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Research Article

Modelling the Impacts of Early Intervention on Desert Locust Outbreak Prevention

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To preserve crop production losses, monitoring of desert locust attacks is a significant feature of agriculture. In this paper, a mathematical model was formulated and analyzed to protect crops against desert locust attack via early intervention tactics. We consider a triple intervention approach, namely, proaction, reaction, and outbreak prevention. The model integrates a stage-structured locust population, logistics-based crop biomass, and blended early intervention via pesticide spray. We assume that the amount of pesticide spray is proportional to the density of the locust population in the infested area. Conventional short residual pesticides within ultralow volume formulation and equipment control operations are considered. The trivial and locust-free equilibrium of the model is unstable, whereas the interior equilibrium is asymptotically stable. Numerical simulations validate the theoretical results of the model. In the absence of intervention measures, desert locust losses are approximately 71% of expected crop production. The model projection shows that effective proactive early intervention on hopper stage locust contained locust infestation and subdued public health and environmental hazards. Relevant and up-to-date combined early interventions control desert locust aggression and crop production losses.

1. Introduction

Locusts are divisions of the grasshopper species Acrididae, which includes most short-horned grasshoppers. The desert locust (*Schistocerca gregaria* Forskål, 1775) is the most devastating migratory member of all locust species [1]. In response to environmental stimuli, compact and extremely mobile adult desert locust swarms can form [2]. The nonflying hopper (or nymph) stage can form cohesive masses that are called hopper bands [3]. They are ravenous eaters who consume their weight per day, targeting food crops and forage. A single adult desert locust can consume two grams, and the hopper stage can consume half of the amount that an adult locust can consume per day. Just a single square kilometer of the swarm can contain up to 80 million adults, with the capacity to consume the same amount of food in one day as 35,000 people. The current desert locust upsurge could have posed an unprecedented consequence, potentially causing large-scale crop damage and threatening food security. The desert locust invasions, recognized for thousands of years, can follow one another at a high frequency if there are no intervening control measures. The recession periods are generally short, whereas the invasions can last for one decade or more [4]. Since the 1960s, desert locust outbreaks are now better controlled and are often shorter in duration and have reduced impact. However, upsurges continue to occur, most often as a result of a reduction in resources during recessions, or due to insecurity in key areas where preventive control should be undertaken. The role of climate change on such outbreaks remains a matter of debate.

Damaging desert locust infestation in decades is at the onset in East Africa since July 2019. The current upsurge of the desert locust is very devastating and reminiscent of situations experienced a very long time ago [5]. Swarms of desert locusts are threatening large areas of pastures and crops, overwhelming countries in the Horn of Africa, the Middle East, and South Asia. The UN Food and Agriculture Organization (FAO) says that these swarms represent the worst infestation in 25 years in Ethiopia and Somalia, 26 years in India, and the worst in 70 years in Kenya. The trauma has affected 23 countries to date, from Pakistan to Tanzania [2, 6, 7]. The Food Security and Nutrition Working Group (FSNWG) conducted a regional desert locust impact evaluation revealing that nearly 42%-69% of crop production has been lost in the fragile areas [8, 9].

Hopper bands and adult swarm stage of the desert locust can cause significant deterioration to vegetation and crops in the infested areas. Food security, industrial raw materials, and export earnings may also be severely threatened in affected areas. Consequently, it is not a surprise that extensive control efforts are mounted whenever hopper bands or swarms of the desert locust emerge in or invade a region. Various strategies are implemented to control the desert locust infestation and conquer crop production losses [10]. Reaction, proaction, and outbreak prevention are three broadly defined desert locust control strategies. However, this has remained a topic of considerable debate, and in recent years, there has been extensive discussion of early intervention strategies [11]. However, the strategy advocated for decades by the FAO of intervening as soon as possible (i.e., proactive or even preventive treatments) seems to have been effective and has largely contributed to containing invasions for over 60 years. Obviously, curative control operations are still essential when outbreaks cannot be stopped at an early stage. Besides, applying standard pesticides sprayed directly onto hopper bands and swarms should be the principal control [12]. Therefore, to prevent catastrophic swarms from maturing from hoppers, it is critical to strengthen ground and aerial surveillance efforts. One means of support is identifying potential breeding sites for timely and effective management of hopper bands. During the hopper stages, proactive ground controls are cost-effective. Once locusts reach the adult stage, aerial control operations will be employed [13]. However, they are very toxic and pose acute risks to human health and the environment [14]. To reduce contingent risks, balancing the control of desert locust populations and the amount of pesticides used is necessary [15, 16]. Currently, the use of ultralow volume (ULV) spraying equipment and oil-based ULV formulations reduces droplet evaporation and allows the use of only 0.5 to 1.0 liter of pesticide per hectare, thus reducing environmental contamination and transportation, handling, and storage costs [17–19]. It is largely considered that ULV treatment technique is the most effective way of applying pesticides for locust control [20].

