigate the socio-economic impacts of this pest, an integrated assessment approach is crucial. This study proposes an integrated assessment model that combines ecological, economic, and social dimensions to analyze the multifaceted impacts of the desert locust on the rate of urbanization changes, farming expansion, and food production and how they lead to food unavailability (demand, supply, and price) and food and nutrition insecurity in Eastern Africa. A system dynamics-based assessment model was first developed for Sudan using the dynamic relations among the factors and their variations over time and how they affect the socio-economic variables. The developed model was used to spatially simulate the impacts over the entire Eastern Africa. Various scenarios were further simulated and analyzed, incorporating different policy options to effectively mitigate the impacts. Results demonstrated that in all the countries, desert locusts extensively contribute to the slowing down of farming expansion and food production and supply. Consequently, these factors lead to increased urbanization rates through people rural-urban migration and food demand at different magnitudes across different countries. By considering both short-term and long-term effects, this approach aims to provide policymakers, researchers, and practitioners with a holistic understanding of the complex dynamics involved and inform effective management strategies. For example, communities equipped with accurate breeding detection tools and employing an integrated pest management strategy combining chemical pesticides and biopesticides had the highest potential for effectively mitigating the future impacts of desert locusts for enhancing community livelihood.

Plain Language Summary Desert locusts are a major problem for agriculture and communities in East Africa. They eat crops and grasslands, which can lead to food shortages and higher prices. To better understand and deal with this issue, we have created a model that looks at how locusts affect things like farming, urbanization, and food supply. We studied this in Sudan and then applied it to the whole of East Africa. The results showed that locusts make farming harder and push more people to move from rural areas to cities. This causes more demand for food in cities. The study tested different ways to deal with locusts and found that communities with good tools for detecting locusts and using both chemical and biopesticide control methods were the best at reducing the impact of locusts on their lives. This study gives policymakers and others a better understanding of how locusts affect communities and how to manage them effectively in the future.

1. Introduction

The socio-economic impacts of desert locusts (*Schistocerca gregaria*) are multifaceted and significant, encompassing a wide range of sectors and communities. An adequate assessment of the impacts on population livelihood is a complex process (FAO, 2006; Li et al., 2022; Srikrishnan et al., 2022). Desert locust is known for its ability to form massive swarms when their numbers increase (Katel et al., 2021; Song, 2004). In 2019, these swarms originating from Yemen invaded East African countries like Ethiopia, Kenya, and Somalia, destroying over 100,000 ha of crops and pastureland in Ethiopia and Somalia, and 175,000 ha in Kenya (Okonji, 2020; World Bank, 2020). This upsurge is the worst in 25 years in Somalia and Ethiopia, and the most severe in Kenya in

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70 years. It had a devastating impact on the affected regions, with uncertain effects on people's livelihoods (International Red Cross, 2022; World Bank, 2020). The desert locust's unique ability to shift from solitary to gregarious phases poses significant challenges for food security. In periods of upsurge or plagues, the desert locust causes extensive and significant vegetation and agricultural crop losses. This is a principal menace to industrial raw materials, food security, and incomes in the affected regions. The swarms have the potential to disperse across areas ranging from less than a square kilometer to several hundreds of square kilometers, with a density of 40–80 million locust adults per square kilometer (Mamo & Bedane, 2021a, 2021b). It is estimated that an adult desert locust consumes approximately its own weight in fresh food per day, which is roughly equivalent to 2 g/day (Mamo & Bedane, 2021a, 2021b). Comparative studies have shown that a desert locust swarm of 1 km^2 in size can consume the same amount of food that would sustain approximately 35,000 people in a single day (Mamo & Bedane, 2021a, 2021b). Regions vulnerable to desert locust infestations have reported vegetation and crop production losses ranging from 42% to 69% (FAO, 2020; FSNWG, 2020). This estimation amounts to around 160,000 tons of food per day (Pandey et al., 2021). By March 2020, it was reported in Ethiopia the following losses due to desert locust invasion: 41,341 tons of maize; 11,163 tons of sorghum; 3,618 tons of wheat; 600.5 tons of barley and 45.3 tons of vegetables (Nandelenga & Legesse, 2020; Pandey et al., 2021). In Sudan, 55,000 tons of cereals losses were attributed to a desert locust invasion in 1958 (Lecoq, 2003). In the event of a desert locust upsurge, it was observed that the control measures adopted in Eastern Africa were mostly spraying of chemical pesticides (Enns et al., 2022; Wiktelius et al., 2003) which are often unsuccessful to contain the pest population. In East Africa, 1.8 million liters of chemical pesticides were sprayed on over 1.76 million hectares only in March 2021 (McConnell, 2021). These pesticides include fipronil, deltamethrin, chlorpyrifos, and other insecticides many of which are prohibited (Than, 2013). Despite spraying of hazardous pesticides, locusts caused significant damage by consuming all green vegetation encountered including farming crops and animal pastures leading to low yield and massive decreases in food production in the whole agricultural system as there is a huge issue with pesticides that are of poor quality, that have not been stored correctly and or using pesticides that are not approved for desert locust control. Desert locusts consume leaves, stems, fruits, seeds, shoots, etc. of a wide variety of plant species including cash crops, food crops, trees, etc (Le Gall et al., 2019; Shrestha et al., 2021). An in-depth analysis of policy documents in the East Africa region for desert locust control reveals a comprehensive approach that encompasses early warning systems, collaboration, sustainable pest management, capacity building, resources mobilization, and environmental considerations (Pantenius & Butrous, 2017). These policies aim to address the complex and evolving challenges posed by desert locusts while promoting long-term resilience and sustainability. However, the management of desert locust outbreaks in the East African region faces a multitude of challenges. One prominent issue is the glaring gap between policy formulation and effective implementation. While policies may appear comprehensive on paper, they often encounter significant hurdles in practice. Resource constraints, administrative challenges, and sometimes a lack of political will all contribute to this implementation gap. As a result, despite well-intentioned policies, the region struggles to mount a timely and coordinated response to locust infestations. Another critical shortfall is the limited coordination among East African countries, despite the advocacy for cross-border collaboration in policy documents. This lack of alignment hampers efforts to control desert locusts effectively, leading to fragmented and less impactful responses. Funding emerges as a persistent issue. Although policies recognize the need for financial resources, securing adequate funding remains a daunting challenge. Consequently, control initiatives are often underfunded, compromising their efficiency. Monitoring and evaluation mechanisms are sometimes lacking in policies, making it difficult to gauge the impact of control measures accurately. Without a clear framework for assessment, it becomes challenging to adjust strategies as needed for better outcomes. Environmental impact assessment is emphasized in some policies, but enforcement and oversight may be insufficient, potentially leading to environmental harm using pesticides. Community engagement is crucial for early detection and response, yet policies may not effectively involve local communities, especially those in remote and marginalized areas. Moreover, while recognizing the influence of climate change on locust behavior, policies may fall short in providing clear strategies to adapt to these changing conditions, introducing uncertainties in control efforts.

The objective of this study was to develop an integrated multi-way feedback dynamics assessment model that synthesizes the dynamics of desert locust outbreaks and population, the agricultural system, and the impacts on food and nutrition security, thereby providing insights into the socio-economic situation of people in Eastern Africa. The created holistic analysis allows for a better exploration of mitigation options. As desert locusts invade a given region, their density and population dynamics are influenced by environmental and climatic conditions. Moreover, their presence might also have significant impacts on food and livestock production. These interactions

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are complex, characterized by counteractions and dependencies within the system. Therefore, focusing on a specific component or sub-system within the broader context of the impact on population livelihood when developing a desert locust impact system would oversimplify the system and reduce it to a singular source (Pandey et al., 2021; World Bank, 2020). Such a system should include desert locust outbreaks and population dynamics, agricultural system component, country-specific populations, and food and nutrition sub-systems that are interdependent. From a system perspective, the change at any component level will affect the behavior of the whole system, which however, is not just an accumulation of the elements of the system (Bala et al., 2018; Mahajan et al., 2019). When examining such a system in isolation, it becomes challenging to fully comprehend the dynamic interplay between its elements (Lin & Yang, 2022). Models that combine different system processes into a unique framework seem to be more relevant tools for analyzing such impact and their outcomes in an integrated assessment manner (Kelly et al., 2013). Among those models, there are agent-based models (Filatova et al., 2011; Gao et al., 1992), Bayesian networks (Levontin et al., 2011; Pérez-Miñana et al., 2012), coupled components models (Münier et al., 2004; Rivington et al., 2007), knowledge-based models (Giordano & Liersch, 2012; Vellido et al., 2007) and system dynamics (Lauf et al., 2012; Qin et al., 2011). However, most of these model's present limitations. Agent-based models lack aggregated effect behavior of a system while only focusing on interactions between autonomous individuals and complex descriptions of a specific process (Gross et al., 2006; Le et al., 2012). On the other hand, Bayesian networks lack quantitative data to populate the model (Bacon et al., 2002) while knowledge-based models lack not only quantitative data but also system understanding (Chevalier et al., 2012; Fleming et al., 2007) and coupled components models lack the variation over time pattern of the system (Krol et al., 2001; Lehtonen et al., 2007). The application of the system dynamics approach (Chang et al., 2007) allows the systematic analysis of the structure of the system and the dynamic relationship among the elements of the system.

In this paper, the key factors influencing the implications of desert locust invasion in community livelihoods were identified. Using a system dynamics approach, an assessment model of the socio-economic implications of desert locusts in Eastern Africa was developed. Overall, we uncover the dynamic relationships among these factors and establish how their variations affect socio-economic indicators, namely urbanization, farming expansion, food production, food demand and supply, food prices, and food and nutrition insecurity at both the country and regional levels. Additionally, we simulate various scenarios and analyze management options to mitigate the impacts.

2. Materials and Methods

2.1. Study Area and Data Sources Description

2.1.1. Study Area

The study was conducted in Eastern African member countries composed of Djibouti, Kenya, Ethiopia, Eritrea, Sudan, South Sudan, Somalia, Tanzania, and Uganda. These countries comprise five frontline countries of desert locust invasion that is, Sudan, Eritrea, Ethiopia, Somalia, and Djibouti, and four countries of potential desert locust invasion that is, Kenya, Tanzania, Uganda, and South Sudan (Kimathi et al., 2020) (Figure 1). The land surface area of all member countries covers about 6,157,725 km^2 with an estimated population of 361 million inhabitants.

