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Perspective

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Critical gaps in the global fight against locust outbreaks and addressing emerging challenges

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Locust outbreaks significantly threaten the livelihoods of billions of people globally, and this number continues to increase. Latest projections show that crop losses due to insect infestations will increase by up to 50% with a 2 °C increase in global warming. We propose strategies for mitigating and managing future locust outbreaks by integrating communities' perspectives, needs, and insights with new technologies for effective large-scale monitoring, early detection, reporting, verification, and control.

Main

The locust outbreak crisis is a pressing climate-induced disaster today, directly impacting over a quarter of the global population. Yet, it remains underprioritized in climate space. Regrettably, this lack of discussion stems from the fact that those most impacted by locust outbreaks reside in the global south, given climate discourse remains heavily biased toward issues facing citizens in the global north[1]. Urgent attention and better mitigation designs are imperative to address this dire and underreported crisis of recurring locust outbreaks[2]. The frequency and extensive spread of recent recurring locust outbreaks unequivocally underscore the pivotal role of anthropogenic climate change in exacerbating the severity and intensity of these outbreaks[3]. The United Nations Food and Agriculture Organization (FAO) conducts some of the most critical work in addressing locust outbreaks worldwide. The FAO operates a 24/7 surveillance scheme that provides forecasts, early warning, and alerts on the timing, scale, and location of locust invasions and breeding locations through its global Desert Locust Information Service (DLIS). However, ground-truthing remains a significant challenge, as locust breeding occurs in remote and sparsely populated areas spread across continents (Fig. 1), many of which are becoming increasingly unsafe for ground surveys. This perspective offers a comprehensive assessment of current knowledge and gaps, and presents a new conceptual framework to improve existing mitigation strategies in the global fight against locust and pest outbreaks. Our analysis draws from literature and gray literature reviews, consultations with UN colleagues leading the global fight against outbreaks, as well as firsthand insights gained from a consultative workshop conducted in Tigrai, northern Ethiopia, one of the most impacted regions in the world. For instance, the 2020 locust outbreak, which damaged an estimated 200,000 hectares (490,000 acres) of land in Ethiopia alone[4], led to communities resorting to various improvised methods to deter the desert locusts, including throwing rocks, firing bullets, drums, shouting, vehicle sirens, and locally made automated sprayers.

Climate change, geomorphology, and locust outbreaks

Close to 11,000 known species of grasshoppers inhabit tropical, temperate grassland and desert areas, with desert locusts (*Schistocerca gregaria*) standing out as one of the most destructive migratory pests in the world[5]. A single swarm of desert locusts can cover up to 1200 km^2 and contain as many as 80 million locusts per square kilometer[6]. Historical records document seven large climate-induced locust outbreaks from 1912 to 2020[7]. However, since 2018, two major locust outbreaks across the eastern African region, the Arabian Peninsula and the Indian subcontinent, have threatened the livelihoods of over a billion people[8]. Recent desert locust outbreaks have seen