Mathematical modelling can be essential to better understand pest population dynamics and different control strategies to optimize the efficacy of desert locust management [21]. Mathematical models have been widely used to assess the impact and effectiveness of viral infection control strategies against crop pests [22–24]. Anguelov et al. [25] formulated and analyzed pest-insect control using mating disruption and trapping. Various authors have studied the role of integrated pest management (IPM) and farmer awareness campaigns on crop pest management [26–30]. Farmers use insecticides to kill insects to protect the crop. Excessive use is hazardous to human health and the environment. Therefore, it is assumed that the amount of insecticides used are proportional to the density of insects. The computational mathematical model assessed the effects of insects and insecticides on crop production [31, 32]. Nevertheless, during our review of the literature on models, we did not find a dynamic model of interaction between crop damage and desert locust attacks. Moreover, the control strategies and attack aggressiveness of desert locust attacks are different from other crop pests. To address this gap, we aimed to study the dynamics of interactions between desert locusts, crop damage, and various management strategies. We formulated our model based on the well-known general pattern of invasions and the practices commonly used to control desert locust populations.

In this paper, we considered ongoing control intervention strategies, crop biomass, and stage-structured locust populations. We divided the locust population into two subgroups: wingless hoppers or nymphs and adult locusts. We admitted that hoppers and adult locusts do not have an equivalent attack rate. At all stages, pesticide spraying of hopper bands and adult swarms was considered the main method of desert locust control. The model is derived assuming that the amount of pesticide spray is proportional to the number of desert locusts in the infested area. In addition to locust pesticides, calibrating integration, ultralow volume (ULV) formulation, and equipment control operation leads minimizing pesticide-driven human health and environmental uncertainty. Mathematical analysis of system dynamics and parameter value identification are studied. Finally, we perform numerical simulations to illustrate the theoretical results and assess the impact of intervention strategies.

2. Development of Model System

We have proposed a model using a stage-structured desert locust population via hopper/nymphs (locusts without wings) (H) and adult locust (A), crop biomass (C), and amount of pesticides (P). Before presenting our mathematical model, we make the following assumptions.

A1. In the absence of locusts, the production of crops grows in a logistic manner with a carrying capacity of $K(K \in R^+)$ and a growth rate constant such that $r(r \in R^+)$. This is expressed as follows:

$$\frac{dC}{dt} = rC\left(1 - \frac{C}{K}\right). \tag{1}$$

A2. Considering the stage structure of a locust population, the total locust population L is divided into two classes: one is the juvenile locust or hopper (H) and the other is the adult locust (A), i.e., $L = H + A$. The nymphs become adults at a rate of σ ($1/\sigma$ is the development or maturity period of hopper stage locusts).

A3. It is assumed that only an adult locust is capable of reproducing.

A4. We consider that locusts attack the crop at the rate β, which reduces crop production. Due to this consumption of crops by locusts, the density of the locust population increases at a rate $\xi\beta$, where ξ represents the conversion efficiency of locusts. It is reduced by the rate of μ due to natural mortality.

A5. In a real-world natural ecological system, it is clear that the attack rate of nymphs is lower than that of adult locusts. So, we introduce a modification parameter η, which is $0 < \eta < 1$.

A6. The intervention measure is implemented on both the hopper and adult locust populations at a rate of $\varphi\gamma_1$ and $\varphi\gamma_2$, respectively. The parameter γ_1 represents the uptake rate of hoppers, γ_2 represents the uptake rate of adults, and φ is the proportionality constant.

A7. The amount of pesticide spray is proportional to the locust population (L). Its growth rate is θ, which is depleted at a rate of θ_0.

Based on the above assumptions, our model is formulated as follows:

$$\begin{aligned}\frac{dC}{dt} &= rC\left(1-\frac{C}{K}\right)-\beta(A+\eta H)C,\\ \frac{dH}{dt} &= \xi\beta CA-\phi\gamma_1 HP-(\sigma+\mu)H,\\ \frac{dA}{dt} &= \sigma H-\phi\gamma_2 AP-\mu A,\\ \frac{dP}{dt} &= \theta(H+A)-\theta_0 P,\end{aligned} \tag{2}$$

and the initial conditions are given as follows:

$$C(0), M(0), L(0), P(0) \geq 0. \tag{3}$$

2.1. Model Parameter Identification. We estimate the baseline parameters of the model from available FAO desert locust data and sources from the published literature. The desert locust, like all other locusts and grasshoppers, passes through three stages: egg, nymph (hopper), and adult. Hoppers develop over a period of about 30-40 days. We consider an average maturity period (taken from these ranges) of 35 days, so that $\sigma = (1/35) = 0.0286$ per day [3, 33]. A desert locust adult can consume roughly its weight in fresh food per day, which is about two grams every day [3, 34]. We set the consumption rate of a desert locust at $\beta = 0.002$ kg per day. However, the consumption rate of hoppers is relatively half that of adult locusts, that is, the modification parameter value $\eta = 0.5$ [35]. There can be at least 40 million and sometimes as many as 80 million locust adults in each square kilometer of a swarm [34]. We consider 1000 milliliters of pesticide per hectare for effective desert locust control. Therefore, we estimate the spray rate (θ) to be $\theta = (1000\,\text{mL/hectare})/(400000\,\text{locust/hectare}) = 0.0025$ mL pesticide per locust. Following this, we set 10% pesticide depletion, and we estimate the depletion rate (θ_0) to be $\theta_0 = \theta \times 0.1 = 0.00025$ mL per locust. We consider that total sprayed pesticides are equivalent to the sums of uptakes and depletions. Therefore, the uptake rate of pesticides per locust (γ_1 and γ_2) is estimated as $\gamma_1 = \gamma_2 \approx \theta - \theta_0 = 0.0025 - 0.00025 = 0.00225$ mL per locust. Spraying a straightforward ULV formulation chemical pesticide on hopper bands and a settled swarm is considered to cause 80% mortality on desert locusts [36]. Therefore, the numbers of deceased desert locust (φ) due to a milliliter of pesticide is computed as follows:

$$\phi = \frac{400000\,\text{locust/hectare}}{1000\,\text{mL/hectare}} x0.8 = 320\text{locust per milliliter}. \tag{4}$$