The preferred habitat for locusts in Eastern Africa, which includes the countries mentioned above, is primarily influenced by a combination of biophysical dynamics. These dynamics are related to climate, vegetation, and other environmental factors that create favorable conditions for locust breeding, migration, and infestation (Kimathi et al., 2020; Wang et al., 2021). *Climate and weather patterns*: Locusts thrive in warm and moist conditions. Eastern Africa experiences a climate characterized by periods of heavy rainfall followed by dry spells. These climatic fluctuations create suitable breeding conditions for locusts. Rainfall allows vegetation to grow, providing locusts with food, while subsequent dry periods encourage them to migrate in search of new food sources. *Vegetation and crop availability*: The region's diverse landscapes include both arid and semi-arid areas as well as fertile farmland. Locusts prefer to lay their eggs in sandy soils, and the region's diverse vegetation provides ample food sources for locusts, making it an attractive habitat. Crops like sorghum, millet, and maize cultivated in the region are particularly vulnerable to locust infestations. *Long-distance migration*: Locusts are known for their ability to migrate over long distances in search of food. The favorable wind patterns in Eastern Africa facilitate locust swarms' movement across borders and into neighboring countries. *Environmental changes and human activities*: Human-induced environmental changes such as deforestation, land-use changes, and urbanization in

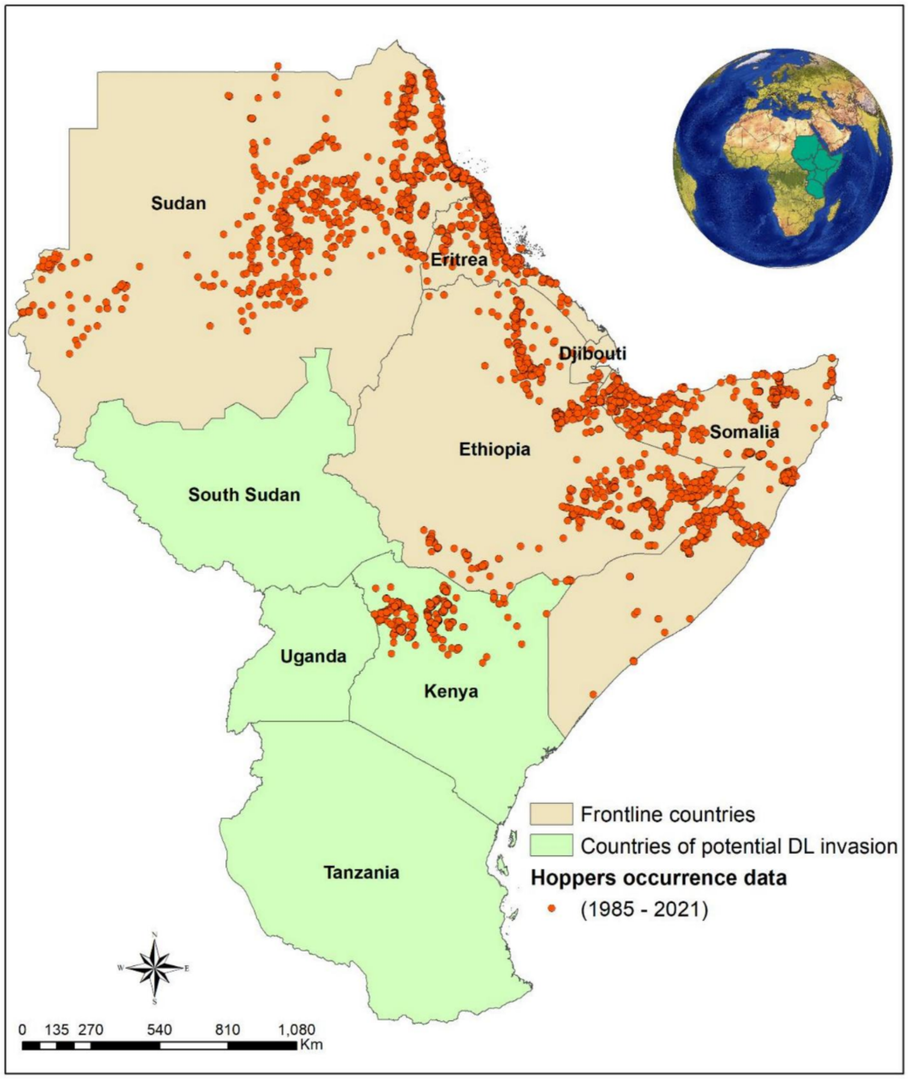

Figure 1. Study area and desert locust (DL) observation (1985–2021) locations. DLIS–FAO data set https://locust-hub-hqfao.hub.arcgis.com/.

the region can disrupt natural predator-prey dynamics and create conditions that favor locust outbreaks. Additionally, the misuse of pesticides and other agricultural practices can inadvertently contribute to locust population growth. *Historical factors*: Historical records show that locust outbreaks have occurred in this region for centuries, and the presence of locusts has become somewhat cyclical due to the interplay of these factors. Factors such as economic capacity, infrastructure, resilience, and regional cooperation also play a crucial role in determining how effectively countries can mitigate the effects of locust infestations on agriculture and food security.

2.1.2. Data Sources

The data utilized in this study encompassed various components to holistically capture the multifaceted impacts of the desert locust in Eastern Africa. The data were assembled from several sources, including literature reviews using published articles and authentic web site information (see Open Research section), government official and international organization reports and field surveys. The data collected spanned multiple years, providing a time series (1990–2020) that allowed for the analysis of changes and trends over time. This longitudinal perspective was key in understanding the temporal dynamics of locust infestations and their impacts. The Covid19 pandemic might have affected the desert locust data in the last year of the study, hence it was not considered as we were conducting a long-term analysis for over 30 years. The main type of data was categorized as follow:

1. **Ecological Data**: Information about locust breeding sites, migration patterns, and population dynamics were collected. This also included climatic data such as temperature, precipitation, given their influence on locust breeding and migration. Temperature and rainfall data were sourced from the Worldclim data portal (https://worldclim.org/).
2. **Agricultural Data**: Detailed crop data were collected, including agricultural yield, farming practices, the extent of locust damage, food production, cultivated fields surface, etc. The control strategies and interventions, the vegetation in the cultivated fields and food production per unit area were also collected. These data were crucial for understanding the direct impact of locust infestations on food production.
3. **Socio-Economic Data**: Agriculture Gross Domestic Product (GDP), global GDP, per capita net income, food production, food security and other relevant economic indicators were gathered to assess the economic impact of locust infestations. The food security data mainly focused on the information on food production, food supply, and demand, food price and safety. Furthermore, country population dynamics data, covering the total population, rural and urban population, rural-urban migration patterns population, human natural growth rate, and death cases were obtained, given their relevance to the study.
4. **Spatial Data**: Geographic Information System|geographic information system (GIS) data were crucial for the spatial simulation of the impacts. This included data on regional boundaries, land use, and topography, among others.

All data were subjected to thorough preprocessing and validation procedures to ensure their reliability and accuracy. This included dealing with missing values, checking for inconsistencies, and standardizing data from different sources. Specifically, to ensure the quality of our data set, we engaged in an extensive data preprocessing and validation phase, which addressed several challenges:

Missing Data: In cases where data were missing, we employed imputation methods tailored to the nature of the data. For categorical data, mode imputation was applied, while for numerical data, median or mean imputation was used.

Inconsistencies: All data were rigorously cross-checked for inconsistencies. In cases where discrepancies were found between sources, priority was given to official reports and expert literature. Furthermore, any outlier data points were investigated for validity and corrected or omitted as necessary.

Lack of standardization: Given the diverse range of data sources, standardizing the information was a paramount concern. We achieved this by first identifying common metrics and units across sources. Subsequently, any data that did not conform to these standardized units were transformed accordingly. When merging data sets, we ensured that common identifiers existed and were consistently applied.

By adhering to these rigorous procedures, we ensured that the data underpinning our analysis was both reliable and accurate, allowing us to draw meaningful conclusions from our research.

2.2. Integrated Assessment Process Design

The overall process designed to provide a comprehensive understanding of the multifaceted impacts of desert locusts, and to inform effective management strategies that can be implemented at both the local and regional levels to mitigate the impacts. The following steps are involved:

1. **Integrated Assessment Framework**: The study begins by proposing an integrated assessment framework that combines ecological, economic, and social dimensions. This approach ensures a holistic understanding of the complex dynamics involved in desert locust infestations and their socio-economic impacts.
2. **System Dynamics-Based Assessment Model**: The core of the methodology relies on a system dynamics-based assessment model, which captures the dynamic relations among various factors and their variations over time. The model integrates several socio-economic variables such as urbanization, farming expansion, food production, food demand and supply, food price, and food and nutrition insecurity.
3. **Spatial Simulation**: Once the model is developed and calibrated, it is used to spatially simulate the impacts of desert locusts over the entire Eastern Africa. This allows to understand the geographical spread and intensity of the impacts.
4. **Scenario and Policy Options Analysis**: Various scenarios are then simulated and analyzed, incorporating different policy options to effectively mitigate the impacts. This provides a comparative analysis of potential mitigation strategies.

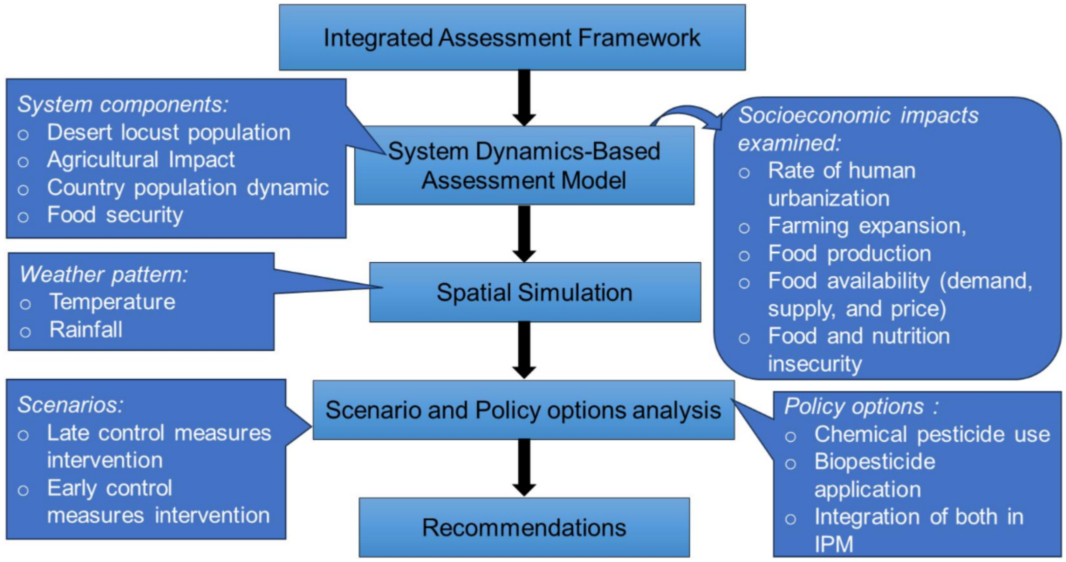

Figure 2. Methodological flowchart of the integrated assessment framework. IPM is integrated pest management.

5. **Policy Recommendations**: The results of the model and scenario analyses are then used to make policy recommendations.

Figure 2 presents the methodological flowchart of the integrated assessment approach. This flowchart illustrates the methodological process for analyzing the socio-economic impacts of desert locusts in East Africa. The process begins with the development of an integrated assessment framework, which informs the creation of a system dynamics-based assessment model. The model is then used to conduct a spatial simulation of the impacts, which informs a scenario analysis. The findings from the scenario analysis are then used to develop policy recommendations.

2.3. System Dynamics Modeling

System dynamics modeling is a computer-based method, founded on the theories of feedback control and the nonlinear dynamics (Sterman, 2000). It uses system feedback, time delay, amplifications, nonlinearities, and structural relationships between the elements of a system that could be more relevant in determining the behavior of an aggregated system than if individual components were to be used (Forrester, 1961; Sterman, 2000). System dynamics modeling approaches have been largely described in the literature (Cavana, 2003; Maani & Cavana, 2007; Sterman, 2000) and they have been used in impact assessment (Çelebi, 2019; Chica-Morales et al., 2021; Haron & Hawari, 2017; Karami et al., 2017). The approach commences with dynamic hypothesis development, known as a causal loop diagram (CLD) or conceptual model, which is then translated into stocks and flows diagrams (SFDs) for quantifications and simulations (Sokame et al., 2021).

