1. Introduction

A solitarious Desert Locust (*Schistocerca gregaria*) is the most devastating migratory pest in the world. The Desert Locust persists as the principal threat to food security in the infested region and beyond. In the inadequacy of reliable and efficient prevention and control measures, strategies for controlling and mitigating the trouble of the Desert Locust are focused on non-risk-free interventions such as chemical pesticides. We formulated and analyzed a mathematical model to assess the impact of this devastating pest on crop production. The theoretical analysis of the model shows that the trivial and locust free equilibriums are unstable, whereas interior equilibrium is asymptotically stable if crop growth rate $r$ is greater than a maturity rate $\sigma$. Numerical simulations of the model using the baseline parametric values are consistent with theoretical analysis. The conventional scenario projections for crop production (based on the baseline levels of anti-Desert Locust interventions considered in the study) increase by 70.44% (2663.26 kg per hectare) if the low depletion pesticide measures performed are maintained proportionally with locust population. This study notes that high-level depletion of the chemical pesticide spray measures could lead to devastating crop losses (similar to those projections before the onset of the pesticide spray) and severe human health and environmental risks. At a baseline harvesting coverage could shelter 44.43 kg to 1176.82 kg per hectare of mature crops. Combining early harvesting and low depletion chemical pesticide with ultra-low volume (ULV) spray devices and formulation could mitigate and eliminate Desert Locust infestation.

The serious Desert Locust infestation in decades is begun in East Africa since July 2019. This is the most harmful aggression in over 25 years in Ethiopia and Somalia, and the gravest witnessed in over 70 years in Kenya [2, 5]. The latest updates from the Food and Agriculture Organization of the United Nations (FAO) show that a substantial Desert Locust upsurge is currently advancing in the same region [6]. The Food Security and Nutrition Working Group (FSNWG) conduct a regional Desert Locust impact evaluation revealed that nearly 42% – 69% of crop production are losses in the fragile areas [7, 8]. The continued measures are not practiced, to control the invasion in East African countries, the pest will spread to other parts of the world. FAO begins control strategies to reduce food security and livelihoods crisis. It mitigates the further spread of the pest to other susceptible countries. Control measure needs large-scale aerial and ground pest handle operations, monitoring, trajectory forecasting, and data gathering endeavors. Hopper bands and adult swarms stage of the Desert Locust can cause significant deterioration to vegetation and crops in the infested areas. Therefore, to prevent catastrophic swarms from maturing hop pers, it is critical to strengthen ground and...
aerial surveillance efforts [9]. It is supporting to identify potential breeding sites for timely and effective management of hopper bands. During the hopper stages, ground controls are cost-effective. Once locusts reach adult stage, aerial control operations will be employed [10, 11, 12].

After 1980, applying of standard pesticides sprayed directly onto hopper bands and swarms has been the principal control strategy [13, 14, 15]. However, they are very toxic and pose acute risks to human health, and the environment [16]. Minimizing both side risks balancing Desert Locust population with pesticides sprayed is fundamental [17, 18]. Nowadays, Ultra-Low Volume (ULV) spray equipment and formulation are emerged. ULV formulations are oil-based, reducing droplet evaporation such that only 0.5 – 1.0 L of the pesticide is required per hectare, decreasing environmental contamination and costs of transportation, handling, and storage [19, 20, 21, 22].

The current size of the Desert Locust invasion in East Africa is unique and thought to be the most damaging outbreak for the past 100 years [23]. Various strategies are implementing to control the Desert Locust infestation and conquer crop production losses [24]. A machine-learning algorithm prediction manifested that enormous areas of the region are at tremendous risk of providing a favorable breeding situation for the Desert Locust. This result implied strengthen ground monitoring to control the pest in a timely, cost-effective, and environmentally friendly manner [9]. Model-based forecasting of the location of Locust swarms can help people get ready and tackle the infestation issue more effectively [25]. The efficacy of Integrated Pest Management (IPM) optimal control methods in reducing environmental contamination and costs of transportation, handling, and storage [19, 20, 21, 22].