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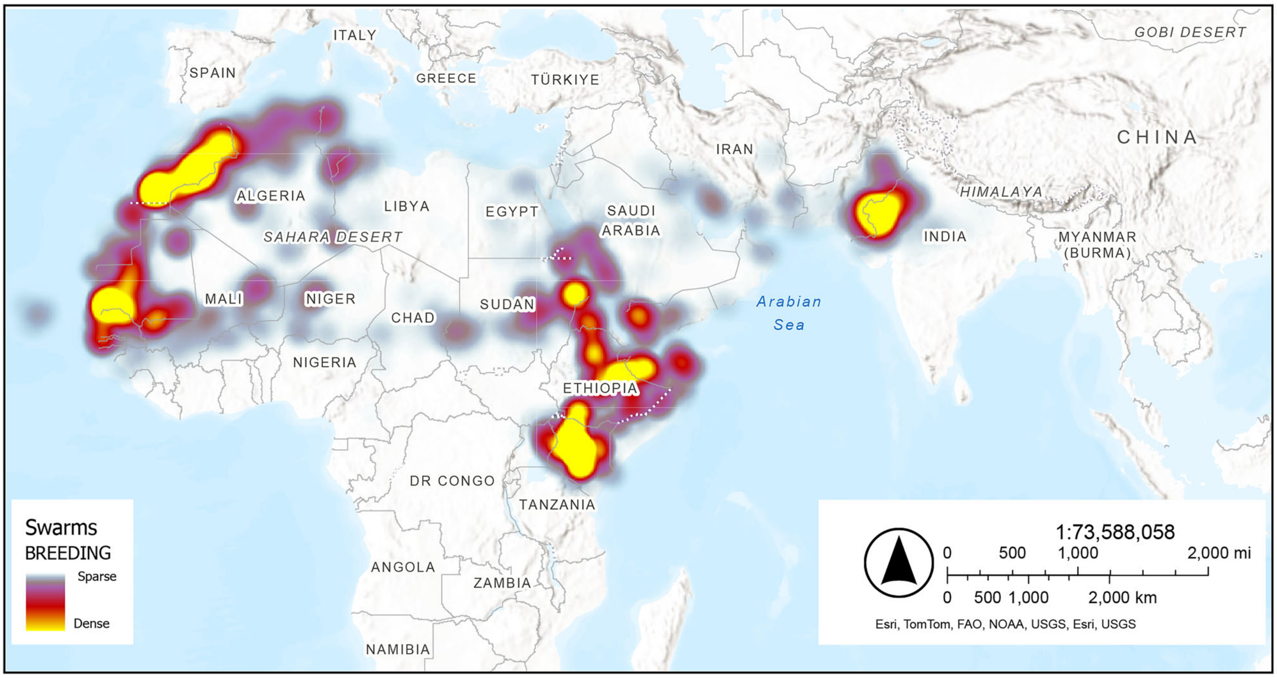

Fig. 1 | Spatial hotspots of historical locust outbreaks (1985–2020). Data sourced and map generated using the UN FAO's Locust Hub platform.

swarms that breed in Saudi Arabia's Rub al Khali expanding to eastern Africa, India, and Pakistan in response to ecological factors associated with changes in vegetation type and soil properties that sustain increased desert locust populations and densities[8]. According to the FAO, the 2020 locust outbreak in eastern Africa was one of the worst locust outbreaks recorded in history. The outbreak brought significant economic, social, and environmental challenges, put over 20 million people at risk of acute food insecurity in six eastern African countries, and caused a US$ 8.5 billion loss across Yemen and eastern Africa.

Latest estimates show that crop losses to insects in Africa alone may increase by up to 50% at 2 °C of global warming[9]. Global warming creates suitable conditions for desert locust invasions, increasing both the available landmass to be affected by future outbreaks[10] and the geographical distribution of species[11,12].

Spatial and temporal weather fluctuations significantly impact the ecological niche and breeding of locust populations[3]. The breeding, maturation, and diffusion of desert locusts heavily rely on soil humidity and vegetation, both of which are sensitive to changes in rainfall[13,14] and are the primary natural factors influencing locust numbers[15,16]. Extreme rainfall during warm seasons, in particular, results in warm and moist soil, creating conditions most conducive for breeding desert locusts (Fig. 1). Large-scale desert locust invasions in the Sahel and West Africa (from 2003 to 2005), and eastern Africa and Southwest Asia (from 2018 to 2020), triggered by torrential rainfall events stand as a testament to this causal relationship[17]. The most severe case of locust outbreaks in history was preceded by tropical Cyclones Luban and Mekunu, which formed over the Arabian Sea between May and October 2018, bringing heavy rainfall to eastern Yemen and Southwest Oman, respectively. This warm and extreme rainfall created the perfect environment sustaining three generations of locust outbreaks over the two years leading up to 2020, causing significant damage to settled agriculture and pastoralists in eastern Africa, the Arabian Peninsula, and the Indian subcontinent[18]. Frequent and intense rainfall conditions in eastern Africa, a major regional cluster for locust outbreaks, are regulated by ocean–atmosphere coupled modes of variability, such as the Indian Ocean Dipole (IOD) and the El Niño-Southern Oscillation (ENSO)[19]. It should come as no surprise that long-term trends in locust dynamics are sensitive to the changes in the IOD and ENSO states independently or in phase[3]. ENSO and IOD-driven changes in the intensity and frequency of extreme rainfall in crucial locust breeding regions like eastern Africa highlight that the impact of climate change is not solely due to changes in mean temperature, but also a result of increases in extreme and unprecedented events[2]. State-of-the-art projections show that extreme rainfall events, both in frequency and intensity, are expected to increase in a warmer climate. Consequently, locust outbreaks are highly likely to increase, given that soil moisture and temperature—two key variables that favor locust breeding—-are also projected to rise (Fig. 2). This increase presents a significant challenge to monitor and control future desert locusts and outbreaks.

