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Research article

Modelling the effect of desert locust infestation on crop production with intervention measures

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ABSTRACT

The Desert Locust, *Schistocerca gregaria(Forskål),* 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 σ 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 $44.43kg$ to $1176.82kg$ 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.

1. Introduction

A solitarious Desert Locust *(Schistocerca gregaria)* is the most devastating one of all locust species, because of the ability of swarms to fly rapidly across great distances and easily affect high coverage of an agricultural land [1]. In response to favourable ecological conditions, dense and highly mobile Desert Locust swarms can form [2]. According to the Food and Agriculture Organization of the United Nations (FAO), Desert Locust crisis report a single adult Desert Locust can consume their own weight per day and a typical swarm can be made up of 150 million locusts per square kilometer and is carried on the wind, up to 150 km in one day, with the capacity to consume the same amount of food in one day as $35,000$ people. The Desert Locust upsurge could have posed an unprecedented consequence, potentially causing large-scale crop damage and threatening food security. The Desert Locust invasions, known for thousands of years, can follow one another at a high frequency if no control measures are taken. The recession periods are generally short whereas the invasions can last for one decade or more [3, 4].

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

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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 various approaches are tested by mathematical model-based studies [26, 27, 28, 29, 30]. Coupling models of insect pests and disease are analyzed and estimate yield loss and the advancement of support capabilities to schedule scouting or pesticide applications [31, 32, 33]. To investigate the role of the awareness program in the control of insect pests, mathematical models are implied [34, 35, 36]. A dynamic model to analyzing the effects of insects and insecticides on crops has recently developed [37, 38].

In this study, we develop a computational model, which assesses the impacts of prevention and control measures on Desert Locust infestation. Because of their maturity, we divide the crop biomass into two groups for early harvesting prevention strategies. We considered the harvesting of crops implemented on mature crops. Pesticide spray-on hopper and swarms are also one of the intervention measures to mitigate Desert Locust infestation. Mass usage of pesticides is not advisable from public health, environmental, and economic perspective, so it must be low depletion and proportional to the Desert Locust population.

2. Model description

We develop and analyze a mathematical model to assess the impact of the 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 σ($1/\sigma$ 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 Eh, where E denotes the harvesting effort. The maturity rate σ is less than the growth rate r ($r > \sigma$).
4. We consider Locust attacks the crop at the rate β, which reduces crop production. Due to this consumption of crops by locusts, the density of 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 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 θ. The parameter θ_0 stands for the depletion of pesticides ($\theta_0 \leq \theta$).
6. The locust population is decreasing due to pesticide uptake at a rate of $\varphi\gamma$, where the parameter φ represents proportionality constant.

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

$$\begin{aligned}
\frac{dC}{dt} &= rC\left(1-\frac{C+M}{K}\right) - \sigma C - \beta CL \\
\frac{dM}{dt} &= \sigma C\left(1-\frac{C+M}{K}\right) - hEM - \beta ML \\
\frac{dL}{dt} &= \xi\beta(M+C)L - \varphi\gamma PL - \mu L^2 \\
\frac{dP}{dt} &= \theta L - \theta_0 P
\end{aligned} \tag{1}$$

and the initial conditions are given as

$$C(0), M(0), L(0), \text{and } P(0) \geq 0. \tag{2}$$

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 $\beta = 0.002$kg per day. There can be at least 40 million and sometimes as many as 80 million locust adults in each square kilometre 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 (θ), to be $\theta = \frac{1000\text{mL/hectare}}{400000\text{Locust/hectare}} = 0.0025$ mL pesticides per locust. Following, we set 10% pesticides depletion, and we estimate the depletion rate (θ_0), to be $\theta_0 = \theta \times 0.1 = 0.00025$ 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 (γ), to be estimate as $\gamma \approx \theta - \theta_0 = 0.0025 - 0.00025 = 0.00225$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 (φ), due to a milliliter of pesticide, to be $\varphi = \frac{400000\text{Locust/hectare}}{1000\text{mL/hectare}} \times 0.8 = 320$ 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 $E_1\left(\frac{EhK(r-\sigma)}{Ehr+\sigma^2}, \frac{K\sigma^2(r-\sigma)}{r(Ehr+\sigma^2)}, 0, 0\right)$.
3. The model system exhibits a coexistence equilibrium $E_2(C^*, M^*, L^*, P^*)$. By setting $\frac{dC}{dt} = \frac{dM}{dt} = \frac{dL}{dt} = \frac{dP}{dt} = 0$, we have the following system.