2. Model description

We develop and analyze a mathematical model to assess the impact of Desert Locust outbreak on crop production. The model incorporates a couple of interventions reasonably implemented to curtail Desert Locust invasion, is formulated based on scaling the total crop biomass at time \( t \) into the mutually-exclusive class Premature crop \( C(t) \) and Mature crop \( M(t) \), Pesticides amount \( P(t) \), and the Locust population \( L(t) \). All stages of crop biomass are not appropriate for the harvest process. Here for this, we have taken stage-structured crop biomass via premature and mature crops. To formulate our mathematical model, we set the following assumptions:

1. Considering stage-structure crop biomass, it is divided in two class: one is Premature \( C \) and other Mature \( M \).
2. Due to the limited size of the crop field, Premature crops grow logistically with a fixed growth rate \( r \) and carrying capacity \( K \).
3. The premature crop becomes mature by the rate of \( \sigma (1/\sigma \) is the maturity period of crops). We consider mature crops also obey logistic growth over the same carrying capacity \( K \). It is harvested at a rate of \( E_h \), where \( E \) denotes the harvesting effort. The maturity rate \( \sigma \) is less than the growth rate \( r (r > \sigma) \).
4. We consider Locust attacks the crop at the rate \( \beta \), which reduces crop production. Due to this consumption of crops by locusts, the density of locust population increases at a rate \( \xi \beta \), where \( \xi \) represents the conversion efficiency of locusts. It is reduced by the rate of \( \mu \) due to intra-specific competition.

5. Standard Operating Procedures (SOP) for Desert Locust ground and aerial control guidelines provide concise instructions for conventional pesticide application against the Desert Locust. ULV spraying uses small amounts of concentrated pesticide. The calibration of pesticide is adjusted proportionally to suspected biomass of Desert Locust in the range of 0.5 – 1.0 liter/hectare [39, 40]. We consider pesticide spray is proportional to the density of locust population at the rate \( \theta \). The parameter \( \theta \) stands for the depletion of pesticides \( (\theta_0 < \theta) \).

6. The locust population is decreasing due to pesticide uptake at a rate of \( \psi \), where the parameter \( \psi \) represents proportionality constant.

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

\[
\begin{align*}
\frac{dC}{dt} &= \alpha C \left( 1 - \frac{C + M}{K} \right) - \sigma C - \beta CL \\
\frac{dM}{dt} &= \alpha C \left( 1 - \frac{C + M}{K} \right) - \delta ML - \beta ML \\
\frac{dL}{dt} &= \xi \beta (M + C)\ell - \psi \ell P - \mu L \\
\frac{dP}{dt} &= 0L - \theta_0 P
\end{align*}
\]

and the initial conditions are given as

\[\begin{align*}
C(0), M(0), L(0), \text{ and } P(0) \geq 0.
\end{align*}\]

2.1. Baseline values of model parameters

We estimate the baseline parameters of the model from available FAO Desert Locust data and sources from the published literature. Days to first harvest of major agricultural corps is estimated to range from 60 – 140 days [41]. We consider an average maturity period (taken from these ranges) of 100 days, so that \( \sigma = 1/100 \) per day. A Desert Locust adult can consume roughly its own weight in fresh food per day, that is about two grams every day [40, 42]. We set the consumption rate of Desert Locust \( \beta = 0.002kg \) per day. There can be at least 40 million and sometimes as many as 80 million locust adults in each square kilometer of swarm [42]. We consider 40 million locust adults in each square kilometre of swarm or 400,000 locust adults per hectare. Ultra low volume (ULV) spraying uses 0.5 – 1.0 litre/hectare pesticides for locust control [11, 40]. We consider 1000 milliliter pesticides per hectare for effective Desert Locust control. Therefore, we estimate the spray rate \( \theta \), to be \( \theta = \frac{1000 \text{mL/hectare}}{0.0025 \text{kg/hectare}} = 0.0025 \text{ mL per locust} \). We consider total sprayed pesticides are equivalent to the sums of uptakes and depleted. Therefore, the uptake rate of pesticides per locust \( \gamma \), to be estimate as \( \gamma = \theta - \theta_0 = 0.0025 - 0.00025 = 0.00225 \text{ mL per locust} \). Direct ULV formulation chemical pesticides spray on hopper bands and settled swarm consider to be caused 80% mortality of Desert Locust [43]. Following, the numbers of Desert Locust deceased \( \varphi \), due to a milliliter of pesticide, to be \( \varphi = \frac{400000 \text{locust/hectare}}{1000 \text{mL/hectare}} \times 0.8 = 320 \text{ Locust per milliliter} \).