2.3.1. The Conceptual Model (CLDs) Development

Causal loop diagrams (CLDs) are tools that allow quantification and analysis of systems by representing relationships and connectivity among variables of a system to produce dynamic feedback structures (Sterman, 2000). These CLDs map the hypotheses of the structure of the system through causal relationship linkage among system variables. The diagram consists of four fundamental elements: variables (with the characteristic to vary over time), the coupling links joining the variables, the signs (positive or negative) on those links indicating how they are interconnected (change direction that one variable imposes on the other in the model), and the loop sign showing the type of behavior that the system will produce. When the relationship is positive (+), all things being equal, a decrease/increase in a given variable A will lead to a decrease/increase in a given variable B in the model. On the other hand, when the relation is negative (−), a decrease/increase in variable A in the model would increase/decrease in variable B. Aggregation of causal relationships (positive and/or negative) lead to feedback loops, which might be either negative (balancing) or positive (reinforcing) (Sterman, 2000). While balancing

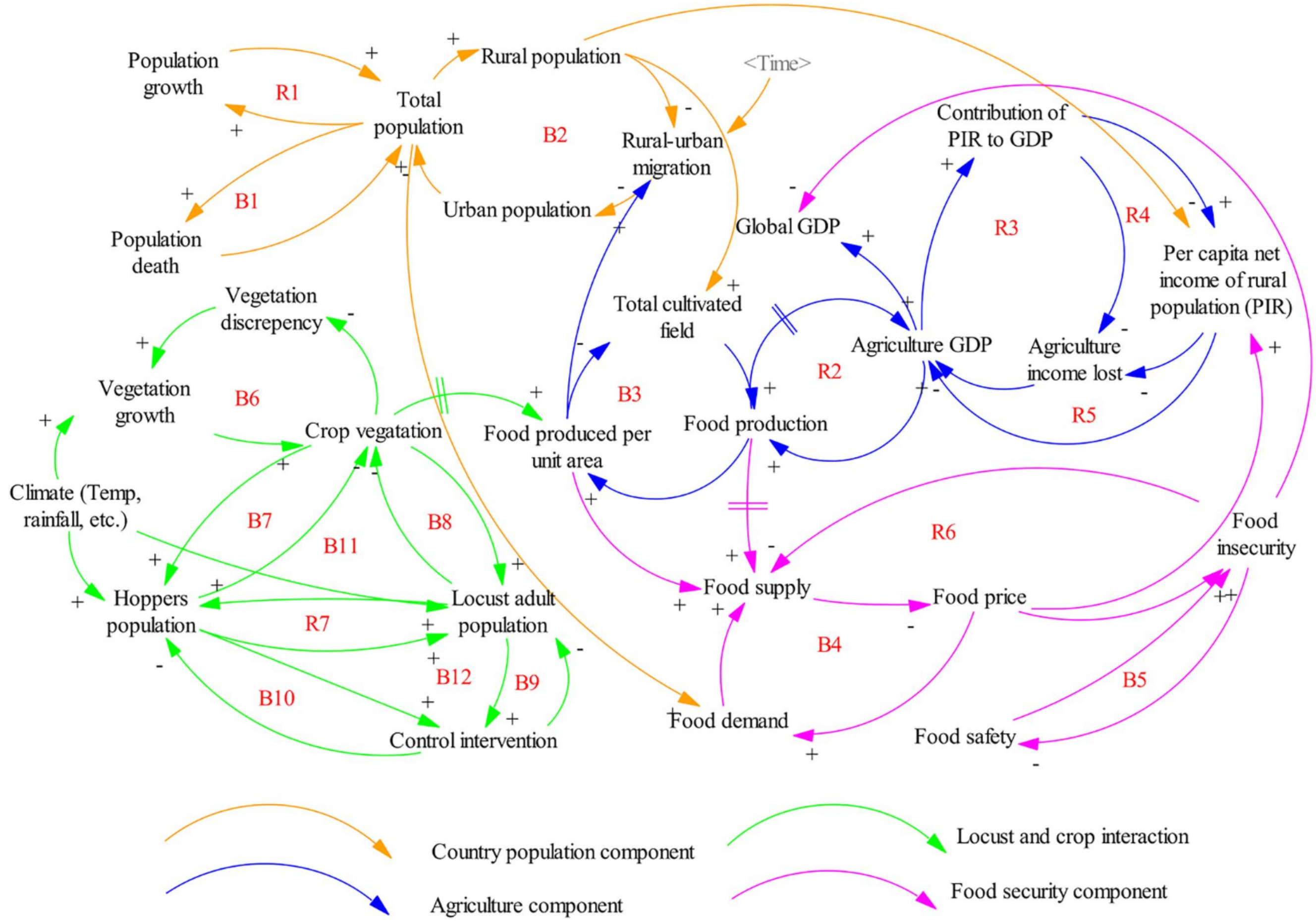

Figure 3. The causal loop diagram for the desert locust impact on socio-economic components in Eastern Africa.

feedback loops resist change in the system, reinforcing feedback loops quicken change in the model leading to a rapid decline or growth of the system (Simonovic, 2008).

The CLD for the socio-economic impact of desert locust invasion presented in Figure 3 was developed based on authors' knowledge, literature reviews of published articles, authentic website information, and government reports. Firstly, the research problem and key variables crucial for understanding the dynamics of desert locusts were identified to encompass and represent the critical variables and feedback loops. The CLD was then developed by connecting variables with links and the appropriate polarity signs and by connecting several feedback loops to map the complex structure of the desert locust system using the VENSIM modeling platform (Ventana Systems Inc., DSS 8.2).

In the current context, four different components or sub-systems were identified for the holistic analyses of the complex system of desert locust socio-economic impacts within the communities. These include the country's human population dynamics, agriculture domain, food security component, and desert locust and crop/vegetation interactions. The key variables within each component were identified and CLDs were connected as shown in different colors in Figure 3 to reflect the interactions within the whole system. Overall, the conceptual system model comprised 26 system variables, which were linked to each other with a total of 48 links. The interactions between them resulted in 19 feedback loops, consisting of 7-positive (reinforcing: R) and 12-negative (balancing: B), which capture the essential components and variables of the whole system (Figure 3).

The balancing and reinforcing loops for each of the four components are further described in Table 1.

The causal loops were transformed into a dynamic model by employing stocks, flows, auxiliary links, and clouds, which enable the system to be numerically simulated and quantified.

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Table 1
Causal Loop by System Components

	Loop description	Implication
	Country Population Component	
B1	Total population—loss through death–Total population	Country population is reduced by the death rate
B2	Total population—Rural population—Rural-urban migration—Urban population–Total population	Within the total population, there is rural and urban population with rural-urban migration interaction between them
R1	Total population—Human population growth—Total population	Country population is increased by the number of births
	Agriculture Component	
B3	Food production—Food produced per unit area –Total cultivated field—Food production	The quantity of food produced depends on the per unit area production and total cultivated territory
R2	Food production—Agriculture GDP—Food production	The value of agricultural GDP is based on the food production
R3	Agriculture GDP—Contribution of PIR to GDP—Agriculture income lost–Agriculture GDP	The value of agricultural GDP determines contribution of per capita net income of rural population to the country GDP which depends on agricultural income losses.
R4	Agriculture GDP–Contribution of PIR to GDP—Per capita net income of rural population (PIR)—Agriculture income lost—Agriculture GDP	High agriculture income losses result in low rural population income and agriculture contribution to country GDP.
R5	Agriculture GDP –Contribution of PIR to GDP—Per capita net income of rural population (PIR)—Agriculture GDP	Rural population incomes determine the level of agriculture contribution to the country GDP
	Food Security Component	
B4	Food supply—Food price—Food demand–Food supply	Food supply drives the demand and price in the market.
B5	Food insecurity—Food safety—Food insecurity	Food safety decreases the level of food insecurity and vice versa
R6	Food insecurity—Food supply—Food price—Food insecurity	When there is a lack of food supply, the price increases in the market, leading the high food insecurity.
	Crop and Desert Locust Component	
B6	Crop vegetation—Vegetation discrepancy—Vegetation growth- Crop vegetation	Naturally, the level of vegetation density influences the rate of its growth
B7	Crop vegetation—Hoppers population–Crop vegetation	The abundance of hoppers population determines the level of available crop vegetation and vice versa
B8	Crop vegetation—Locust adult population–Crop vegetation	The abundance of locust adult population determines the level of available crop vegetation and vice versa
B9	Locust adult population—Control intervention–Locust adult population	Control methods reduce the number of adult locusts, which lowers the damage they cause and their ability to spread to other areas, ultimately determining how effective the control measures are.
B10	Hoppers population—Control intervention–Hoppers population	Control methods reduce the number Hoppers population, which lowers the damage they cause and their ability to spread to other areas, ultimately determining how effective the control measures are.
B11	Vegetation–Locust adult population–Hoppers population—Vegetation	The population dynamic of either adult or hoppers depends on the green vegetation available.
B12	Control intervention–Hoppers population—Locust adult population–Control intervention	The whole population of locusts (either hoppers or adults) is driven by the control measures.
R7	Hoppers population—Locust adult population–Hoppers population	Hoppers increase adult population and vice versa.

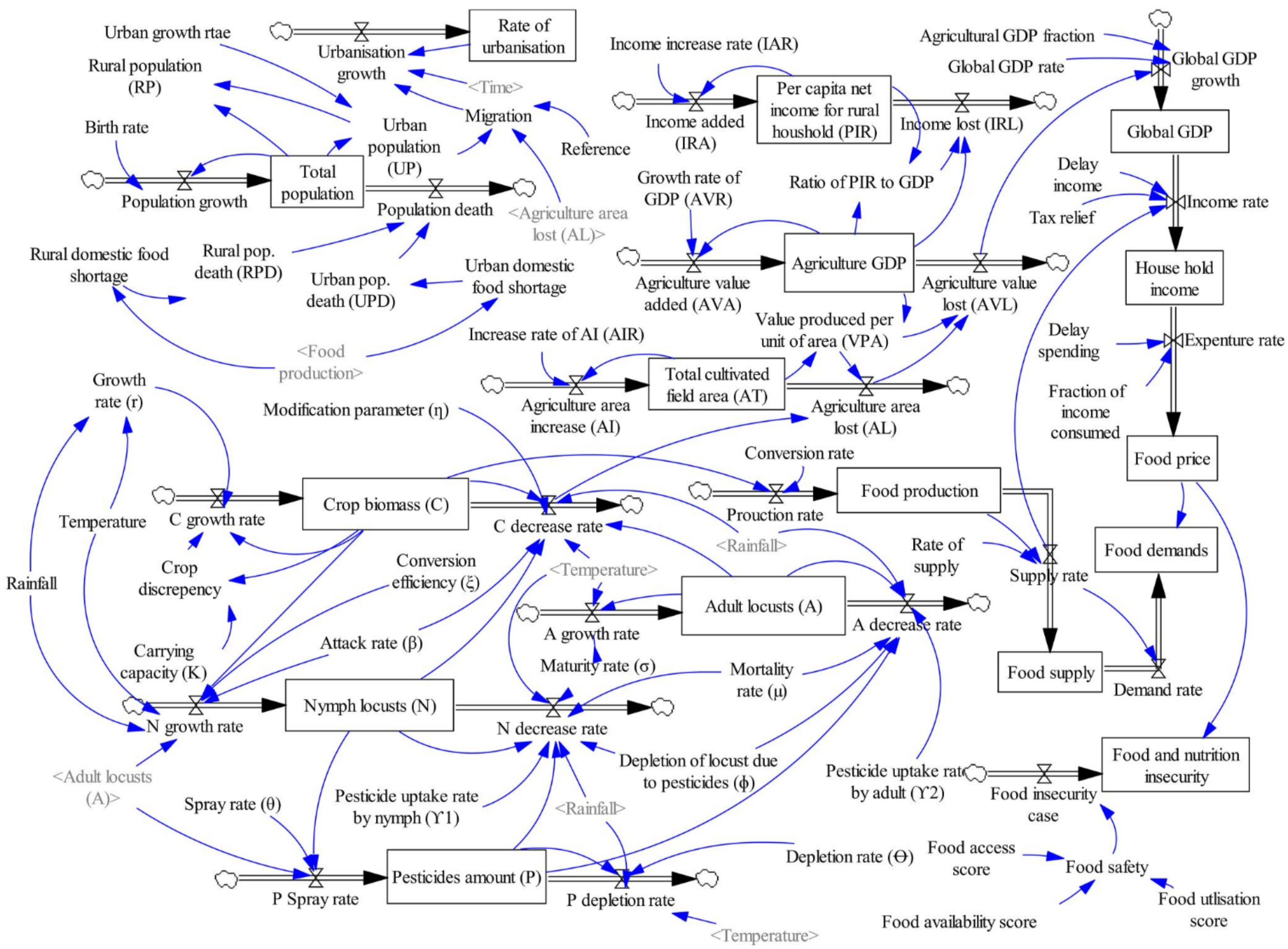

Figure 4. The stocks and flows diagram of the desert locust impact on socio-economic components in Eastern African countries.