$$r\left(1-\frac{C+M}{K}\right)-\sigma-\beta L=0 \tag{3}$$

$$\sigma C\left(1-\frac{C+M}{K}\right)-hEM-\beta ML=0 \tag{4}$$

$$\xi\beta(M+C)-\varphi\gamma P-\mu L=0 \tag{5}$$

$$\theta L-\theta_0 P=0 \tag{6}$$

From Eq. (3) we obtain

$$C+M=\frac{K}{r}(r-\sigma-\beta L). \tag{7}$$

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

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

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

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

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

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

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

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:

$$J=\begin{pmatrix} -A_1 & -A_2 & -A_3 & 0 \\ -A_4 & -A_5 & -A_5 & 0 \\ A_7 & A_7 & -A_8 & -A_9 \\ 0 & 0 & \theta & -\theta_0 \end{pmatrix}. \tag{8}$$

where

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

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

$$A_7=\beta\xi L, A_8=2\mu L+\gamma\varphi P-\beta\xi(C+M), A_9=\gamma\varphi L.$$

3.2.1. Stability of trivial and locust free equilibria

Theorem 1. *The trivial equilibrium, $E_0(0,0,0,0)$, is always unstable if $r > \sigma$.*

Proof. The evaluation of the Jacobian matrix at E_0 is

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

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

Theorem 2. The Locust-free equilibrium, E_1, is unstable if $r > \sigma$.

Proof. The Jacobian matrix at $E_1\left(\frac{EhK(r-\sigma)}{Ehr+\sigma^2}, \frac{K\sigma^2(r-\sigma)}{r(Ehr+\sigma^2)}, 0, 0\right)$ is

$$J(E_1)=\begin{pmatrix} \frac{Ehr(\sigma-r)}{Ehr+\sigma^2} & -\frac{Ehr(r-\sigma)}{\sigma^2+Ehr} & -\frac{EhK\beta(r-\sigma)}{\sigma^2+Ehr} & 0 \\ \frac{\sigma^4-Ehr\sigma(r-2\sigma)}{r(Ehr+\sigma^2)} & -Eh-\frac{Er(r-\sigma)h}{\sigma^2+Ehr} & \frac{\beta K\xi(r-\sigma)}{r} & 0 \\ 0 & 0 & \frac{\beta K\xi(r-\sigma)}{r} & 0 \\ 0 & 0 & \theta & -\theta_0 \end{pmatrix}$$

Following some algebraic calculation, we obtain the eigenvalues $\lambda_1 = \frac{\beta k\xi(r-\sigma)}{r}$ and $\lambda_2 = -\theta_0$. The remaining eigenvalues are obtained from the polynomial

$$\lambda^2+a_1\lambda+a_2=0 \tag{9}$$

where,

$$a_1=\frac{Eh(Ehr+r^2+(r-\sigma)^2)}{Ehr+\sigma^2},$$

$$a_2=\frac{Eh(r-\sigma)\left(E^2h^2r^2+Ehr((r-\sigma)^2+2\sigma^2)+\sigma^4\right)}{(Ehr+\sigma^2)^2}.$$

The characteristics polynomial (9) coefficients a_1 and a_2 are greater than zero. So, by Routh-Hurwitz criterion, the eigenvalues λ_3 and λ_4 are negative or negative real part.