3. Equilibria and stability analysis

3.1. Existence of equilibria

Now, the feasible non-negative equilibria of the system (1) are stating below:
1. The trivial equilibrium $E_0(0, 0, 0, 0)$ always exist.

2. The locust-free equilibrium $E_1(\frac{\beta K(r - \sigma)}{\beta r + \sigma r + \mu r}, \frac{K\theta}{r(\beta r + \sigma r + \mu r)} - 0)$. 

3. The model system exhibits a coexistence equilibrium $E_2(C^*, M^*, L^*, \beta L')$. By setting $\frac{dC}{dt} = \frac{dM}{dt} = \frac{dL}{dt} = \frac{d\beta L'}{dt} = 0$, we have the following system.

$$r \left(1 - \frac{C + M}{K} \right) - \sigma - \beta L = 0$$

(3)

$$\sigma C \left(1 - \frac{C + M}{K} \right) - hEM - \beta ML = 0$$

(4)

$$\xi \beta (M + C) - \phi \gamma P - \mu L = 0$$

(5)

$$0L - \theta_0 P = 0$$

(6)

From Eq. (3) we obtain

$$C + M = \frac{K}{r}(r - \sigma - \beta L).$$

(7)

Now, from Eqs. (5), (6), and (7) we obtain

$$L^* = \frac{\beta_0 K\xi (r - \sigma)}{\beta^2 \theta_0 K^2 \xi + \gamma \phi \gamma + \theta_0 \mu r}$$

And substituting the value of $L^*$ in Eq. (6) and we obtain

$$P^* = \frac{\beta_0 K\xi (r - \sigma)}{\beta^2 \theta_0 K^2 \xi + \gamma \phi \gamma + \theta_0 \mu r}$$

From Eqs. (3) and (4) we get

$$C^* = \frac{K(r - \sigma)(\gamma \phi \gamma + \theta_0 \mu r)(\beta^2 \theta_0 K^2 \xi + \gamma \phi \gamma + \phi \gamma + \theta_0 \mu r) + \beta^2 \theta_0 K^2 \xi (r - \sigma))}{(\beta^2 \theta_0 K^2 \xi + \gamma \phi \gamma + \theta_0 \mu r)(\gamma \phi \gamma + \theta_0 \mu r + \beta^2 \theta_0 K^2 \xi)}$$

$$M^* = \frac{K\sigma(r - \sigma)(\theta_0 \mu r + \gamma \phi \gamma + \phi \gamma + \theta_0 \mu r + \beta^2 \theta_0 K^2 \xi)}{(\beta^2 \theta_0 K^2 \xi + \gamma \phi \gamma + \theta_0 \mu r)(\gamma \phi \gamma + \theta_0 \mu r + \beta^2 \theta_0 K^2 \xi)}$$

The coexistence equilibrium point $E_2$ of system (1) exist if $r > \sigma$.

3.2. Stability analysis

The stability of trivial, locust-free, and coexistence equilibriums are investigating using the sign of eigenvalues of the Jacobian matrix $J$. The eigenvalues of a matrix $J$ are evaluating at the corresponding equilibrium point.