Studies have also shown that temperature changes affect the hatching cycle of the locust eggs, the larvae growth cycle, and reproduction within populations[15,16]. Major locust outbreaks in Asia[20,21] and Europe[22] over the past millennium provide evidence of a causal relationship between changes in seasonal temperatures and locust outbreaks. Laboratory experiments show that the incubation period of the desert locust, *Schistocerca gregaria*, is phase set by diel fluctuations in temperatures[23,24], with temperature ranges between 35 and 41 °C significantly accelerating the development of species[23]. Embryonic development in the desert locust *S. gregaria* occurs at a minimum temperature of 15.1 °C, and the hatchability of the eggs falls within the range of 20–24 °C[23]. Whereas field observations identify fluctuations in temperature, moisture, and light as primary controls of hatching in locusts[25]; earlier field observation on desert locust *S. gregaria* reported oviposition activity during both day and night, underemphasizing the effect of light intensity on the rate of hatching in locusts[26]. These findings suggest that the mechanisms that control hatching time in the desert locust *S. gregaria* are rather complex[27] and depend on a complex combination of weather variables[28]. When weather conditions are most favorable, locusts aggregate and multiply in large numbers and turn into highly destructive plagues. Warming trends in temperature generally lead to range expansion, phenology shift, accelerated development, and an increase in the population of insects[29].

A positive relationship between extreme rainfall, soil moisture, and temperature, as projected (Fig. 2) will directly affect the desert locust's climatic niche and expand its spatial distribution. It is therefore imperative to identify regions most conducive to desert locusts under different climate change scenarios and develop projections for evidence-informed policy-making and disaster mitigation.

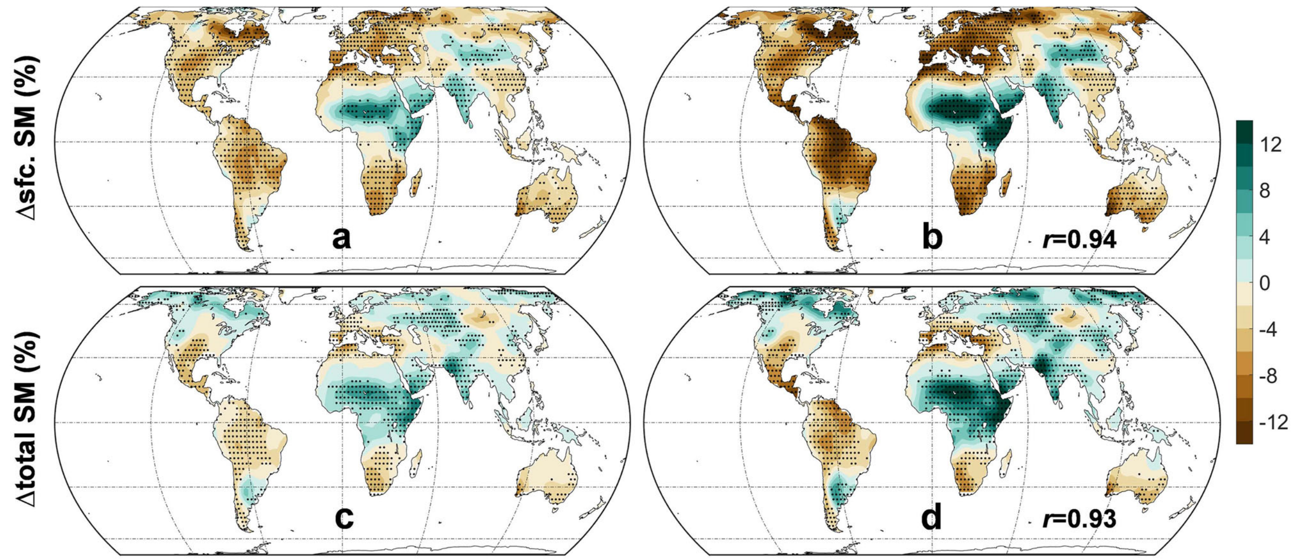

Fig. 2 | End of century projections of soil moiture. CMIP6 multi-model ensemble mean changes in soil moisture (% relative to the multi-model mean for 1979–1999) from 1970–1999 to 2070–2099 under the (left) SSP2–4.5 and (right) SSP5–8.5 scenarios. Panels show annual **a**, **b** top-10 cm soil moisture (SM) and **c**, **d** total SM. Adapted from Zhao & Dai (after ref. 46).