Therefore, the eigenvalue λ_1 of the Jacobian matrix (8) at E_1 is grater than zero, this implies that the equilibrium point E_1 of the system (1) is unstable if $r > \sigma$.

3.2.2. Stability of coexistence equilibrium

Evaluating the Jacobian matrix of the system (1) at the coexistence equilibrium point $E_2(C^*, M^*, L^*, P^*)$ gives,

$$J(E_2)=\begin{pmatrix} -A_1 & -A_2 & -A_3 & 0 \\ -A_4 & -A_5 & -A_6 & 0 \\ A_7 & A_7 & -A_8 & -A_9 \\ 0 & 0 & \theta & -\theta_0 \end{pmatrix},$$

where

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

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

$$A_7 = \beta\xi L^*, A_8 = 2\mu L^* + \gamma\varphi P^* - \beta\xi(C^* + M^*), A_9 = \gamma\varphi L^*.$$

The eigenvalues of $J(E_2)$ satisfy the polynomial

$$\lambda^4 + C_1\lambda^3 + C_2\lambda^2 + C_3\lambda + C_4 \tag{10}$$

where,

$$C_1 = A_1 + A_5 + A_8 - \theta_0,$$

$$C_2 = (\theta A_9 - \theta_0 A_8) + (A_1A_5 - A_2A_4) + A_7(A_3 + A_6) + (A_1 + A_5)(A_8 - \theta_0),$$

$$C_3 = (A_1 + A_5)(\theta A_9 - \theta_0 A_8) + (A_1A_5 - A_2A_4)(A_8 - \theta_0) + A_3A_7(A_5 - A_4)$$

$$+A_6A_7(A_1 - A_2) - \theta_0 A_7(A_3 + A_6),$$

$$C_4 = (\theta A_9 - \theta_0 A_8)(A_1A_5 - A_2A_4) + \theta_0 A_3 A_7(A_4 - A_5) + \theta_0 A_6 A_7(A_2 - A_1).$$

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:

$$\begin{cases} \Delta_1 = C_1 > 0, \\ \Delta_2 = C_1C_2 - C_3 > 0, \\ \Delta_3 = C_3\Delta_2 - C_1^2C_4 > 0, \\ \Delta_4 = C_4\Delta_3 > 0, \end{cases} \tag{11}$$

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* $2\mu L^* + \gamma\varphi P^* > \beta\xi(C^* + M^*)$.

Proof. According to the model assumption 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 $A_1 > 0, A_2 > 0, A_3 > 0, A_4 > 0, A_5 > 0, A_6 > 0, A_7 > 0, A_8 > 0, A_9 > 0$, $C_1 > 0$, $C_4 > 0$, $\Delta_2 > 0$, and $\Delta_3 > 0$, whenever $2\mu L^* + \gamma\varphi P^* > \beta\xi(C^* + M^*)$. 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 ($E_2 = (C^*, M^*, L^*, P^*) = (3754.04, 20.8637, 0.627408, 6.27408)$).

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 (β) in the absence of intervention measures ($\theta = \theta_0 = \gamma = h = 0$), and the other parameters in Table 1 with various values of β.

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 $kgday^{-1}$	[34]
K	Maximum density of crop biomass	4000$kghectare^{-1}$	Estimated [44]
σ	Crop maturity rate	0.01day^{-1}	Estimated [41]
β	Attack rate of locust	0.002$kglocust^{-1}day^{-1}$	Estimated [40, 42]
μ	Intra-specific competition mortality rate	0.02 day^{-1}	[34]
ξ	Conversion efficiency	0.6day^{-1}	[38]
θ	Pesticide spray rate	0.0025 mL locust^{-1}	Estimated [11, 40]
θ_o	Depletion rate of pesticides	0.00025 mL locust^{-1}	Estimated [11, 40]
γ_1	Uptake rate of pesticides by Locust	0.00025 mL locust^{-1}	Estimated [11, 40]
h	Harvesting rates of mature crop	0.1day^{-1}	Assumed
φ	Depletion of locust due to pesticides	320 locust mL^{-1}	Estimated [40, 43]
E	Harvesting effort	1 kg	Assumed