3. Equilibria and Stability Analysis

To study the stability analysis of system (2), the equilibrium points of the respective system (2) need to be calculated. Now, the equilibrium points are given below:

(i) The trivial equilibrium point $E_0 = (0, 0, 0, 0)$

(ii) The locust-free equilibrium point $E_1 = (K, 0, 0, 0)$

(iii) The interior equilibrium point $E^* = (C^*, H^*, A^*, P^*)$, where

$$\begin{aligned} C^* &= \frac{K(r-\beta(A^*+\eta H^*))}{r},\\ H^* &= \frac{\phi\gamma_2 A^* P^* - \mu A^*}{\sigma},\end{aligned} \tag{5}$$

where $P^* = (\theta(A^*+H^*))/(\theta_0)$ and A^* are the positive root of

$$C_1A^3 + C_2A^2 + C_3A + C_4, \tag{6}$$

where

$$\begin{aligned} C_1 &= \beta^2\gamma_2^2(1-\eta)\theta^2K\phi^3,\\ C_2 &= -\gamma_2\theta\phi^2\left(\beta^2\theta_0K(\eta\mu-\eta\sigma+2\sigma)+\gamma_2\theta r(\beta K\phi+\mu+\sigma)\right.\\ &\quad \left.-\gamma_1\theta r(\mu+\sigma)\right),\\ C_3 &= \theta_0\phi\left(\beta^2\theta_0K\sigma(\eta\mu+\sigma)+\gamma_2\theta r\left(\sigma(2\beta K\phi+\sigma)-\mu^2\right)\right.\\ &\quad \left.+\gamma_1\theta\mu r(\mu+\sigma)\right),\\ C_4 &= r\sigma\theta_0^2\left(-\beta K\sigma\phi+\mu^2+\mu\sigma\right).\end{aligned} \tag{7}$$

Theorem 1. *The trivial equilibrium, $E_0(0, 0, 0, 0)$, is always unstable.*

Proof. The evaluation of the Jacobian matrix at E_0 is

$$J(E_0) = \begin{pmatrix} r & 0 & 0 & 0 \\ 0 & -\mu-\sigma & 0 & 0 \\ 0 & \sigma & -\mu & 0 \\ 0 & \theta & \theta & -\theta_0 \end{pmatrix}. \quad (8)$$

The associated eigenvalues of the Jacobian matrix J at $E_0 = (0,0,0,0)$ are $\lambda_1 = r$, $\lambda_2 = -\mu - \sigma$, $\lambda_3 = -\mu$, and $\lambda_4 = -\theta_0$. Obviously, the intrinsic growth rate r is greater than zero, so we obtain a positive eigenvalue $\lambda_3 = r > 0$. Therefore, the equilibrium point E_0 is unstable.

Theorem 2. *The locust-free equilibrium, E_1, is unstable if $\mu(\mu+\sigma) < \beta K \sigma \phi$.*

Proof. The Jacobian matrix at $E_1 = (K,0,0,0)$ is

$$J(E_1) = \begin{pmatrix} -r & -K\beta\eta & -K\beta & 0 \\ 0 & -\mu-\sigma & K\beta\xi & 0 \\ 0 & \sigma & -\mu & 0 \\ 0 & \theta & \theta & -\theta_0 \end{pmatrix}. \quad (9)$$

Following some algebraic calculations, we obtain the following eigenvalues:

$$\begin{gathered} \lambda_1 = -r < 0, \\ \lambda_2 = -\frac{1}{2}\left(2\mu + \sigma + \sqrt{\sigma}\sqrt{4\beta k \xi + \sigma}\right) < 0, \\ \lambda_3 = \frac{1}{2}\left(-2\mu - \sigma + \sqrt{\sigma}\sqrt{4\beta k \xi + \sigma}\right) > 0, \\ \lambda_4 = -\theta_0 < 0. \end{gathered} \quad (10)$$

Therefore, the eigenvalue λ_3 is positive, thus implying that the equilibrium point E_1 is unstable.

Theorem 3. *The interior equilibrium E^* of the model is always locally asymptotically stable.*

Proof. The Jacobian matrix at $E^*(C^*, H^*, A^*, P^*)$ is

$$J(E^*) = \begin{pmatrix} -A_1 & -A_2 & -A_3 & 0 \\ A_4 & -A_5 & A_6 & -A_7 \\ 0 & \sigma & -A_8 & -A_9 \\ 0 & \theta & \theta & -\theta_0 \end{pmatrix}, \quad (11)$$

where

$$\begin{gathered} A_1 = \beta(A^* + \eta H^*) + \frac{2rC^*}{K} - r, \\ A_2 = \eta\beta C^*, \\ A_3 = \beta C^*, \\ A_4 = \xi\beta A^*, \\ A_5 = \gamma P^* + \mu + \sigma, \\ A_6 = \xi\beta C^*, \\ A_7 = \gamma_1 H^*, \\ A_8 = \phi\gamma_2 P^* + \mu, \\ A_9 = \phi\gamma_2 A^*. \end{gathered} \quad (12)$$