2.3.2. Dynamic Simulation Model Settings and Description

The CLD is narrow, static, and reductionist in nature as it is a presentation of a limited human mental model (Sterman, 2001). Since systems change with time, the approach should consider the behavior of each variable temporally. Therefore, we converted the visual mapping of the conceptual model into SFDs which measured the accumulation and dispersal of variables over time in the system (Sterman, 2001). The main assumption of SFDs was that systems could be represented as a set of stocks (accumulations, levels) and flows (rates) so that the energy or material accumulated in the stocks and transited between them through flows (Voinov & Bousquet, 2010). In this context, the obtained CLD (Figure 3) was transformed into SFDs, comprising four interconnected sub-systems: desert locust, agricultural production, country population dynamics, and food security. These sub-systems were integrated into a unified system model (Figure 4). This analysis was conducted over a span of 60 years, specifically from 1990 to 2050. The year 1990 was chosen as the starting point due to the commencement of systematic recording of desert locust invasions, although the recording began in the early 1980s. Similarly, the year 2050 was selected to represent the long-term scenario, enabling the analysis of the system's long-term dynamic behavior.

A detailed description of the envisioned sub-systems for the desert locust socio-economic impacts

Desert locusts sub-system was structured into four stocks: Hoppers or nymph locusts (H), Adult locusts (A), green Vegetation (V) and pesticides/biopesticides use for control purpose (P). The hoppers and adults are distinguished as these two stages have different consumption rates of the green vegetation. These stocks influence each other through either their inflows or their outflows. The flows initiated by the growth and death rate of either hoppers or adult locusts depend on the climatic conditions mostly by temperature and rainfall as well as anthropogenic controls using pesticides. The destruction of green vegetation by hoppers and adult locusts directly and negatively reduces the rate of food production per unit area. The following ordinary differential Equations 1–4 proposed in Mamo and Bedane (2021b) drive the sub-system:

$$\frac{dV}{dt} = rV\left(1 - \frac{V}{K}\right) - \beta\left(A + \eta H\right)V \quad (1)$$

$$\frac{dH}{dt} = \varepsilon\beta VA - \varnothing\gamma_1 HP - (\delta + \mu)H \quad (2)$$

$$\frac{dA}{dt} = \delta H - \varnothing\gamma_2 AP - \mu A \quad (3)$$

$$\frac{dP}{dt} = \theta(H + A) - \theta_0 P \quad (4)$$

Where r = Vegetation growth rate in the absence of locusts, β = adult locusts rate of consumption, η = hoppers rate of consumption correction coefficient, ε = conversion efficiency of desert locusts, ϕ = desert locusts population reduction due to pesticide use, δ = hoppers maturity rate, γ_1 = uptake rate of hoppers, γ_2 = uptake rate of adult desert locusts, μ = mortality rate, θ = pesticide spray rate, θ_o = pesticide depletion rate. The initial conditions are given as V(0), H(0), A(0), P(0) ≥ 0. The complete sub-system model expression and annotation can be found in Tables S1 and S2 in Supporting Information S1.

The agricultural production sub-system comprises four stocks (farming expansion, food production, per capita net income for rural households, and agricultural GDP) with two flows each, inflow, and outflow (Figure 4). The rate of food production previously impacted by desert locusts contributes to the increase of agriculture area losses regarding yield which reduces the agriculture value for the contribution to per capita net income for rural households and the country's GDP, while on the other hand, it contributes to the weakness of the level of food supply. This sub-system's variables are also dependent on the climatic conditions (temperature and rainfall considered most important) in rain-fed agriculture, which is the economic bedrock of the majority of people in eastern Africa.

The country population dynamics sub-system is constituted of two stocks namely total population and rate of urbanization. The model encompasses the dynamics of the population, taking into account factors such as birth and death rates, immigration and emigration rates, and the availability of food for population consumption (Figure 4). Furthermore, the rate of urbanization is estimated to be influenced by the population migration from rural zones to towns depending on the output performance of agricultural production systems.

The food security sub-system is represented by six different stocks: the country's global GDP, household income, food price, food supply, food demand, and food and nutritional insecurity (Figure 4). The country's global GDP is influenced by the contribution of agriculture GDP, which influences household income but depends on the food price. Furthermore, food price, food supply, and food demand directly depend on food production and contribute to the increase in food and nutrition insecurity.

The complete simulation model was implemented using VENSIM modelling software (DSS 8.2), a graphical simulation environment platform (Ventana Systems Inc.). The model has a time step of 0.25 years, meaning that the values of each variable (stocks, flows, auxiliaries) are calculated on a quarterly basis throughout the entire period of simulation. The detailed annotation and the mathematical complete expression of the whole model can be found in Tables S2 and S3 in Supporting Information S1.

2.3.3. Model Testing and Evaluation

For the modeling experiments, we utilized time series data spanning from 1990 to 2020. The data were divided into two parts. The first grouping covered the period from 1990 to 2010 was used for model calibration while the second part from 2011 to 2020 was used for model validation. Seven (7) stock variables were selected for the

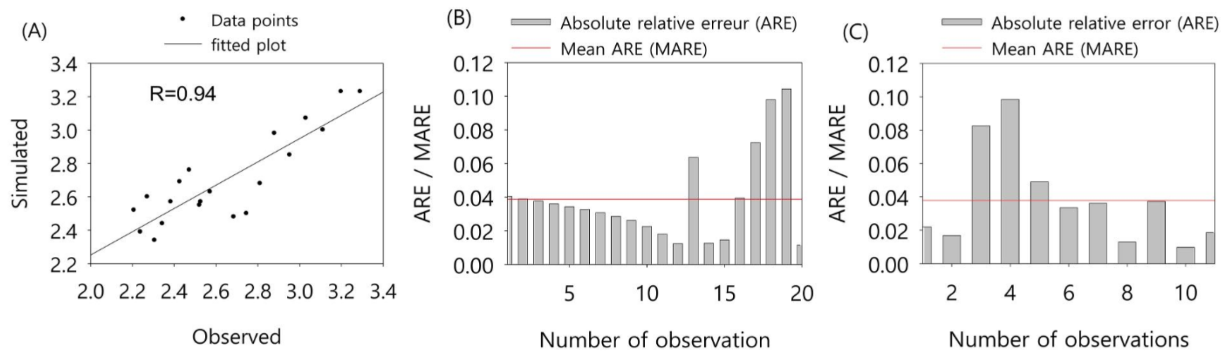

Figure 5. Calibration results of (a) correlation coefficient (R) between simulated and observed outcomes, (b) absolute relative error (ARE) and mean absolute relative error (MARE), and (c) validation results using ARE and MARE.

quantitative analyses, calibration, and validation outputs, these include the rate of urbanization, farming expansion, food production, food supply, food demand, food price, and food and nutrition insecurity.

The model underwent calibration through two distinct steps: (a) we evaluated whether the model parameters corresponded to the appropriate descriptive and mathematical understanding of the real system, and (b) we assessed the accuracy of historical data fitting. The process required several simulations by tunning the model parameters until no improvement of the model output values was possible. The correction coefficient (R) was calculated with the formulation proposed by Wei et al. (2012) given in Equation 5:

$$R = \frac{\sum_{t=1}^{n} (Y_t - \bar{Y}_t)(y_t - \bar{y}_t)}{\sqrt{\sum_{t=1}^{n} (Y_t - \bar{Y}_t)^2 \sum_{t=1}^{n} (y_t - \bar{y}_t)^2}} \tag{5}$$

Where n = number of data, t = time unit, Y_t and y_t represent observed and simulated values, respectively and $\bar{Y}_t$ and $\bar{y}_t$ stand for the mean of observed and simulated data, respectively.

Furthermore, a series of quantitative and qualitative tests were conducted to validate the model. Qualitative tests involve verifying the consistency of system units and the structure of the system. The system unit consistency test was completed automatically in VENSIM software while the system structure test was performed by checking whether the structure of the model reasonably explains the real system and whether the equations of the model fit the physical laws. For quantitative test validation, absolute relative error (ARE) and mean absolute relative error (MARE) were used. Their mathematical expressions are given in Equations 6 and 7. The quantities n, t, Y_t and y_t have the same denotations as in Equation 5 (Wei et al., 2012).

$$\text{ARE} = \left| \frac{(y_t - Y_t)}{Y_t} \right| \tag{6}$$

$$\text{MARE} = \frac{1}{n} \sum_{t=1}^{n} \left| \frac{(y_t - Y_t)}{Y_t} \right| \tag{7}$$

The system unit consistency test was completed automatically in VENSIM software while the checking of the model system structure reasonably explained the real system and the model equations reflected the physical laws. The final calibration results of the model for Sudan country are presented in Figure 5. A relatively high correlation coefficient ($R = 0.94$) was obtained between the observed and simulated outcomes (Figure 5a) and a lower MARE of 0.0387 was also achieved (Figure 5b). Analysis of the model forecasting performance of the real system behaviors is displayed in Figure 5c in which ARE (≤ 0.10) and MARE (0.0379) were provided.

Among the available data of the different countries, only Sudan provided sufficient data to complete the modeling experiments. Therefore, the model calibration and testing were carried out using data from Sudan, and the obtained parameters were used to characterize the model equations with relevant features and extrapolated to the remaining countries to generate model outputs.

2.4. Spatial Extrapolation of the Impact of Desert Locusts in the Entire Eastern African Region

The simulated outputs for Sudan were used to calibrate the equation that establishes the relationship between weather variables, such as temperature and rainfall, and the seven target parameters selected in the system dynamics modeling analysis. These parameters include the rate of urbanization, food production, farming expansion, food supply, food demand, food price and food and nutrition insecurity.

The data were first normalized using the min-max normalization, one of the most popularly used data normalization techniques (Kappal, 2019). It is a technique that normalizes the original data set using the min-max normalization function by considering minimum and maximum values in the data set. Each variable in the data set is normalized by scaling the values within the range of 0 and 1, representing 0%–100% of the variable impact. Min-max normalization preserves the relationships among the original data set (Raju et al., 2020). The min-max normalization function is given in Equation 8:

$$D_{\text{new}} = \frac{D - \min(x)}{\max(x) - \min(x)}(\max_{\text{new } x} - \min_{\text{new } x}) + \min_{\text{new } x} \tag{8}$$

Where:

D is a value from the original data set,

D_{new} is the newly calculated value after normalization,

$\text{man}(x)$ is the maximum value in the data set,

$\min(x)$ is the minimum value in the data set.

After the normalization of the data, we automated the fitting of linear and non-linear equations using R statistical software (R Core Team, 2020) based on the quasi-Newton method that uses the limited-memory Broyden-Fletcher-Goldfarb-Shanno (L-BFGS) approach to approximate the Hessian matrix of the objective function (Liu & Nocedal, 1989). The algorithm is designed for solving nonlinear optimization problems with bound constraints on the variables. The L-BFGS-B algorithm is widely used in optimization problems, including in the fitting of nonlinear models (Zhu et al., 1997). Earlier studies have demonstrated the effectiveness and efficiency of this method in many applications, including in machine learning and data science (Morales & Nocedal, 2011). Specifically, we used exponential function, the quadratic polynomial, power law, logistic function, and linear functions and further customized the codes to select the best model based on defined metrics for the model performance evaluation. The metrics used in evaluating the models' performances include the coefficient of determination (R^2), and root mean squared error (RMSE). The equations of the performance evaluation metrics are defined in Equations 9 and 10.

$$R^2 = 1 - \frac{\sum_{i=1}^{n} y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y}_i)^2} \tag{9}$$

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(\hat{y}_i - y_i)^2}{n}} \tag{10}$$

where $\hat{y}_i$ and y_i are respectively the predicted and observed values, $i = 1, 2, \ldots, n$, $\bar{y}$ is the average of the observed values.