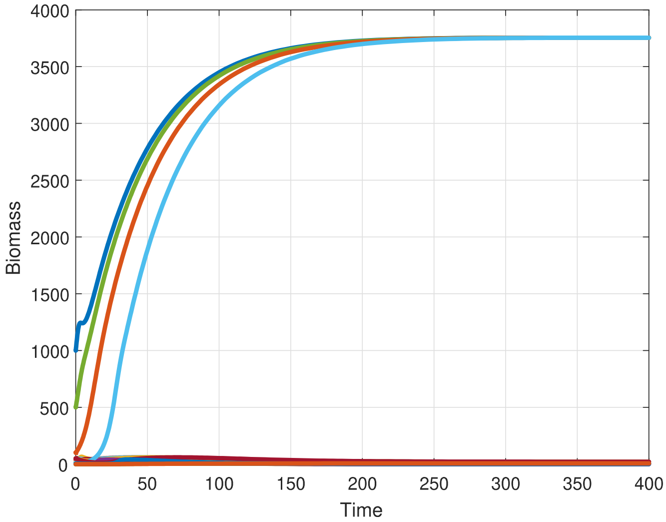

Figure 1. The dynamic stability ofE_2.

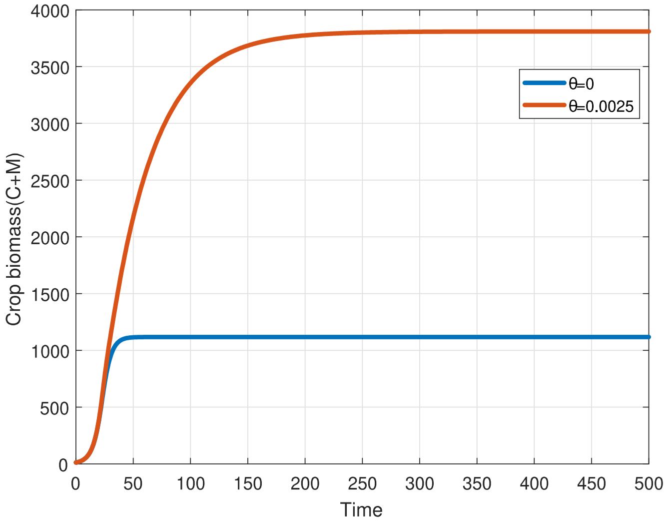

Figure 3. Pesticide effect on $C(t) + M(t)$.

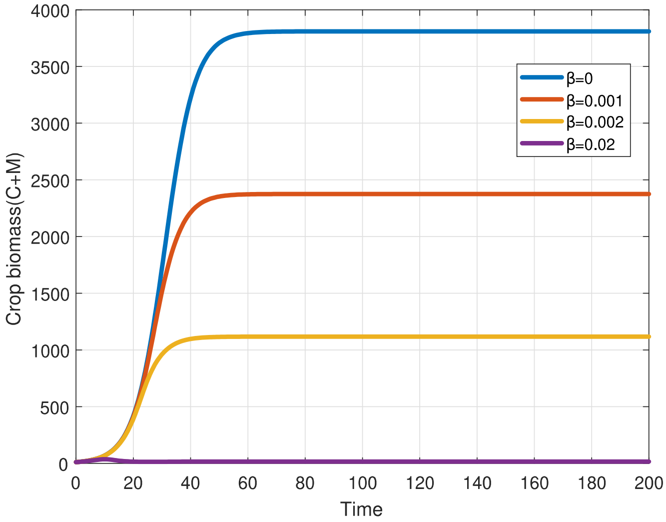

Figure 2. Effect of attack rate β.