So, the corresponding characteristic polynomial of the Jacobian matrix is

$$\lambda^4 + B_1\lambda^3 + B_2\lambda^2 + B_3\lambda + B_4, \quad (13)$$

where

$$\begin{aligned} B_1 &= A_1 + A_5 + A_8 + \theta_0, \\ B_2 &= \theta(A_7 + A_9) + \theta_0(A_1 + A_5 + A_8) + A_2A_4 + A_1(A_5 + A_8) \\ &\quad + A_5A_8 - \sigma A_6, \\ B_3 &= \theta(A_7(A_1 + A_8 + \sigma) + A_9(A_1 + A_5 + A_6)) \\ &\quad + \theta_0(A_2A_4 + A_1(A_5 + A_8) + A_5A_8) + A_4(\sigma A_3 + A_2A_8) \\ &\quad + A_1A_5A_8 - A_6(\theta_0\sigma + A_1\sigma), \\ B_4 &= \theta(A_1(A_7(\sigma + A_8) + A_5A_9 + A_6A_9) + A_4A_9A_2) \\ &\quad + \theta_0(A_4(A_3\sigma + A_2A_8) + A_1A_5A_8) - A_1A_6\theta_0\sigma \\ &\quad - A_4A_9A_3\theta. \end{aligned} \quad (14)$$

Hence, by Routh-Hurwitz's criterion, equation (13) has all the negative roots or roots have a negative real part if and only if $B_1 > 0$, $B_3 > 0$, $B_4 > 0$, and $B_1B_2B_3 > B_3^2 + B_1^2B_4$; otherwise, the system will be unstable around the interior equilibrium point. □ □

4. Numerical Results and Discussions

In this section, we present the numerical results of model (2) using ode45 solver, via MATLAB software. We have to use baseline parameter values, which are list in Table 1 (unless otherwise stated). From this set of parameter values, we have to get the numerical value of equilibrium points of model (2), as follows: the model equilibrium point stability is justified here by using a set of parameter values in Table 1. The eigenvalues of the Jacobian matrix (8) at the equilibrium point $E_0 = (0,0,0,0)$ are $\lambda_1 = 0.2$, $\lambda_2 = -0.079$, $\lambda_3 = -0.05$, and $\lambda_4 = -0.00025$. Here, we confirm that the Jacobian matrix evaluated at equilibrium E_0 has a positive eigenvalue ($\lambda_1 = 0.19 > 0$), which implies that equilibrium E_0 is unstable,

Table 1: Model parameter baseline values.

Parameter	Biological meaning	Value	Source
r	Growth rate of crop biomass	$0.2\,\text{kg}\,\text{day}^{-1}$	[26]
K	Carrying capacity	$4000\,\text{kg}\,\text{hectare}^{-1}$	Estimated [37]
σ	Locust maturity rate	$0.0286\,\text{day}^{-1}$	Estimated [39, 33]
β	Attack rate of locust	$0.002\,\text{kg}\,\text{locust}^{-1}\,\text{day}^{-1}$	Estimated [3, 34]
μ	Natural mortality of locust	$0.05\,\text{day}^{-1}$	[26, 33]
η	Modification parameter	0.5	[35]
ξ	Conversion efficiency	$0.6\,\text{day}^{-1}$	[32]
θ	Amount of pesticides growth rate	$0.0025\,\text{mL}\,\text{locust}^{-1}$	Estimated [3, 38]
θ_o	Depletion rate of pesticides	$0.00025\,\text{mL}\,\text{locust}^{-1}$	Estimated [3, 38]
γ_1	Uptake rate of pesticides by hopper	$0.00025\,\text{mL}\,\text{locust}^{-1}$	Estimated [3, 38]
γ_2	Uptake rate of pesticides by adult	$0.00025\,\text{mL}\,\text{locust}^{-1}$	Estimated [3, 38]
ϕ	Depletion of locust due to pesticides	$320\,\text{locust}\,\text{mL}^{-1}$	Estimated [3, 36]

and it is consistent with Theorem 1. Similarly, we found the corresponding eigenvalues of the locust-free equilibrium point $(E_1 = (4000, 0, 0, 0))$: $\lambda_1 = -0.2$, $\lambda_2 = -0.437877$, $\lambda_3 = 0.308877$, and $\lambda_4 = -0.00025$. The equilibrium point exhibits one positive eigenvalue $\lambda_1 = 4.56 > 0$; hence, locust-free equilibrium E_1 is unstable, which is compatible with Theorem 2.

Here, we focus on coexistence equilibrium dynamic stability $(E^* = (C^*, H^*, A^*, P^*) = (3719.43, 12.0255, 1.0014, 130.269))$. We have to get the corresponding eigenvalues $\lambda_1 = -93.845$, $\lambda_2 = -0.341013$, $\lambda_3 = -0.214883$, and $\lambda_4 = -0.00065645$; note that E^* is stable.

The time series evaluation of system (2) with varying initial values are shown in Figure 1. All solution trajectories eventually become steady to the interior equilibrium point E^*. Our result in Figure 1 shows that all eigenvalues are negatives; this implies that E^* is stable. This numerical result is consistent with Theorem 3.