Geomorphology also plays a significant role in creating conditions conducive to locust breeding. It has been established that five major environmental factors, i.e., surface temperature, precipitation, soil moisture, soil sand content, and greenness, influence locust breeding, maturation, concentration, and migration[15,30]. These environmental factors are closely intertwined with regional and local geomorphological conditions. Regional geomorphology modulates local climatic variables, such as land temperature, rainfall distribution, and wind patterns, while also determining soil type, sand content, soil moisture, and vegetation cover. These links are particularly pronounced in the eastern African region, which shows one of the highest geomorphological diversities in the world.

The East African Rift System (EARS) traverses the Ethiopian and Kenyan highlands, creating a topographic gradient that ranges from the high Ethiopian and Kenyan plateaus (~1500–2000 m a.s.l) to the adjoining high Somalian and Sudanese lowlands (~500 m a.s.l), and further to the low Afar depression (~200 m a.s.l.). This topographic diversity creates a range of local geomorphological gradients with different local climatic zones, soil characteristics, and vegetation cover. The Somalian and Sudanese lowlands and the Afar depression are characterized by arid and semi-arid climates with prominent sandy soils. Ethiopia, Somalia, and Kenya have been the most affected among the 100+ countries threatened by locust outbreaks during the 20th and 21st centuries[7]. The breeding areas for most of the eastern African locust outbreaks are predominantly the Somalian lowlands and the Afar depression, or the Arabian desert across the Red Sea. The major locust outbreaks, including the 2018–2020 outbreak, are closely related to long-term droughts followed by high precipitation in spring and summer[7,31] in these sandy deserts or arid to semi-arid localities.

Challenges and limitations in locust outbreak mitigation strategies in the Global South: insights from Eastern Africa

The first line of defense against locust outbreaks in severely impacted regions such as eastern Africa lies in early detection and targeting locust breeding areas in Somalia, northeastern Kenya, Sudan, the Afar depression in Ethiopia, and the lowlands in Yemen and along the EARS. Yet, desert locust surveillance and control operations are challenged in these areas due to many obstacles—notably remoteness and inaccessibility. Additionally, locust outbreaks are influenced by the interaction between climate conditions and management efforts, highlighting the critical role of proactive management in mitigating the impact of climate change on locust proliferation[32]. However, the effectiveness of desert locust control operations has been hindered by conflicts and dysfunctional governance systems, undermining their implementation[33]. The civil war in Yemen has and continues to disrupt locust breeding control operations, allowing locusts to multiply unchecked and subsequently invade neighboring regions. The 2-year war in Tigrai that lasted from November 2020 to November 2022 has disabled similar efforts, highlighting the imperative for global and inter-state collaboration and engagement.

The FAO and its partners have developed innovative technologies, such as the eLocust platform, allowing real-time transmission of field observations and reports from areas with no network coverage[34]. These advancements have automated numerous aspects of desert locust control operations globally, empowering remote and increasingly automated actors the power to respond to potential outbreaks from afar[35]. However, automation of decision-making in developing locust outbreak mitigation strategies, such as in eastern Africa in recent years, has led to overreliance on aerial control operations, which employ preventative treatments, including chemical and biological insecticides. Between 2018 and 2020, locust outbreaks in eastern Africa resulted in the treatment of a total of 1.6 million hectares with broad-spectrum organophosphate and pyrethroid insecticides[36].