The optimized model for seven target parameters is presented in Table 2 with accuracy metrics.

The developed models in Table 2 were interpolated using the processing toolbox from QGIS 3.10.9 (QGIS Team, 2009), over a grid of 5 km of extracted predictor variables (temperature and rainfall) representing the study area to provide a spatial visualization. Furthermore, the model outputs were categorized into four categories that

Table 2
The Fitted Equations of the Rate of Urbanization, Food Production, Farming Expansion, Food Supply, Food Demand, Food Price, and Food and Nutrition Insecurity

Target parameters	Equation formulation	Coefficient of determination (R^2)	Root mean squared error (RMSE)
Rate of urbanization	$-9.88 + 0.34 * T + 0.003 * R$	0.90	0.21
Food production	$-11.71 + 0.39 * T + 0.002 * R$	0.96	0.16
Farming expansion	$-11.99 + 0.38 * T + 0.003 * R$	0.95	0.21
Food supply	$-12.48 + 0.40 * T + 0.003 * R$	0.90	0.22
Food demand	$-11.48 + 0.40 * T + 0.003 * R$	0.90	0.22
Food price	$0.99 + 0.84 * T - 014 * R -0.028 * T^2 + 0.004 * T * R$	0.90	0.22
Food and nutrition insecurity	$-10.48 + 0.36 * T + 0.003 * R$	0.94	0.22

Note. T = temperature & R = rainfall.

is, low (0.0, 0.25), Moderate (0.25, 0.50), high (0.50, 0.75), and very high (0.75, 1.0) for easy interpretation. For extrapolation over the study area under future scenarios, the Model Intercomparison Project of the Max Planck Institute Earth System Model Lower-Resolved version (MPI-ESM1.2-LR) 2050 projection was used due to its popularity and its good accuracy of projection (Salehie et al., 2021). The future scenario of the shared socio-economic pathways version (SSP2-4.5) was used as it is hypothesized as the more realistic case scenario under the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Agboka et al., 2022).

2.5. Scenarios Analysis and Policy Options

The scenario analysis was conducted initially without considering the impact of desert locusts in order to establish a baseline of stability and effectively assess the effects of desert locust invasion in eastern Africa. This initial analysis helped establish the reference trend for the socio-economic variables within the system, accounting for other influencing factors prior to the desert locust invasion. Subsequently, when the simulations were performed with the inclusion of the desert locust component, it facilitated the identification of the desert locust's contribution and measurement of its impact.

While offering assistance to affected communities and promoting long-term resilience may be a sound policy choice, effective control measures for curbing the spread of desert locusts are crucial in mitigating its impacts on stakeholders' livelihoods (Li et al., 2022). Therefore, we anticipate that such scenarios and policy options will contribute to mitigating the impacts and improving people's livelihoods. With the obtained coupled stability situation-desert locust system, we conducted two scenario analyses:

1. Late control measures intervention. In this scenario we hypothesized that the communities are unaware of the breeding sites of the desert locusts and only encounter them when they have already reached the adult stage and begun forming swarms before taking action to control them. The control measures then target both the adult and hopper stages of the pest.
2. Early control measures intervention. Here, we assumed that the communities possess accurate predictive models and tools to identify the timing and locations of hopper breeding. Consequently, the control measures are specifically targeted toward the immature stage of the pest (hoppers).

In each of the two scenarios, we evaluated three distinct policy options as control measures:

1. The utilization of chemical pesticides as a conventional method,
2. The application of biopesticides (specifically *Metarhizium acridum*), which has demonstrated high potential and successful fungal biocontrol capabilities against desert locusts in various regions (Kamga et al., 2022), and
3. The combination of both methods (conventional and biocontrol) as integrated pest management (IPM) option.

3. Results

3.1. Analysis of the Desert Locust Impact in Sudan

Overall, the outputs of the model showed that the country presents an increased urbanization trajectory and farming expansion over time (Figures 6a and 6b), which might be due to the increase of the total

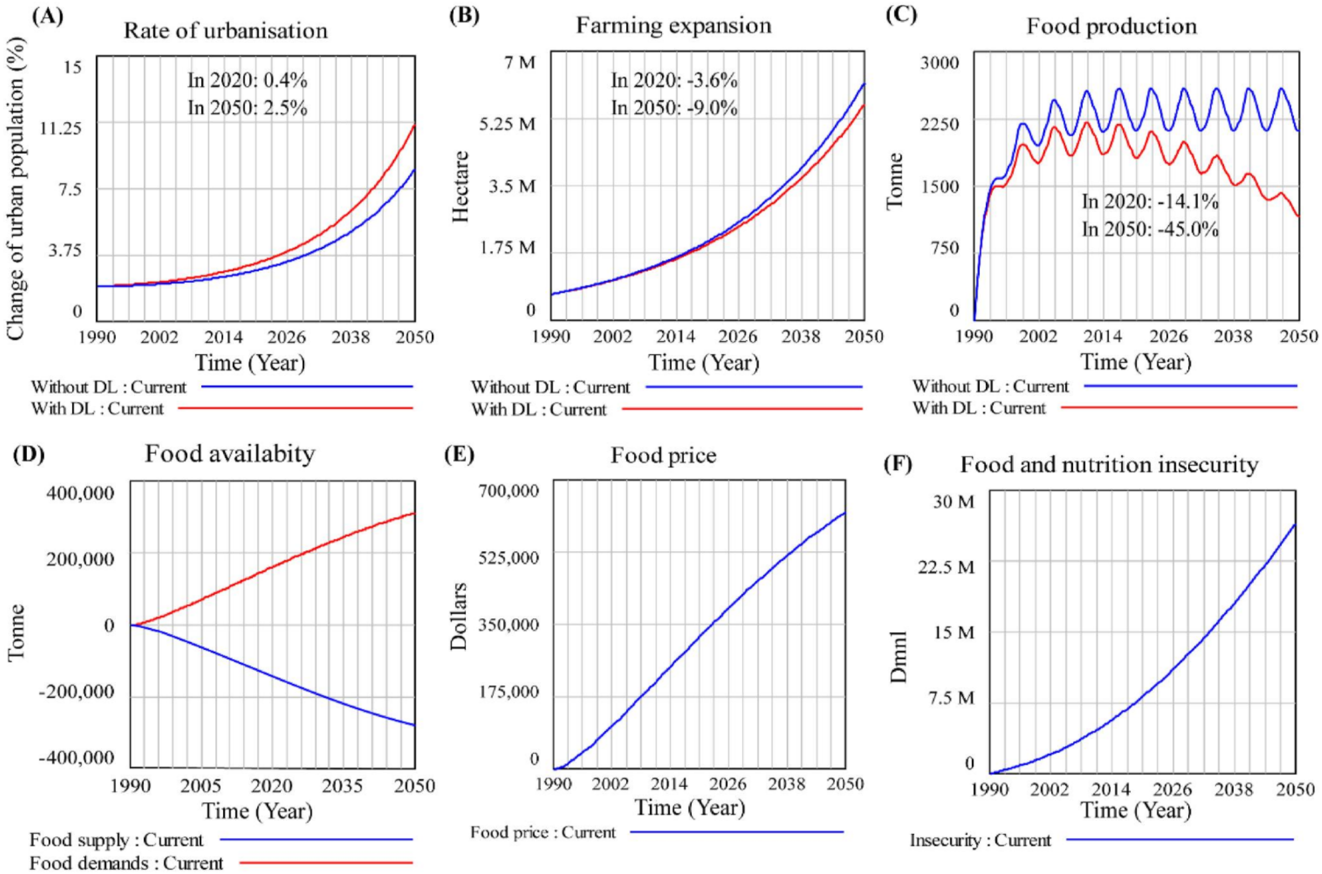

Figure 6. Impact of desert locust invasion on urbanization, agriculture production, and food security in Sudan.

population through birth over death and immigration from other countries, leading to the increase of both urban and rural populations. Together with the presence of desert locusts, the rate of urbanization increased with time, as demonstrated by the annual rate of change of the urban population of 0.4% in 2020 and a prediction of 2.5% in 2050 (Figure 6a). On the other hand, farming expansion decreased slightly. In 2020, a 3.6% reduction of the actual farming area was observed while a 9.0% reduction is anticipated by the year 2050 (Figure 6b). Food production initially increased and reached an optimum but was unstable with oscillations (Figure 6c) because of the dynamics of other factors such as climatic factors such as rainfall, drought, and soil fertility. With the presence of desert locusts, food production decreased from year to year with a reduction of 14.1% in 2020 and a predicted reduction of 45% by 2050 because of the low yield obtained under desert locust impact. This decrease in food production often leads to the disequilibrium between food supply and demand (Figure 6d) and an increase of food price (Figure 6f) and consequently, food and nutrition insecurity exponentially increases (Figure 6f).

3.2. Analysis of the Desert Locust Impact in Eastern Africa

Figure 7 shows the desert locusts' impact on the current distribution of six socio-economic parameters evaluated in this analysis that is, potential urbanization rate, the reduction in the farming area, food production, and food supply, and the increase of food demand in different eastern African regions due to the desert locust invasion.

The current urbanization rate was high in the regions where the population is concentrated for instance in Sudan. Similar trends were observed in other Eastern African countries. Under future climate conditions, the impact on all six parameters is anticipated to increase (Figure 8). In all countries, desert locust is contributing to the slowing down of the expansion of farming areas and food production and supply with an increase in food demand and food and nutrition insecurity at different degrees depending on the regions.