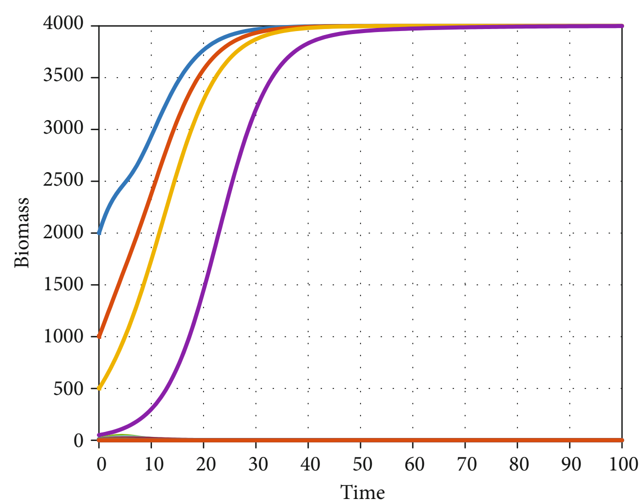

Figure 1: The trajectories of system (2) with the baseline parameters in Table 1 and varying the initial values. The interior equilibrium (3719.43, 12.0255, 1.0014, 130.269) of system (2) is asymptotically stable.

4.1. Impact of Intervention Measures. Here, we observe the impact of attacking rate (β) in the absence of intervention measures ($\theta = \theta_0 = \gamma_1 = \gamma_1 = 0$), and the other parameters in Table 1 with various values of β.

Figure 2 depicts simulation results that show a projected 4000 kg per hectare crop production gain from the agricultural land in the absence of a desert locust attack. However, crop production declines if the locust attack increases. Our model simulation in Figure 2 shows that we obtain 1145 kg out of 4000 kg crop production per hectare at the baseline value $\beta = 0.002$. The model simulation result noted that in the absence of relevant intervention strategies, a more than 71.375% crop production loss is expected. Therefore, the necessity of introducing relevant and appropriate intervention practices is undeniable.

A desert locust outbreak can cause significant and widespread agricultural crop losses. Food security, industrial raw materials, and export earnings may also be seriously threatened in affected areas. Consequently, it is not a surprise that extensive control efforts are mounted whenever hopper bands or swarms of the desert locust emerge in or invade a region. Reaction, proaction, and outbreak prevention are three broadly defined desert locust control strategies. The effect of integrated early intervention is evaluated by simulating model (2) in the absence and presence of intervention.

In Figure 3, we show the impact of integrated early intervention over the crop biomass. The numerical simulation shows that effective early intervention against desert locust outbreaks could protect against crop losses caused by locust invasion. The model projection shows that almost 71.375% expected crop losses are anticipated by baseline value integrated intervention strategies.

Figure 4 depicts results showing how integrated intervention has a significant impact in overcoming the massive growth of the desert locust population. In particular, at the baseline value of the intervention rate ($\theta = 0.0025$, $\gamma_1 = \gamma_2 = 0.00225$), the locust population was eliminated from the

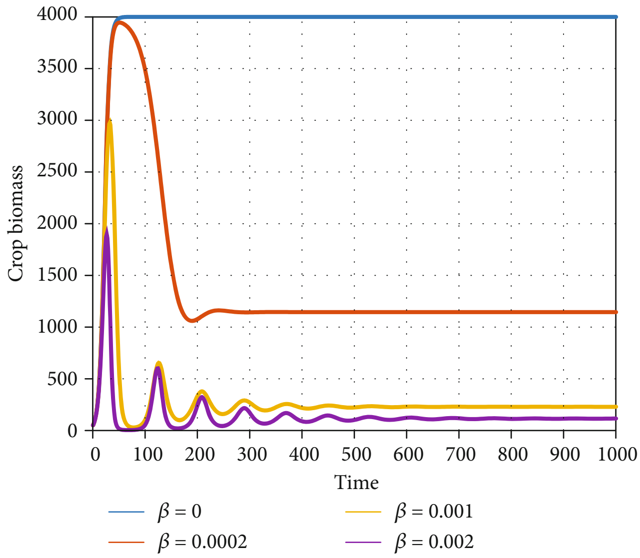

Figure 2: Evaluate the effect of desert locust consumption rate by varying β value.

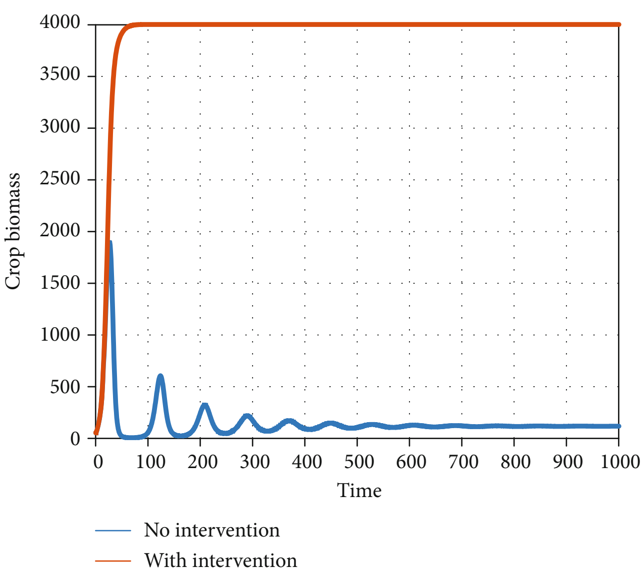

Figure 3: Impact of integrated early intervention on crop biomass. The simulation was conducted in the absence of intervention ($\theta = \theta_0 = \gamma_1 = \gamma_2 = 0$) and within intervention measures ($\theta = 0.0025$, $\theta_0 = 0.00025$, and $\gamma = 0.00225$).

infested area. However, in the absence of integrated intervention ($\theta = \theta_0 = \gamma_1 = \gamma_2 = 0$), the locust population reaches its peak and finally persists in the region.