Such heavy aerial spraying and blanket treatment of “conventional” insecticides like chlorpyrifos, malathion, and fenitrothion pose significant risks. Neither of these substances is recommended for blanket treatments in locust control[37], and their application has resulted in non-target mortality, including birds and honeybees in countries like Ethiopia and Kenya[38,39]. Notwithstanding the economic contributions of honey production as a means of livelihood, honeybees hold significant ontological value for some Indigenous ethnic minority communities in the region. This example illustrates how spraying ‘bycatch’ can be a gravely unacceptable outcome of aerial control operations in certain regions. Similarly, in Somalia, the application of insecticides is a significant concern given the size of its nomadic pastoralism and the potential adverse impact on bees and livestock.

Indigenous and local knowledge and technology in locust outbreak management

In many contexts, indigenous peoples (IPs) and local communities (LCs) possess time-tested knowledge and adaptive practices developed through unique relations with the natural environment, that enhance resilience to climate-related hazards and risks. This includes understanding environmental changes across their lands and territories, including those affecting biodiversity, ecological health, livestock production, and other forms of livelihood. Generations-worth of indigenous and local knowledge (ILK) exist on desert locusts specifically, encompassing insights into indicative weather patterns, anticipated temporalities of upsurges, swarm behaviors, and movements, and potential impacts on local ecologies, which may not be captured by remote data or external experts[35].

Efforts are underway to leverage ILK in planning for, mitigating, and adapting to locust outbreaks—often through integration with scientific-led digital technologies. One of the major hurdles in an effective early warning system is the collection and recording of accurate and complete data in remote locations and its subsequent transmission to inter/national authorities in time to implement effective control operations. If there are delays in receiving this data, then its value declines, and well-informed decisions and plans cannot be made. During the 2020–2021 upsurge in eastern Africa, IPs and LCs in remote areas acted as sentinels for locust breeding, feeding into a wider early warning system to alert countries about the potential development of outbreaks and plagues. Engaging farmers, pastoralists, and other community-level actors, such as wildlife rangers, in scouting and establishing channels of communication and hotlines for reporting findings can help with locust monitoring. Community informational networks can also help with early warning, acting as channels for awareness about hazards and appropriate actions and behaviors in response.

An assessment of current challenges and limitations in locust outbreak mitigation highlights the importance of integrating ILK into all stages of desert locust planning and response. For example, digital technologies—such as EarthRanger, eLocust, or WhatsApp—used recently in eastern Africa, may foster greater opportunities for IPs and LCs to support monitoring activities in their lands and territories. ILK has also proven effective in understanding the long-term ecological consequences of (bio)pesticides, contrasting with sole reliance on experiments conducted in controlled or laboratory settings. This knowledge can be used to guide context-specific decisions on which pesticidal substances are appropriate for certain locations and under what conditions, following principles of free, prior, and informed consent. The inclusion of IPs and LCs in disaster planning, including for desert locust outbreaks, is also a right protected by international agreements, such as the United Nations Declaration on the Rights of Indigenous Peoples and The United Nations-endorsed Hyogo Framework for Action. Similarly, integrating Indigenous knowledge systems with digital technologies for desert locust control aligns broadly with the UN Secretary-General's *Roadmap for Digital Cooperation*[40].

Yet, significant challenges remain in co-creating and integrating community-based and science-based approaches to desert locust management[41]. These challenges include ensuring adequate participation among IPs and LCs, particularly the most vulnerable, in the design and use of digital technologies; that decisions about response, mitigation, and planning activities are shaped by local experiences, knowledge, and priorities; and avoiding harm and safeguarding the rights of IPs and LCs. The next section charts a potential way forward in light of these challenges, based on evidence from eastern Africa in particular.

The Way Forward

Our goal is to stimulate dialog and establish the framework for a decision support system for informed policy-making, addressing what we have identified as critical gaps in existing mitigation strategies, at the intersection of technology, society, and climate policy and decision-making. Alongside our analysis of the challenges faced by existing mitigation strategies at the global and regional scale, our recommendations draw significantly from insights garnered during a consultative workshop conducted in Tigrai, northern Ethiopia, in December 2023. This region has endured a series of devastating human-made and natural disasters, including a brutal 2-year war from 2020 to 2022, drought, and locust outbreaks. The workshop brought together locust and environmental researchers and local agricultural experts who have been at the forefront of efforts to mitigate the recent locust invasions in the region. In addition, farmers from the highland agricultural zones of Tigrai, who have been affected by several desert locust swarms in recent years, and pastoralists from the lowland Afar region, where many of the known locust breeding areas are located, were active participants in this workshop. Repeatedly, the participants emphasized the need for ILK integration with technological solutions for efficient mitigation of locust outbreaks[35]. We call for the adoption of the following pipeline of steps to address what we have identified as four strategic gaps across various sectors of global locust control operations (Fig. 3).