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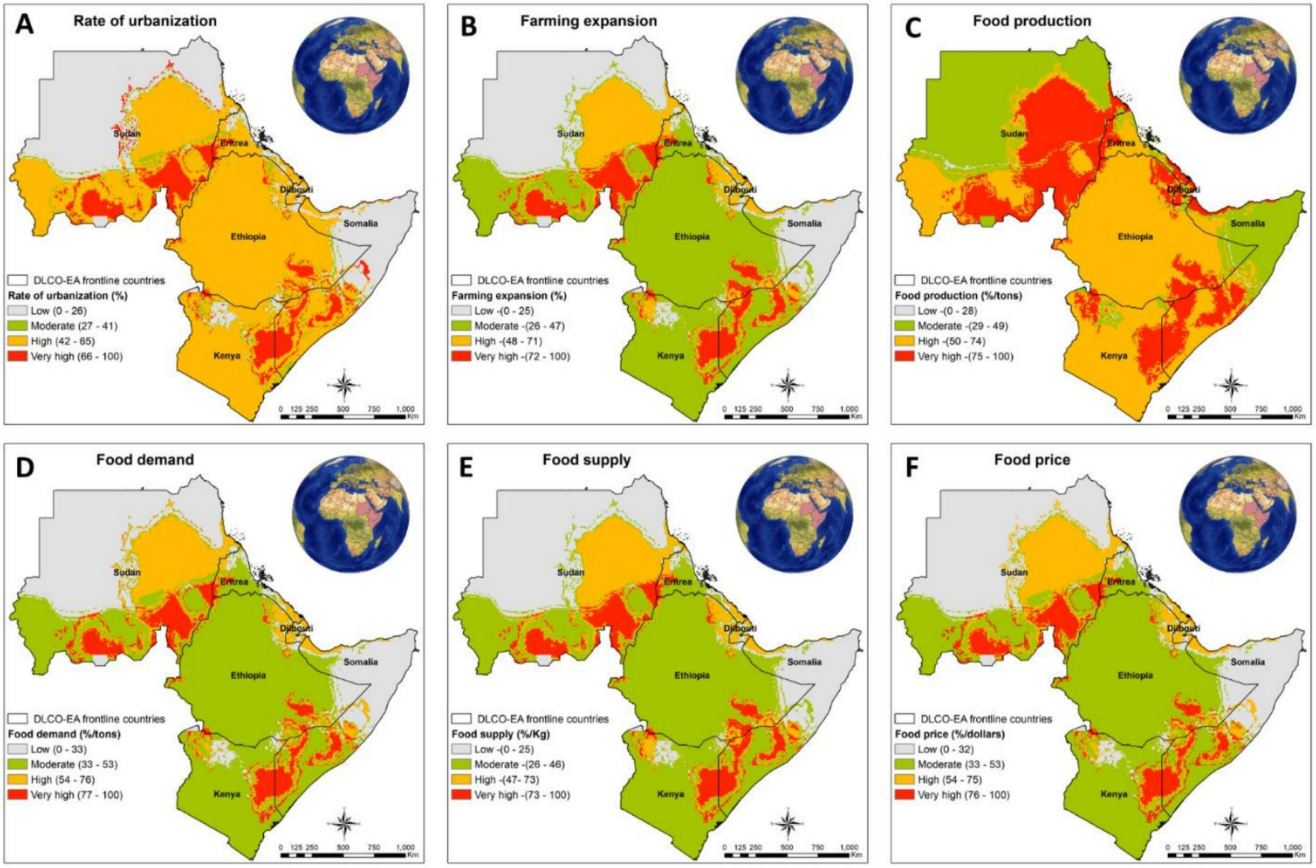

Figure 7. Impact of desert locust invasion on the current distribution of (a) the annual rate of change of urban population, (b) reduction of farming expansion, (c) food production, (d) food supply, (e) increase of food demand, and (f) food price in Eastern Africa.

Overall, the desert locust invasion impacts on the annual rate of change of urban population, reduction of farming expansion, food production, food supply, increase of food demand, and food price in Eastern Africa led to high levels of food and nutrition insecurity across eastern Africa under current climatic conditions (Figure 9a) with an anticipated potential increase in the future (Figure 9b). Under the current or future climatic conditions and across all the measured socio-economic parameters in Eastern Africa, Sudan is the most affected country as compared to all others.

3.3. Scenarios Analysis and Policy Options for Impact Forecasting and Mitigation

The simulation outcomes depicting the impacts of desert locust invasion under various scenarios and control intervention measures are presented in Figure 10. The results demonstrate that across the six analyzed scenarios and policy options, the rate of urbanization shows an increasing trend (Figure 10a), whereas both farming expansion and food production exhibit a declining trend (Figures 10b and 10c). The simulation results revealed that the majority of Eastern African countries will experience significant socio-economic impacts, which escalate further under the first scenario, commonly observed in those regions where communities initiate control measures only after locusts have already reached the adult stage and begun forming swarms. In contrast, the second scenario, characterized by knowledge of breeding sites and prompt intervention, demonstrates comparatively better outcomes. When considering the control measure options, the interventions exhibited higher efficacy, leading to a significant reduction in impacts under scenario two. However, the effectiveness varied depending on the specific control methods employed (Figure 10). In scenario one where the control focuses on both adult and hopper in late intervention:

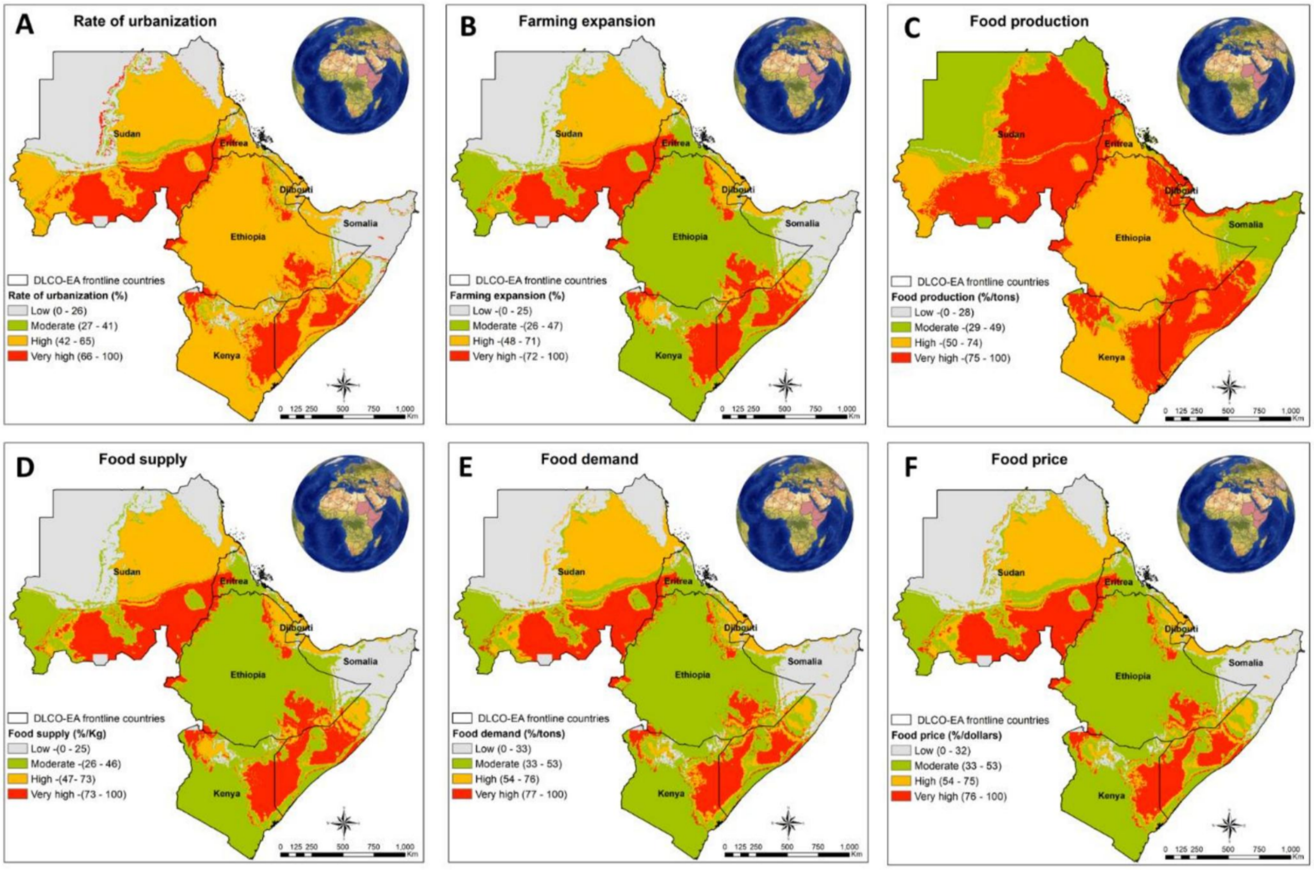

Figure 8. Impact of desert locust invasion on the future distribution of (a) the annual rate of change of urban population, (b) reduction of farming expansion, (c) food production, (d) food supply, (e) increase of food demand, and (f) food price in Eastern Africa.

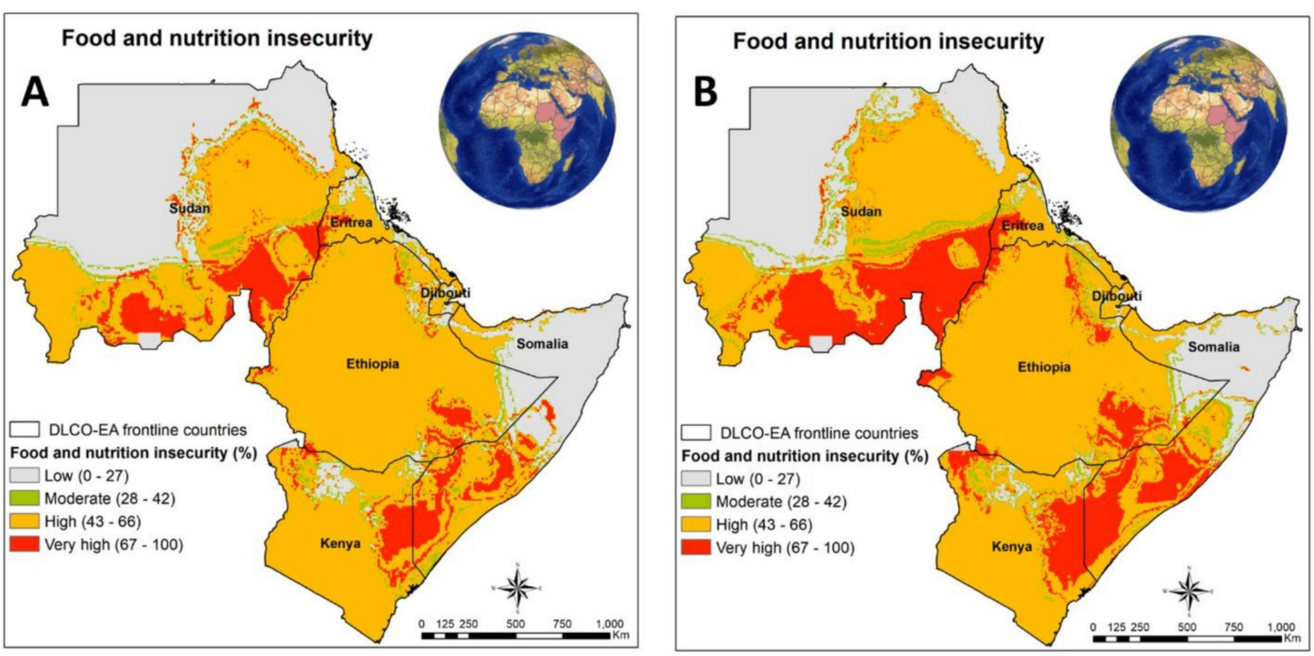

Figure 9. Impact of desert locust invasion on the (a) current and (b) future distribution of potential food and nutrition insecurity in Eastern Africa.