Reaction and outbreak prevention control strategies protect crops against swarms, but it is costly and disruptive. Proaction involves early intervention during outbreaks to avert further development to plague status; it is in current use because it is effective, relatively inexpensive, and it is the best available option for now. In desert locust control, proaction entails intervention against localized outbreaks to prevent them from reaching plague status. Proaction relies on early detection of bands and swarms, preferably in breeding areas, and prepositioning of campaign resources. Here,

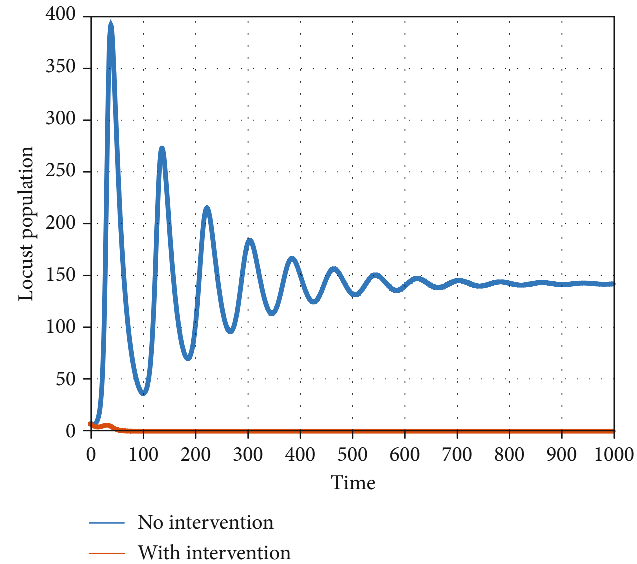

Figure 4: Impact of integrated early intervention on total desert locust population. The simulation was conducted in the absence of intervention ($\theta = \theta_0 = \gamma_1 = \gamma_2 = 0$) and within integrated intervention ($\theta = 0.0025$, $\theta_0 = 0.00025$, and $\gamma_1 = \gamma_2 = 0.00225$).

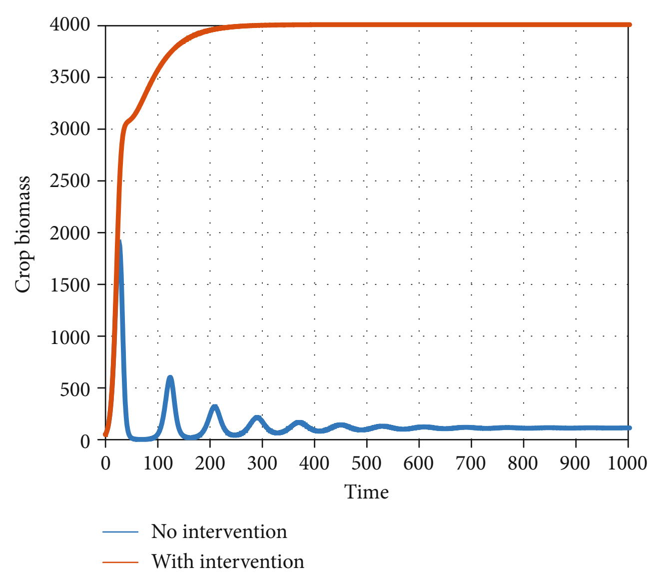

Figure 5: Impact of the proaction approach of early intervention on crop biomass. The simulation was conducted in the absence of intervention ($\theta = \theta_0 = \gamma_1 = \gamma_2 = 0$) and within early intervention only on hopper bands ($\theta = 0.0025$, $\theta_0 = 0.00025$, $\gamma_1 = 0.00225$, and $\gamma_2 = 0$).

we assess the impact of early intervention (only on hoppers) on desert locust control (γ_1).

Figure 5 depicts results showing how early intervention on hopper stage locusts protects crop production against desert locust attack. In particular, the simulation shows that in the absence of intervention, the agricultural land provides 1145 kg per hectare. Furthermore, at the baseline value of the intervention ($\gamma_1 = 0.00225$) only on hopper stage locusts, the

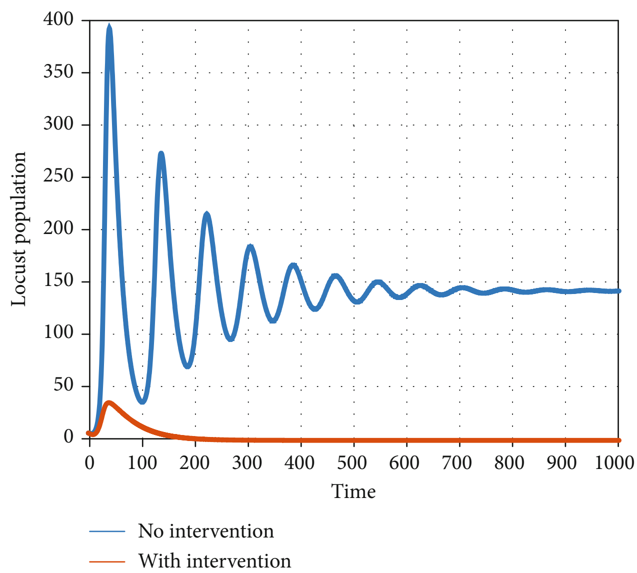

FIGURE 6: The impact of the proaction approach of early intervention on total locust populations. The simulation was conducted in the absence of intervention ($\theta = \theta_0 = \gamma_1 = \gamma_2 = 0$) and within early intervention only on hopper bands ($\theta = 0.0025$, $\theta_0 = 0.00025$, $\gamma_1 = 0.00225$, and $\gamma_2 = 0$).

crop losses are rapidly recovered, and the optimal expected crop production is finally reached.