The Jacobian matrix $J$ for the dynamic system (1) is obtaining as follows:

$$J = \begin{pmatrix}
-A_1 & -A_2 & -A_3 & 0 \\
-A_4 & -A_5 & -A_6 & 0 \\
A_7 & A_7 & -A_8 & -A_9 \\
0 & 0 & \theta & -\theta_0
\end{pmatrix}$$

(8)

where

$$A_1 = \frac{r(2C + M)}{K} + \beta L + \sigma - r, A_2 = \frac{rC}{K}, A_3 = \beta C,$$

$$A_4 = \sigma(2C + M - K), A_5 = \frac{EhK + rC + \beta KL}{K}, A_6 = \beta M,$$

$$A_7 = \beta_2 L, A_8 = 2\mu L + \gamma \phi P - \beta \xi (C + M), A_9 = \gamma \phi L.$$
The local stability of coexistence equilibrium $E_2(C', M', L', P')$ is investigated by applying the Routh-Hurwitz criterion on (10). The relevant Routh-Hurwitz determinants are:

$$
\begin{align*}
\Delta_1 &= C_1 > 0, \\
\Delta_2 &= C_1C_2 - C_0 > 0, \\
\Delta_3 &= C_1C_2 - C_0 > 0, \\
\Delta_4 &= C_1C_3 > 0.
\end{align*}
$$

This leads to the following theorem about the stability of the coexistence equilibrium in model (1).

**Theorem 3.** The coexistence equilibrium $E_2$ of system (1) is locally asymptotically stable if $r > \sigma$ and $2\mu L^* + \gamma P^* > \beta\gamma (C' + M')$.

**Proof.** According to the model assumptions all parameters of the model (1) are positive. Moreover, from the above derivation, the coexistence equilibrium $E_2(C', M', L', P')$ state variables also positive if $r > \sigma$, it follows that $A_1 > 0, A_2 > 0, A_3 > 0, A_4 > 0, A_5 > 0, A_6 > 0, A_7 > 0, A_8 > 0, A_9 > 0, C_0 > 0, C_1 > 0, C_2 > 0, \Delta_2 > 0$, and $\Delta_3 > 0$, whenever $2\mu L^* + \gamma P^* > \beta\gamma (C' + M')$. Furthermore, it is clear that $\Delta_4 > 0$. Hence, $E_2(C', M', L', P')$ is locally asymptotically stable.

### 4. Numerical results and discussions

In this section, we have simulated the model (1) using the baseline parameter values tabulated in Table 1 (unless otherwise stated) to validate theoretical results and assess the effectiveness of control strategies against the infestation of Desert Locust in the agricultural area. Numerical simulation are conducted using MATLAB software with ode 45 solver.

#### 4.1. General dynamics

The model equilibrium points stability is justifying 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 $\lambda_1 = 0.19, \lambda_2 = -0.1, \lambda_3 = 0$, 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, and it is consistent with Theorem (1). Similarly, we found the corresponding eigenvalues of locust free equilibrium point $(E_1 = (3781.09, 18.9055, 0, 0))$, $\lambda_1 = 4.56, \lambda_2 = -0.303805, \lambda_3 = -0.174305$, 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 $(E_2 = (C', M', L', P') = (3754.04, 20.8627, 0.62708, 0.27408))$.

The time series evaluation of system (1) with varying initial values shown in Figure 1. All solution trajectories eventually become steady to the interior equilibrium point $E_2$. We obtain the corresponding eigenvalues $\lambda_1 = -0.299985$, $\lambda_2 = -0.136865$, $\lambda_3 = -0.0263035 + 0.0277148i$, and $\lambda_4 = -0.0263035 - 0.0277148i$. Our result shows that all eigenvalues are negatives or negative real parts this implies that $E_2$ is stable. This numerical result is consistent with Theorem 3.

#### 4.2. Impact of intervention measures

According to FAO report, a Desert Locust adult can consume approximately its weight in fresh food per day, that is about two grams every day. Here, we observe that the impact of attacking rate ($\beta$) in the absence of intervention measures ($\theta = \theta_1 = \gamma = h = 0$), and the other parameters in Table 1 with various values of $\beta$.