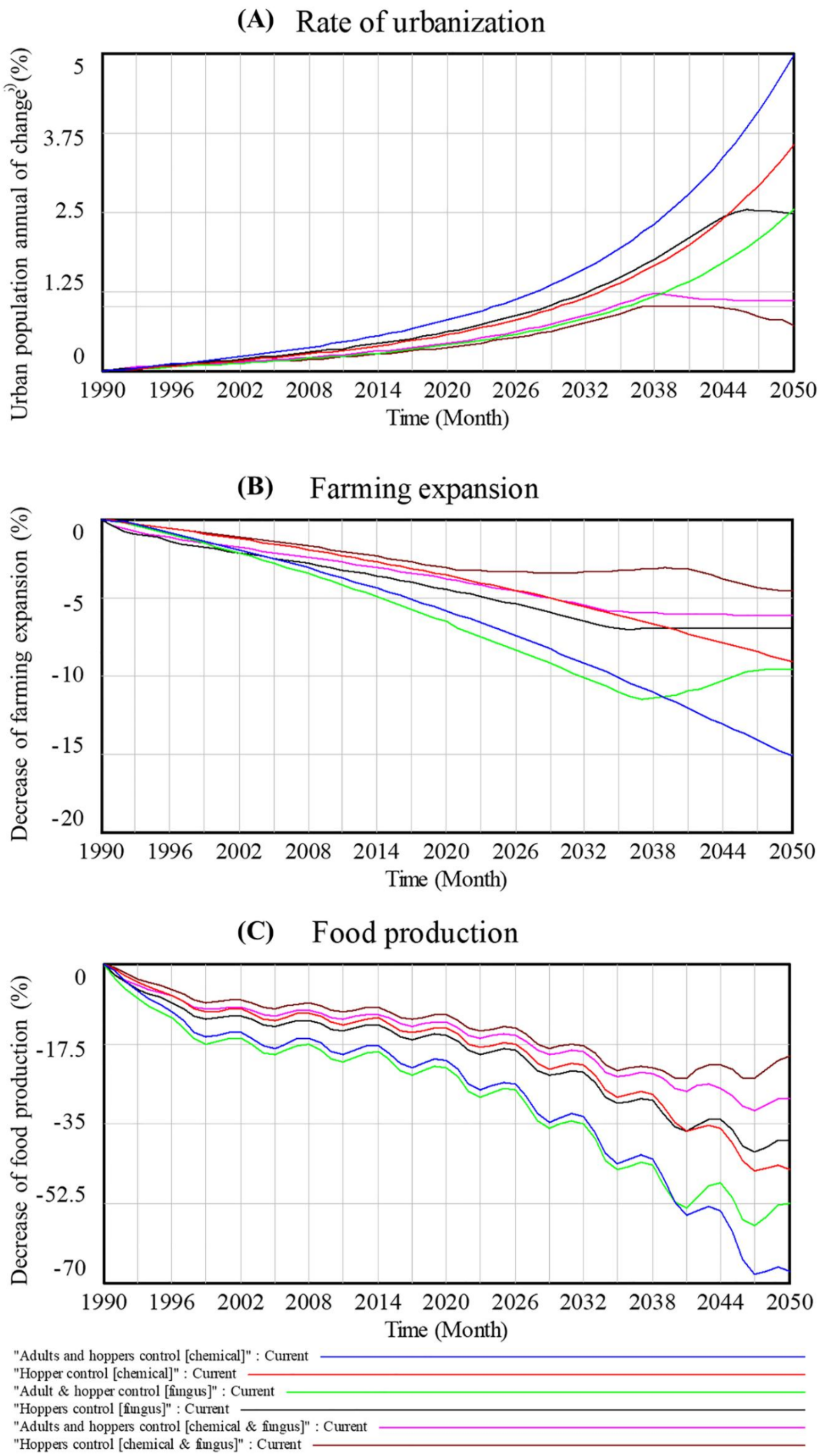

Figure 10. Impact of desert locust on (a) rate of urbanization, (b) farming expansion, and (c) food production when using different control options and targeting either adult stage or hoppers of the pest.

- In the chemical control option:
  - The rate of change of human urban population due to desert locust invasion increased of 0.56% in 2020 and is predicted to attain 3.55% in 2050.

   - It is observed a decrease of 5.87% for farming expansion and 21.21% for food production in 2020 while the projections estimated a decrease of 15.14% for farming expansion and 67.62% for food production by 2050.
- In the use of biopesticide,
   - The increase of urbanization rate was 0.60% in 2020 and will reach 2.45% in 2050.
   - A decrease of 6.56% for farming expansion and 22.71% for food production in 2020 was observed, which will come to 9.57% for farming expansion and 38.87% by 2050.
- When combining the two methods in IPM approach:
   - The increase of urbanization rate was 0.38% in 2020 and will rise to 2.53% in 2050
   - farming expansion experienced a decrease of 3.82% and food production of 12.81% in 2020 with a projection of 6.18% of farming expansion and 29.56% of food production in 2050.

In scenario two where control measures focus on only hoppers in early intervention:

- In the chemical control option:
   - The rate of change of urban population has increased of 0.39% in 2020 and is predicted to attain 3.55% in 2050.
   - Farming expansion and for food production have decreased of 3.50% and 14.13%, respectively in 2020 while the projections estimated a decrease of 9.09% and 45.07% for farming expansion and for food production, respectively in 2050.
- In the use of biopesticide:
   - The increase of urbanization rate was 0.43% in 2020 and will reach 1.11% in 2050.
   - The decrease was 4.49% for farming expansion and 15.63% for food production in 2020 which will come to 6.18% for farming expansion and 29.56% in 2050.
- In the combination of the two methods in IPM approach:
   - The increase of urbanization rate was 0 0.34% in 2020 and will rise to 2.34% in 2050.
   - Farming expansion experienced only a 3.12% of decrease and food production of 11.31% in 2020 with a projection of 4.53% of farming expansion and 20.36% of food production in 2050.

4. Discussion

4.1. Integrated Assessment Approach

The system dynamics modeling approach was implemented in this study as it has the advantages of system understanding and allows for a more in-depth representation of individual components of the whole system (Chang et al., 2007). The approach is useful to map the different variables of the desert locust invasion impact system and model the feedback, non-linear effects, and delays as it is a set of numerical and conceptual methods for understanding complex system structure and behavior and helps to foster system thinking skills and knowledge integration (Fernández et al., 2004). It is a hybrid method that combines the advantages of discrete and continuous time concepts (Sahin et al., 2015). The time discrete concept is based on the differentiation of finite time and time-point intervals whereas the continuous time concept considers over-time changes, based on minuscule calculus (Sahin et al., 2015). The system dynamics modeling approach provides more understanding of the behavior of complex systems and their evolution over time, leading to the dynamics of such systems (Kelly et al., 2013). In addition, the approach has a broad ability to accommodate different components where many systems can be put together as sub-systems, and simulated and analyzed within the same model (Sušnik et al., 2012). Furthermore, the system dynamics approach allows not only combining models from different sectors or disciplines as components or sub-systems such as agriculture subsystem, desert locust component, food security, and country population of the current understudied system to come up with an integrated outcome but also to explore feedbacks dynamics within variables and incorporate more detailed representations of individual components and their linkages (Lauf et al., 2012; Qin et al., 2011).

The weakness of system dynamics modeling approach is that it does not inherently include spatial analysis techniques. However, it is possible to integrate a spatial component by incorporating geographic information and considering the spatial relationships and interactions among different system elements. By leveraging geospatial data and spatial relationships, we incorporate spatial considerations into the developed system dynamics model to capture the influence of spatial factors on system behavior. In this integration process, GIS was utilized for visualizing and analyzing spatial relationships. The GIS allows the representation of georeferenced data, within a system dynamics framework. By incorporating GIS data and techniques, the developed model account for spatial heterogeneity, spatial dependencies, and the impact of location-specific factors on the system dynamics. This enables the exploration of spatially diverse scenarios and the assessment of the impacts of interventions or policies in specific regions.

4.2. Socio-Economic Impacts of the Desert Locust in Eastern Africa

The impacts of desert locust invasion in Eastern Africa were evaluated using system dynamics modeling approach to develop and validate the model. Additionally, a rule-based modeling approach was employed to extrapolate the impact at larger scales. The study showcased the significance of incorporating enhanced causal feedback mechanisms related to various aspects of food production, including agriculture, forestry, and fisheries. It also considered country demographic changes, such as urban-rural migration and the rate of urbanization, as well as factors like farming expansion, food availability (price, demand, and supply), and food security.

Through a comprehensive analysis of the four components, namely the desert locust component, agricultural subsystem, country population dynamics, and food security component, as a unified system, the simulation results indicated that the invasion by desert locusts has significant effects on all four components. The outcomes observed across these components were found to be diverse and distinct from one another. The overall outputs of the model showed that the targeted countries have experienced a drop in food production and farming expansion following the invasion of desert locusts while at the same time, the urbanization rate has increased. Due to persistently low crop yields in years, there is a possibility that the younger generation may become discouraged from farming and choose to migrate from rural to urban areas in search of improved livelihood opportunities. This trend can help explain the observed increase in the rate of urbanization, as evidenced by the annual rate of change of the urban population in this study. The rate of urbanization is influenced by population migration from rural zones to urban centers, which in turn is dependent on the outputs of agricultural production. The direct consequence of rural-urban migration is a drop in farming areas and food production as the valid hands to cultivate become limited in those rural regions when they have moved to towns. Therefore, the decrease of food production reported in this study resulted from low crop yields because of desert locust attacks, which more likely contribute to people migration from rural to urban areas in search of better job opportunities and improved livelihoods, as cities often offer a wider range of employment options. The rate of urbanization is then affected since urbanization is driven by population movement from rural to urban areas. The influence of the increase in the rate of urbanization on food and farming has been reported as a decline in the ratio of food producers to food consumers (Satterthwaite et al., 2010).

On the other hand, the study has demonstrated that the decrease in food production and farming expansion results in an increase in food demand and food price with a drop in food supply across the countries, leading to an increase in food and nutrition insecurity in the region. Therefore, the decrease in food production often leads to the disequilibrium between food supply and demand and an increase in the food prices in the country, and consequently, food and nutrition insecurity exponentially increases. As voracious feeders, the upsurge of the desert locusts often leads to famine (Le Gall et al., 2019). The disturbance of food demand and supply chain and the issues of food security in affected areas of desert locusts have been much reported in the literature. According to Brader et al. (2006) and Kietzka et al. (2021), the losses to crops and pastures caused by desert locusts often lead to severe shortages of food, insufficient grazing areas, strong price oscillation in markets, low price sale of livestock to meet household subsistence needs and large human migrations to urban areas. Furthermore, the other economic impact reported was the contamination of crop harvest with locust parts which downgrades feed food sold at lower prices and the low income of the population may have a long-term impact on population livelihood mostly in rural areas (De Vreyer et al., 2015).

The spatial simulation of desert locust impacts across Eastern Africa serves as a pivotal component of our integrated assessment framework. This simulation allows for a nuanced understanding of the geographical distribution of locust-inflicted damages and their intensity, as well as the regional vulnerabilities to locust outbreaks (Cressman, 2013). Our findings indicate that the impacts of desert locusts are far from uniform across the region. Some areas, particularly those with substantial agricultural activity, are more prone to experiencing severe effects. This spatial heterogeneity in impacts across the different countries could be due to the complex interplay of biophysical dynamics, including climate, vegetation, and environmental factors in each country that experience desert locust impacts. Djibouti's arid climate and sparse vegetation make it less conducive conditions for sustained locust breeding. However, it often serves as a transit route for locust swarms moving into neighboring countries.