Figure 6 depicts results that show the impact of early intervention on the total locust population. In particular, the simulation shows that in the absence of intervention desert locust persists in the infested area. However, effective proaction can contain locust populations. Early detection and strengthening survey and control capabilities at the hopper stage might be correlated with reduced pesticide application, economic costs, environmental risks, and duration and extent of the locust threat.

5. Conclusion

The desert locust is considered one of the world's most dangerous migratory pests. A typical swarm can have up to 80 million locusts per km^2 and consume the equivalent of crops that could feed 35,000 people for a day. We have evaluated the impact of early intervention to control outbreaks of this insect. We developed a mathematical model integrating crop biomass, locust population (structured by stages), and early interventions.

From our theoretical analysis model, we got three nonnegative equilibrium points. The trivial and locust-free equilibriums are unstable, whereas the interior equilibrium is asymptotically stable. The overall dynamic numerical results supported and verified the theoretical analysis of the model. Our numerical simulation has shown that the dynamical stability of interior equilibrium using times series evaluation. If antilocust measures are not implemented, numerical results have shown that we would get less than 28.8% of the expected agricultural production from infested areas. This will allow the emergence of a socioeconomic crisis and altered food security. Thus, developing and implementing an appropriate and timely control intervention is extremely important. Our study shows that the implementation of an integrated early intervention protects more than 70% of the total agricultural production. The simulation result showed that in the absence of pesticide treatment, this expected agricultural production would be lost due to desert locust attacks. In addition, early proaction intervention on hopper bands, with a standard implementation rate could protect against almost all agricultural crop losses.

In general, our study shows that crop production losses due to desert locust attacks should be manageable using efficient prevention and control strategies. In particular, proactive early intervention using ULV insecticides is cost-effective, and has low risks to human health and the environment. However, the proposed model cannot address some of the concerns of integrated desert locust management. The main limitations of our study are as follows: (1) values of some parameters are not established from survey data; (2) the effects of weather and climate changes on locust breeding and movement are not considered; and (3) technologies related to geopositioning, spatial analysis, remote sensing, and early warning are not incorporated. Such limitations should be addressed in our future work.

Data Availability

The data used in this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] S. J. Simpson, A. L. A. N. R. McCAFFERY, and B. F. Hägele, "A behavioural analysis of phase change in the desert locust," *Biological Reviews*, vol. 74, no. 4, pp. 461–480, 1999.

[2] A. A. M. Salih, M. Baraibar, K. K. Mwangi, and G. Artan, "Climate change and locust outbreak in East Africa," *Nature Climate Change*, vol. 10, no. 7, pp. 584-585, 2020.

[3] P. M. Symmons and K. Cressman, *Desert Locust Guidelines: Biology and Behaviour*, FAO, Rome, Italy, 2001.

[4] FAO, *Desert Locust Situation Update*, FAO, Rome, Italy, 2021, http://www.fao.org/ag/locusts/en/info/info/index.html.

[5] G. A. Sword, M. Lecoq, and S. J. Simpson, "Phase polyphenism and preventative locust management," *Journal of Insect Physiology*, vol. 56, no. 8, pp. 949–957, 2010.

[6] FAO, *Desert Locust Bulletin*, FAO, Rome, Italy, 2021, http://www.fao.org/ag/locusts/common/ecg/1914/en/DL512e.pdf.

[7] S. Devi, "Locust swarms in east Africa could be "a catastrophe"," *The Lancet*, vol. 395, no. 10224, p. 547, 2020.

[8] FSNWG, *East Africa Regional Desert Locust Impact Monitoring—Round 1 (4 September 2020)*, 2020, https://reliefweb.int/organization/fsnwg.

[9] FSNWG, "East Africa regional desert locust impact monitoring—round 2," 2021, https://reliefweb.int/report/ethiopia/east-africa-regional-desert-locust-impact-monitoring-round-2-12-january-2021.

[10] A. Van Huis, "Strategies to control the desert locust *Schistocerca gregaria*," in *Area-Wide Control of Insect Pests*, pp. 285–296, Springer, Dordrecht, Netherlands, 2007.

[11] A. T. Showler, M. A. Ould Babah Ebbe, M. Lecoq, and K. O. Maeno, "Early intervention against desert locusts: current proactive approach and the prospect of sustainable outbreak prevention," *Agronomy*, vol. 11, no. 2, p. 312, 2021.

[12] A. van Huis, K. Cressman, and J. I. Magor, "Preventing desert locust plagues: optimizing management interventions," *Entomologia Experimentalis et Applicata*, vol. 122, no. 3, pp. 191–214, 2007.

[13] D. Dent and R. H. Binks, *Insect Pest Management*, Cabi, 2020.

[14] L. Rani, K. Thapa, N. Kanojia et al., "An extensive review on the consequences of chemical pesticides on human health and environment," *Journal of Cleaner Production*, vol. 283, article 124657, 2021.