The simulation results obtain, depicted in Figure 2, shows a projected 3,809.5 kg per hectare crop productions gain from the agricultural land in the absence of Desert Locust attack. However, crop production declines if the locust attack increases. Our model simulation in Figure 2, shows that we obtain 1,117.65 kg out of 3,809.5 kg crop production per

### Table 1. Model parameter baseline values.

| Parameter | Biological Meaning | Value | Source |
|-----------|--------------------|-------|--------|
| $R$       | Growth rate of crop biomass | 0.2 kg/day$^{-1}$ | [34] |
| $K$       | Maximum density of crop biomass | 4000 kg/ha | Estimated [41] |
| $\sigma$  | Crop maturity rate | 0.01 day$^{-1}$ | Estimated [41] |
| $\beta$   | Attack rate of locust | 0.002 kg/locust day$^{-1}$ | Estimated [40, 42] |
| $\mu$     | Intra-specific competition mortality rate | 0.02 day$^{-1}$ | [34] |
| $\xi$     | Conversion efficiency | 0.6 day$^{-1}$ | [38] |
| $\theta$  | Pesticide spray rate | 0.0025 mL/locust$^{-1}$ | Estimated [11, 40] |
| $\theta_1$| Depletion rate of pesticides | 0.00025 mL/locust$^{-1}$ | Estimated [11, 40] |
| $\gamma$  | Uptake rate of pesticides by Locust | 0.00025 mL/locust$^{-1}$ | Estimated [11, 40] |
| $h$       | Harvesting rates of mature crop | 0.1 day$^{-1}$ | Assumed |
| $\phi$    | Depletion of locust due to pesticides | 320 locust mL$^{-1}$ | Estimated [40, 43] |
| $E$       | Harvesting effort | 1 kg | Assumed |
hectare at the baseline value $\beta = 0.002$. The result noted that if appropriate and early intervention measures are not implemented, major crop productions are lost (more than 70% crops).

Desert Locust upsurge can cause significant and widespread crop losses. Food security, industrial row material, and export earning may also be severe threats 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. At present, the primary intervention of controlling Desert Locust swarms and hopper bands is with mainly chemical pesticides applied in small concentrated doses (referred to as ultra-low volume (ULV) formulation) by vehicle-mounted and aerial sprayers and to a lesser extent by a knapsack and hand-held sprayers. The effect of pesticide is evaluating by simulating the model (1) using the baseline parameter values and various levels of spray rate $\theta$ in the absence of harvesting.

The results obtained, depicted in Figure 3, shows that spray of pesticide has a significant impact in conquering massive losses of crop production. In particular, at the baseline value of spray rate ($\theta = 0.0025$), the crop production reach to 3780.89 kg per hectare. However, in the absence of pesticide spray ($\theta = 0$), the crop production quickly declines to 1117.64 kg per hectare. The simulation result obtained, depicted in Figure 4, shows that in the absence of intervention, locust population sovereign over the area, whereas if baseline intervention of pesticide applies, the locust population eliminates from the infested areas. Our model projected result shows that 0.0025 mL per hectare pesticides spray with 10% depletion preserves 70.44% (2663.26 kg per hectare) of crop losses.

A large amount of pesticide depletion provides acute human health and environmental hazards. The selection and use of appropriate spray equipment play an essential role in safe and efficient pesticide use. In particular, the Desert Locust controlling method uses ultra-low volume (ULV) equipment and formulation. ULV formulation reduces droplet evaporation of the pesticide, decreasing environmental contamination and costs of transportation handling and storage. The effect of pesticide depletion is evaluated by simulating the model (1) using the baseline parameter values and various levels of depletion rate $\theta_0 (0 \leq \theta_0 \leq \theta = 0.0025)$.

The results obtained, depicted in Figure 5 and Figure 6, shows that pesticide depletion has a significant effect on crop production and Desert Locust population, respectively. In particular, in Figure 5, in the absence of pesticide depletion ($\theta_0 = 0$), the crop biomass reaches 3809.5 kg per hectare. However, the model projection shows at the maximum depletion rate ($\theta_0 = 0.0025$), crop production reduces to 1117.63 kg per hectare. Figure 6, shows that if the depletion rate approaches zero, then Desert
Locust population eliminated from the infested areas. Our result gives a deep insight that the elimination of pesticide depletion reduces human health and environmental hazards.