Kenya exhibits a diverse climate spectrum, from arid and semi-arid zones in the north to more favourable conditions in the south (Kimathi et al., 2020). Vegetation in certain areas provides suitable breeding grounds for locusts, especially during periods of abundant rainfall. Ethiopia boasts a diverse topography, including lowlands and highlands. Lowland regions can offer ideal breeding habitats for locusts during the rainy seasons. The nation's extensive agricultural sector can be vulnerable to locust infestations, potentially impacting food production (Kimathi et al., 2020). Eritrea shares similarities with Djibouti, featuring arid terrains with limited vegetation. Coastal areas may be more susceptible to locust infestations due to milder temperatures. Sudan exhibits a wide range of climate zones, from desert conditions in the north to more favourable environments in the south. Vegetation along the Nile River and in select southern regions can create suitable breeding conditions for locusts (Eltoum et al., 2014; Kimathi et al., 2020). South Sudan's wetlands and grasslands can be conducive to locust breeding, particularly during the rainy season. However, the region's limited infrastructure and resources can hinder effective locust control efforts. Somalia's arid and semi-arid regions provide favourable breeding habitats for locusts, especially during rainy seasons. Unfortunately, ongoing conflicts and insecurity can impede locust monitoring and control. Tanzania experiences varied climates and vegetation, making it less susceptible to locust infestations compared to some neighboring East African countries. However, southern regions with more abundant vegetation can be vulnerable during locust outbreaks (Palmer et al., 2023). Uganda's climate and vegetation are generally less conducive to desert locusts compared to neighboring nations. Although locust infestations are less frequent, they can still occur, particularly in the northeastern region (Palmer et al., 2023). Indeed, a comparative analysis of desert locust control policies across the East African region reveals both strengths and limitations that certain countries possess:

Kenya and Ethiopia demonstrate a strong commitment to policy implementation, capitalizing on their more developed administrative systems (Mohamed et al., 2018). This commitment provides a solid foundation for executing effective locust control measures. They boast well-established monitoring and evaluation systems, which play a pivotal role in facilitating the implementation of locust control policies. These systems enable data-driven decision-making, improving response times. With more resources at their disposal, they are better equipped to enforce environmental impact assessments, thereby minimizing potential harm to ecosystems and the environment as a whole. This proactive approach aligns with sustainable practices. Countries with larger economies, such as Kenya, Ethiopia, and Tanzania, can allocate more resources to bolster their locust control efforts (Bitanihirwe et al., 2021). These financial capabilities enhance their capacity to respond swiftly and comprehensively to locust outbreaks. They have the infrastructure and resources necessary to foster cross-border coordination, thereby strengthening regional locust control initiatives. This collaborative approach amplifies their effectiveness in managing locust threats. Their stronger infrastructure and communication networks enable them to engage more successfully with local communities. This engagement fosters better community participation, leading to improved early detection and response to locust infestations. Access to modern technology and data resources in Kenya, Ethiopia, and Tanzania significantly enhances their capacity for data collection and analysis (Deichmann et al., 2016). These tools empower informed decision-making, allowing for more effective and efficient locust control strategies. These countries' inclination to invest in research and innovation holds the potential to yield cutting-edge locust control strategies. This commitment to advancement ensures that they remain at the forefront of locust management practices. They generally benefit from more stable political environments, creating a conducive atmosphere for the effective implementation of locust control policies. Political stability fosters continuity and consistency in policy execution.

In the other hand, Djibouti, Eritrea, Somalia, and South Sudan grapple with significant resource limitations, which impede their ability to effectively implement locust control policies (Oğultürk, 2021). These constraints have a direct impact on their capacity to respond adequately to locust outbreaks. Additionally, Djibouti and Eritrea face challenges in cross-border coordination due to geopolitical tensions, which strain regional cooperation and hinder collective efforts to combat desert locusts effectively. One of the major obstacles faced by these countries is the difficulty in securing adequate funding for desert locust control initiatives. This chronic financial shortfall limits their ability to invest in critical resources and infrastructure necessary for effective control and mitigation measures. Furthermore, ongoing conflicts and insecurity in Somalia and South Sudan severely disrupt locust monitoring and control efforts, making it challenging to mount timely and coordinated responses to locust infestations (Cliffe et al., 2009; Oğultürk, 2021). The limited infrastructure in Djibouti, Eritrea, Somalia, and South Sudan impacts both control measures and communication with local communities. This lack of infrastructure hampers their ability to deploy resources and engage communities effectively in locust control efforts. Moreover, these countries may experience restricted access to data resources, potentially undermining the reliability of monitoring and prediction systems, thereby impeding their ability to anticipate and respond to locust outbreaks. Another concerning issue is the allocation of limited resources to research and innovation, hindering the development of effective control strategies. This can result in a lack of innovative and sustainable approaches to locust management. Additionally, political instability and institutional weaknesses in these nations can hinder the effective implementation of locust control policies, leading to inconsistency and inefficiencies in policy execution. In the case of Somalia and South Sudan, ongoing conflicts make it difficult to conduct effective public awareness campaigns, reducing the capacity to engage communities in early reporting and response efforts (Read-Hamilton & Marsh, 2016). Addressing these multifaceted challenges is crucial to building resilience against locust outbreaks and ensuring the well-being of these vulnerable regions.

The simulation results also demonstrate the potential amplifying effects of locust infestations on existing socio-economic disparities within and across countries. Regions with limited resources and higher rates of food insecurity may be disproportionately affected, underscoring the need for targeted support and resources to these areas. It's also worth noting that the spatial simulation provides insight into potential future patterns of locust infestations. By incorporating variables such as climatic conditions and vegetation cover, the model can help predict areas that may become desert locust high-risk in the future. This predictive capability is crucial for proactive locust management and mitigation strategies, allowing for early interventions that can prevent or minimize damage. However, it is important to recognize the inherent uncertainties in any spatial simulation. Factors such as climate change, land-use changes, and socio-economic developments can influence future patterns and impacts of desert locust infestations in ways that are difficult to predict accurately. As such, our model should be seen as a tool to inform decision-making, rather than a definitive forecast of future outcomes. Going forward, we recommend further refining the spatial simulation model by incorporating additional variables and improving the resolution of the analysis. This could include factors such as local farming practices, the availability and effectiveness of desert locust control measures, and more detailed socio-economic data. Policy Scenarios analysis against the identified policy options will be an add value. Such enhancements can help to produce even more accurate and useful simulations, providing a robust foundation for informed policy-making and resource allocation.

4.3. Scenarios Analysis and Policy Options

Scenario analysis and policy options are critical tools for policymakers to prepare for and mitigate the socio-economic impacts on communities livelihood (Ding et al., 2019; Yu et al., 2018). These tools help them to identify potential outcomes, develop appropriate policies, and allocate resources effectively. This study revealed a remarkable impact of desert locusts on the decrease of farming areas and food production while the urbanization rate has increased, all leading to the increase of food demand and food price with less food supply resulting in high food insecurity across the affected countries. Previous research has shown that desert locust outbreaks can have significant socio-economic impacts, including food shortages, crop losses, and economic losses for affected communities (FAO, 2020). The World Bank estimates that desert locusts have caused up to $8.5 billion in economic losses in Africa alone since 2019 (World Bank, 2020).

The scenario analysis outputs revealed that the most severe impact was observed in the scenario of late control measures intervention. In this scenario, the communities are unaware of the breeding sites of the desert locusts and only become cognizant of their presence when they have already reached the adult stage and commenced the formation of swarms. Consequently, control measures are initiated at a later stage, resulting in more significant impacts. Similarly, the impact was significantly less in scenario 2 where the communities have used accurate predictive models and tools that detect when and where the insect breed and initiate early control of the hoppers. These findings highlight the importance of early warning systems and prompt response in mitigating the impacts of desert locusts. Consequently, it is crucial for governments and policymakers to allocate resources toward the establishment of near-real-time monitoring and surveillance systems capable of detecting and tracking desert locust breeding sites. Additionally, investment in research and development for innovative technologies and approaches, as well as training and equipping national and regional teams, is necessary to enable swift and effective implementation of control measures. Furthermore, as locusts do not know country barriers, regional cooperation is very important in promoting coordination and information sharing among affected countries and regions, to facilitate the exchange of expertise, resources, and best practices, and to avoid duplication and gaps in the response.

The policy options that were developed and analyzed revealed that, under the chemical control option, long-term analysis showed an exponential increase in urbanization rate and a decrease in farming expansion and food production. This trend can potentially be attributed to the development of pest resistance after years of exposure to the pesticide (Hawkins et al., 2019) leading to the increase of the damage and the impacts. When comparing the use of biopesticide as an eco-friendly method to chemical options, it was observed that the initial impact reduction is relatively lower. However, the biopesticide option demonstrates a positive long-term effect on mitigating the impacts. Unlike chemical control, biopesticides have non-specific modes of action, allowing them to effectively control even resistant insect pests (Kumar et al., 2021). As a result, the increase in impact observed under the chemical control option follows an exponential trend, while the biopesticide option helps slow down the impacts over time. Moreover, we discovered that the option of chemical pesticide and biopesticide combination as an IPM strategy was the best case of the mitigation of desert locust socio-economic impacts, this is supported by (Li et al., 2022) who reported that integrating nature-inspired control strategy within IPM provides the best solution to control desert locust population. Biopesticides can indeed be utilized in rotation programs or in combination with chemical pesticides as part of IPM strategy. This approach helps to mitigate the potential for resistance development and enhances the overall effectiveness of control measures against desert locusts. Governments can play a crucial role by investing in capacity building and training programs for local communities, extension workers, and other stakeholders involved in desert locust management. By improving knowledge and skills in implementing various control strategies, including the proper use of biopesticides, stakeholders can contribute to more sustainable and effective management practices. Furthermore, government support in ensuring the availability of IPM components, including biopesticides, is essential. It is acknowledged that biopesticides can be more expensive than chemical pesticides. Therefore, government assistance, such as subsidies or incentives, can help make biopesticides more accessible and affordable to users. This type of support promotes the adoption of sustainable control measures, like IPM, which can effectively manage desert locust populations while reducing the risks of socio-economic and environmental impacts associated with chemical-intensive approaches.

5. Conclusions

This study revealed the impacts of desert locust invasion in Eastern Africa on various socio-economic factors, such as countries' rate of urbanization changes, farming expansion, and food production and how they lead to food unavailability (demand, supply, and price) and food and nutrition insecurity in those countries. We utilized a holistic analysis approach through system dynamics to investigate the impacts mentioned above. By considering the complex interconnections and feedback loops among the various factors, we were able to gain a comprehensive understanding of the consequences of desert locust invasion in Eastern Africa. Based on our findings, which are specific to East Africa, we can draw the conclusion that the desert locust is indeed playing a significant role in impeding the expansion of farming areas and the production and supply of food though we acknowledge the significance of Covid-19 pandemic and other possible factors. This situation is further compounded by an increase in food demand and a rise in food and nutrition insecurity, albeit to varying degrees across different regions within regions affected in Africa by this pest.

The results obtained from the scenario simulations and policy options analysis indicate that the most effective mitigation strategy for desert locust socio-economic impacts and environmental health involves two key components. Firstly, the availability of accurate predictive models and tools that can detect the breeding locations and timing of desert locust hoppers, enabling rapid intervention measures to be implemented. Secondly, the adoption of an IPM strategy that combines the use of chemical pesticides and biopesticides. By implementing these measures, the negative socio-economic impacts caused by the desert locust can be significantly reduced. Additionally, this approach promotes environmental health by minimizing the reliance on chemical pesticides alone and incorporating more sustainable alternatives such as biopesticides. The combination of accurate predictive models and the use of IPM strategies demonstrates the most effective approach for mitigating the socio-economic impacts of desert locusts while ensuring environmental sustainability.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

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Data Availability Statement

All resources of data sets utilised in this study are comprehensively documented and deposited at the International Centre of Insect Physiology and Ecology (*icipe*) data warehouse at Senagi (2024). Data sets integral to the research are derived and adapted from various reputable sources. The Demographic data, encompassing metrics like migration, population growth, rural and urban population were sourced from WORLD BANK (2023). Food security data and all agricultural commodities aligns with the production and consumption, demand and supply parameters delineated in the Food and Agriculture Organisation Food Balance Sheets (FAO, 2023) and world bank databank (WORLD BANK, 2023). The data of desert locust structured in hoppers, swarms, and bands used was from FAO (2022). Different parameters were sourced from various relevant references. Vegetation growth rate in the absence of locusts (Al Basir et al., 2019); adult locusts rate of consumption (Watch, 2021); desert locusts population reduction due to pesticide use (Ritchie et al., 2022); hoppers maturity rate (Roffey & Magor, 2003); Carrying capacity (Ritchie et al., 1998); Temperature and rainfall data (Fick & Hijmans, 2017), hoppers rate of consumption correction coefficient (Davey, 1954), Conversion efficiency of desert locusts (Misra et al., 2020), desert locusts' population reduction due to pesticide use (Wakil et al., 2022), Agriculture GDP, food and nutrition (FAO, 2023).

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Erratum

The originally published version of this article omitted an affiliation from coauthor Henri E. Z. Tonnang. The affiliation is as follows: School of Agricultural, Earth, and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa. The error has been corrected, and this may be considered the authoritative version of the record.