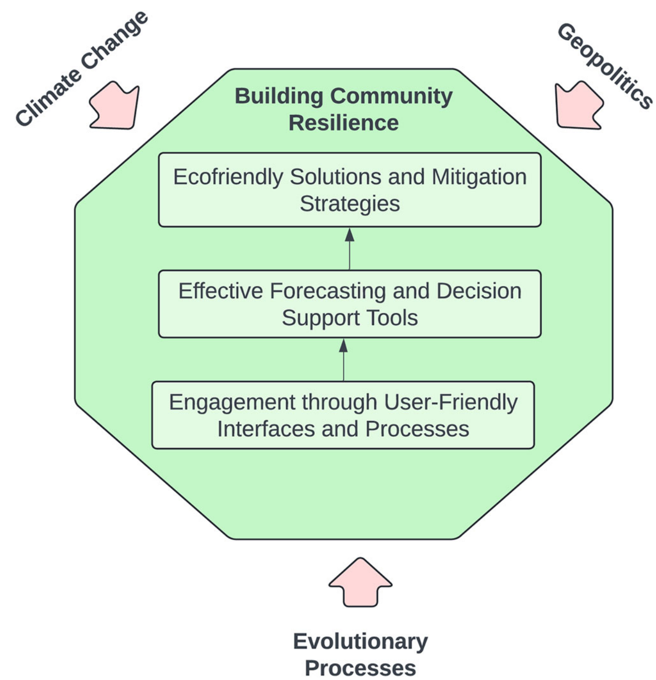

Fig. 3 | Schematic representation of strategic gaps in existing locust outbreak control and mitigation strategies, along with proposed solutions. Similar to how climate change and geopolitics impact locust control operations in distinct ways, evolutionary processes play a significant role in the context of locusts' elasticity and their ability to adapt to new pesticides. These processes enable locust populations to evolve in response to selective pressures, such as pesticide applications.

Creating more user-friendly platforms

Analyzing information for desert locust control operations demands an elevated level of automation and data collection at the local level, encompassing the monitoring, reporting, and verification of locust breeding sites. Despite the potential shown by existing applications like the eLocust platform, they remain underutilized due to language barriers, difficulty of usage, and limited access at the local level. Hence, data collection schemes must immediately integrate automated data gathering with increased community engagement. Community-based monitoring systems, exemplified by indigenous administrative and communication systems like *Dagu* and *Abogereb* in Afar and Tigrai, Ethiopia, respectively, have proven effective in recent outbreaks. Such systems facilitate efficient information transfer through careful selection and language translation facilitated through meetings of elders. While such systems underscore the importance of active community engagement in locust monitoring, the process of information sharing is time and resources-intensive. Digital technologies and interactive tools must be improved to facilitate the process of information sharing within a framework where local communities are both key actors and beneficiaries. From a technological perspective, natural language processing (NLP) models have the potential to enhance various aspects of locust control by leveraging textual data to improve early warning systems, risk assessment, communication, decision support, and policy development. It is also worth noting here that traditional, ground survey methods are inefficient to adequately address the large spatial scale of the locust problem. Yet major technological gaps remain. Remote sensing and associated geospatial technologies can provide timely data to assess the risk of impending locust outbreaks. This information could be used for targeted preventive management actions in the locust breeding areas.

A critical aspect of integrating NLP models in locust control operations is the incorporation of IPs and LCs in the decision-making processes. Lessons drawn from NLP applications in other sectors, such as healthcare underscore the significance of inclusively engaging communities in the co-creation of community-based NLP models to foster inclusion, innovation, and discovery[42]. The FAO's Locust Hub, supported by the eLocust3 system, can be significantly enhanced with AI and NLP to revolutionize locust management. NLP can process multilingual reports from farmers and field officers, translating and categorizing them in real time to generate geotagged alerts for rapid response. AI algorithms can integrate this data with satellite imagery, vegetation indices, and weather patterns to predict locust breeding and swarm movements weeks in advance. These predictive insights enable decision-makers to deploy resources strategically, reducing the impact of outbreaks. Together, these technologies can transform the FAO's locust management efforts from reactive to anticipatory, equipping local communities with timely and actionable information to safeguard agriculture and food security.