To examine the desirable impact of early harvesting, within and without pesticides spray using parameter value in Table 1, and by varying the value of $h$.

The results obtained, depicted in Figure 7 and Figure 8, shows that early harvesting reduces the vulnerability of mature crops. In particular, Figure 7, shows that in the absence of pesticides ($\theta = \theta_0 = \gamma = 0$), 44.43 kg per hectare crops are sheltering from Desert Locust attack by 50% mature crop harvesting coverage. Furthermore, the impact of harvesting at the baseline values depicted in Figure 8, shows that the intervention shelters 1176.82 kg of crop per hectare. Our results show that combine implementation of both intervention measures provides a better result.

5. Conclusion

The Desert Locust has been recognized as the most devastating migratory pest in the world. Since 2019, swarms of Desert Locusts are threatening vast regions of pastures and crops, overwhelming countries in the Horn of Africa, the Middle East, and South Asia. The UN Food and Agriculture Organization (FAO) states these swarms describe the most dangerous infestation in 25 years in Ethiopia and Somalia, in 26 years in India, and the worst in 70 years in Kenya. Desert Locust aggression can cause significant and extensive agricultural crop losses. The upsurge of this devastating pest is the principal threat to food security, industrial raw materials, and export incomes in the affected areas. Locust swarms can deviate from less than one square kilometer to numerous hundred square kilometers. There can be at least 40 million and sometimes as many as 80 million locust adults in each square kilometer of a swarm. A Desert Locust adult can consume approximately its weight in fresh food per day, that is about two grams every day. A 1 km$^2$ size swarm eats the same quantity of food in one day as about 6 elephants or 20 camels or 35,000 people. Nowadays, no reliable and adequate prevention and control tactics against Desert Locust. The struggle against Desert Locust is not without risk. Consequently, control and mitigation efforts against desert locusts are limited to chemical pesticide intervention. This study is based on the scheme, analysis, and simulations of a new mathematical model for providing more profound insights toward the dynamical consequence and control of desert locusts in the overwhelmed areas.

Extensive numerical simulations were conducted to assess the impact of proposed intervention strategies. With the baseline levels of a couple of intervention strategies considered (pesticides and early harvesting),
the crop biomass projected to observe asymptotically steady to the interior equilibrium ($E_2$). As a result of our model projections, we obtained 3774.9 kg per hectare crops at the baseline parameter values. However, in the absence of intervention measures, we lost 70.4% of expected crops per hectare. The rapid implementation of pesticide spraying measures (during the early stage of the outbreak), sustained over an inherent coverage, will undoubtedly effectively contend the effect of Desert Locust aggression. High depletion of chemical pesticides measures will recruit catastrophic human health and environmentally hazardous and absolute crop losses. For example, our study notes that measures will recruit catastrophic human health and environmentally hazardous crop losses. For example, our study notes that the pre-pesticides time in the affected areas. In particular, up to 70.66%, crop production losses will have been recorded in the infested area if the conventional and low depleted pesticide interventions were not implemented. Eliminate pesticide depletion by ultra-low volume (ULV) spray devices, and formulation significantly declines the likelihood of locust devastation. Early harvesting shelters the sustainability of mature crops. Our study shows that early harvesting protects 44.43 kg per hectare and 1176.83 kg per hectare of crop production in the absence and within intervention of baseline chemical pesticide, respectively.

In summary, our study recommends that Desert Locust infestation be controllable using adequate prevention and control interventions. In particular, ULV based pesticide spray and early harvesting of mature crops (when implemented in combinations) eradicated the pest. The factors that are critically crucial to the advance of the anti-locust control campaign are the early implementation (and improvement of effectiveness) of these intervention measures and ensuring null depletion of chemical pesticides.

Declarations

Author contribution statement

D. K. Mamo, D. S. Bedane: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Additional information

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