[15] M. W. Aktar, D. Sengupta, and A. Chowdhury, "Impact of pesticides use in agriculture: their benefits and hazards," *Interdisciplinary Toxicology*, vol. 2, no. 1, pp. 1–12, 2009.

[16] V. der Valk, R. D. C. Harold, K. Cressman et al., "Fighting the locusts...Safely. Pesticides in desert locust control: Balancing risks against benefits," *Food and Agriculture Organization of the United Nations(FAO)*, p. 15, 2006.

[17] A. Sharma, "Locust control management: moving from traditional to new technologies—an empirical analysis," *Entomology, Ornithology & Herpetology*, vol. 4, no. 1, p. 1, 2015.

[18] A. T. Showler, "Desert locust control: the effectiveness of proactive interventions and the goal of outbreak prevention," *American Entomologist*, vol. 65, no. 3, pp. 180–191, 2019.

[19] S. Cisse, S. Ghaout, A. Mazih, M. A. O. Babah Ebbe, A. S. Benahi, and C. Piou, "Effect of vegetation on density thresholds of adult desert locust gregarization from survey data in Mauritania," *Entomologia Experimentalis et Applicata*, vol. 149, no. 2, pp. 159–165, 2013.

[20] G. A. Matthews, "The principles of Ultra-Low volume spraying in relation to the application of microbial insecticides for locust control," in *Biological Control of Locusts and Grasshoppers*, C. J. Lomer and C. Prior, Eds., pp. 245–248, CAB International, Wallingford, UK, 1992.

[21] K. E. F. Watt, "Mathematical models for use in insect pest control," *The Memoirs of the Entomological Society of Canada*, vol. 93, no. S19, pp. 5–62, 1961.

[22] S. Bhattacharyya and D. K. Bhattacharya, "Pest control through viral disease: mathematical modeling and analysis," *Journal of Theoretical Biology*, vol. 238, no. 1, pp. 177–197, 2006.

[23] X. Wang, Y. Tao, and X. Song, "Mathematical model for the control of a pest population with impulsive perturbations on diseased pest," *Applied Mathematical Modelling*, vol. 33, no. 7, pp. 3099–3106, 2009.

[24] I. R. Fitri, F. Hanum, A. Kusnanto, and T. Bakhtiar, "Optimal pest control strategies with cost-effectiveness analysis," *The Scientific World Journal*, vol. 2021, Article ID 6630193, 17 pages, 2021.

[25] R. Anguelov, C. Dufourd, and Y. Dumont, "Mathematical model for pest-insect control using mating disruption and trapping," *Applied Mathematical Modelling*, vol. 52, pp. 437–457, 2017.

[26] A. Basir, A. Banerjee, and S. Ray, "Role of farming awareness in crop pest management—a mathematical model," *Journal of Theoretical Biology*, vol. 461, pp. 59–67, 2019.

[27] T. Abraha, F. Al Basir, L. L. Obsu, and D. F. M. Torres, "Pest control using farming awareness: impact of time delays and optimal use of biopesticides," *Chaos, Solitons & Fractals*, vol. 146, article 110869, 2021.

[28] F. Al Basir, "A multi-delay model for pest control with awareness induced interventions—Hopf bifurcation and optimal control analysis," *International Journal of Biomathematics*, vol. 13, no. 6, article 2050047, 2020.

[29] N.-F. Wan, X.-Y. Ji, J.-X. Jiang, and B. Li, "A modelling methodology to assess the effect of insect pest control on agro-ecosystems," *Scientific Reports*, vol. 5, no. 1, 2015.

[30] J. Páez Chávez, D. Jungmann, and S. Siegmund, "Modeling and analysis of integrated pest control strategies via impulsive differential equations," *International Journal of Differential Equations*, vol. 2017, Article ID 1820607, 18 pages, 2017.

[31] A. K. Misra, N. Jha, and R. Patel, "Modeling the effects of insects and insecticides with external efforts on agricultural crops," *Differential Equations and Dynamical Systems*, vol. 28, pp. 1–18, 2020.

[32] A. K. Misra, N. Jha, and R. Patel, "Modeling the effects of insects and insecticides on agricultural crops with NSFD method," *Journal of Applied Mathematics and Computing*, vol. 63, no. 1-2, pp. 197–215, 2020.

[33] J. Roffey and J. I. Magor, "Desert locust popualation dynamics parameters," Technical Series-Desert Locust Field Reserch Stations (FAO), 2003.

[34] L. Watch, "How much food can a desert locust eat?," 2021, http://www.fao.org/ag/locusts/en/info/info/faq/index.html.

[35] P. M. Davey, "Quantities of food eaten by the desert locust, *Schistocerca gregaria* (Forsk.), in relation to growth," *Bulletin of Entomological Research*, vol. 45, no. 3, pp. 539–551, 1954.

[36] H. Ritchie and M. Roser, "Crop yields, Our World in Data," 2013, https://ourworldindata.org/crop-yields.

[37] J. T. Ritchie, U. Singh, D. Godwin, and W. T. Bowen, "Cereal growth, development and yield," in *Understanding Options for Agricultural Production*, G. Y. Tsuji, G. Hoogenboom, and P. K. Thornton, Eds., pp. 79–98, Springer, Dordrecht, 1998.

[38] H. M. Dobson, *Desert Locust Guidelines: Control*, FAO: Rome, 2001.