Improving decision support through forecasting

A recent study by Piou and Marescot[43] highlights the diverse methodologies necessary for effective locust forecasting, with a particular emphasis on the critical role of scale—from global to local levels. This research underscores the necessity of integrating various datasets, including the normalized difference vegetation index (NDVI), meteorological, and remote sensing information, to develop forecasting models tailored for different scales. However, numerous challenges hinder the transition from scientific research to operational forecasting systems. These challenges include harmonizing disparate data from disconnected repositories, integrating essential local-level information, and calibrating models across multiple scales. To address these issues, there is a pressing need for an open-access platform that democratizes data access and fosters methodological harmonization—standardizing methodologies and data formats—to ensure consistency and interoperability among various forecasting models and data sets. Such a platform would encourage collaboration among stakeholders at all levels, enhancing the collective effort to improve locust forecasting accuracy. By streamlining the integration of diverse data and forecasting methods, such a platform would pave the way for a unified and more robust strategy for locust management.

Giving local communities greater voice and control

The success of the eLocust platform underscores the transformative potential of digital technologies in facilitating community involvement in the decision-making process. There is an urgent need to develop a comprehensive decision support system that considers dynamic socio-ecological conditions, with an emphasis on local community empowerment and capacity building. Immersive training environments, leveraging artificial intelligence (AI), large language models (LLMs), and augmented/virtual reality (AR/VR) may be utilized to train community volunteers and leaders with relevant activities pertaining to ground operations, such as species identification, biology and behavior of locusts, and control operations. Incorporating major stakeholders and local communities into developing and utilizing innovative technology via a tailored AR/VR training method is key for effective locust control, given that such engagements ensure technology adoption and scalability, which remains a primary challenge today. Prioritizing customizable mobile applications to overcome language barriers is essential to engage citizens and farmers in 'incentivized' locust control operations such as reporting locust sightings and submitting geotagged photos or videos. Mobile applications also provide educational resources, alerts, and guidance on locust identification and control measures. Remote sensing technologies, such as satellite imagery and aerial drones, are better utilized for large-scale monitoring of locust habitats and movements. The integration of available tools in different platforms can provide real-time data on vegetation health, weather patterns, and locust swarms. This integration also enables early detection and rapid response, allowing authorities to plan and prioritize control interventions more effectively. Nevertheless, utilizing AI and big data analytics in locust control operations needs to recognize the significant ethical and moral responsibilities that come with deploying AI systems in both the data collection scheme and the decision-making process[44]. There is an urgent need to implement ethical frameworks to guide AI and big data use in all locust outbreak control operations and mitigation.

Eco-friendly solutions

Community-centric approaches ensure that the proposed technical solutions are grounded in local engagement, minimizing reliance on heavy automation and innovative technology. Such approaches are especially relevant given the potentially adverse effects of insecticides and pesticides, which continue to serve as the primary line of defense. The fact that locusts show an extreme form of phenotypic plasticity[45], which describes the ability of individual genotypes to produce different phenotypes when exposed to different environmental conditions, poses a significant challenge to the development and implementation of effective pest control mitigation strategies. The continued use of chemicals carries long-term risks to human health, the environment, and agroecology. Recent applications underscore the potential of eco-friendly biopesticides in locust control operations, mitigating spillover effects and ensuring environmentally safe practices. Mitigation approaches and strategies must account for the capacity of the locust to mutate when exposed to different environmental conditions and the impacts of climate change. Given these challenges, the need for environmentally friendly alternative biopesticides, scalable for use against locusts cannot be emphasized enough.

We call for a holistic co-design system that facilitates active collaboration between diverse stakeholders—including impacted communities, decision-makers, and other relevant groups—in the design and implementation of locust control operations. A holistic co-design system engages and integrates local communities' perspectives, needs, and insights with different data types for effective large-scale monitoring, early detection, reporting, verification, and control.

Data availability

No datasets were generated or analysed during the current study.

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Competing interests
The authors declare no competing interests.

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