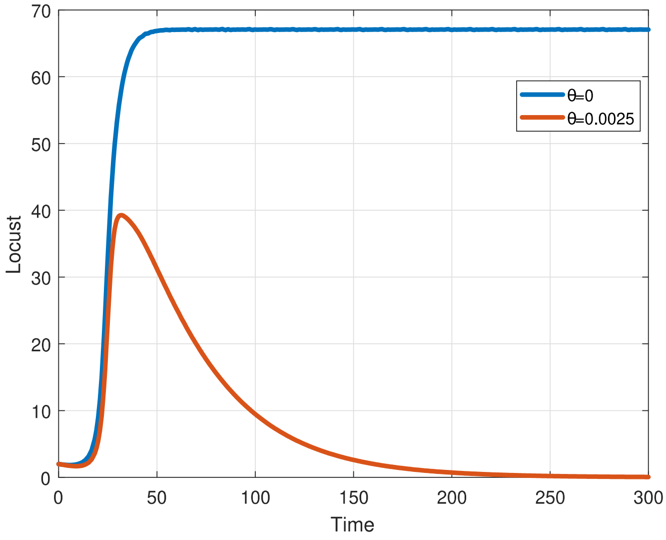

Figure 4. Pesticide effect on $L(t)$.

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 θ 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 0.0025mL per hectare pesticides spray with 10% depletion preserves 70.44%(2663.26 kg per hectare) of corp 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 $3,809.5$ 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

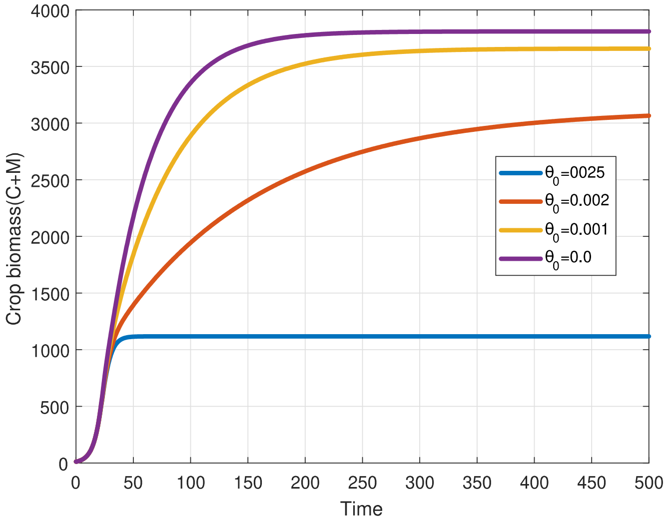

Figure 5. Depletion effect on crops.

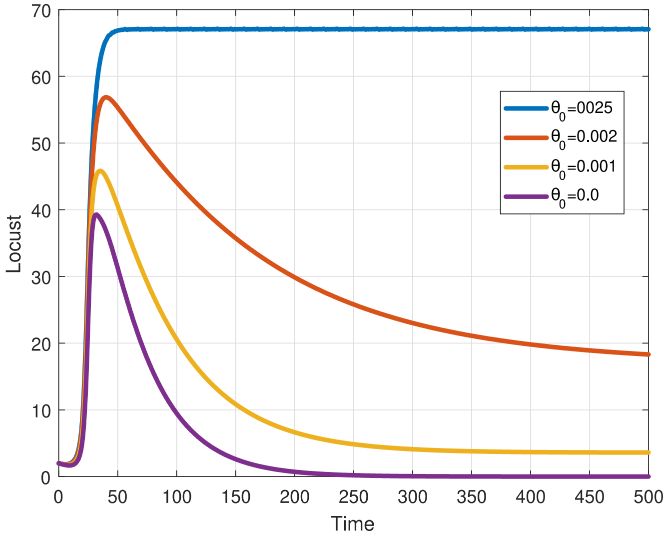

Figure 6. Depletion effect on $L(t)$.

Locust population eliminate 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),

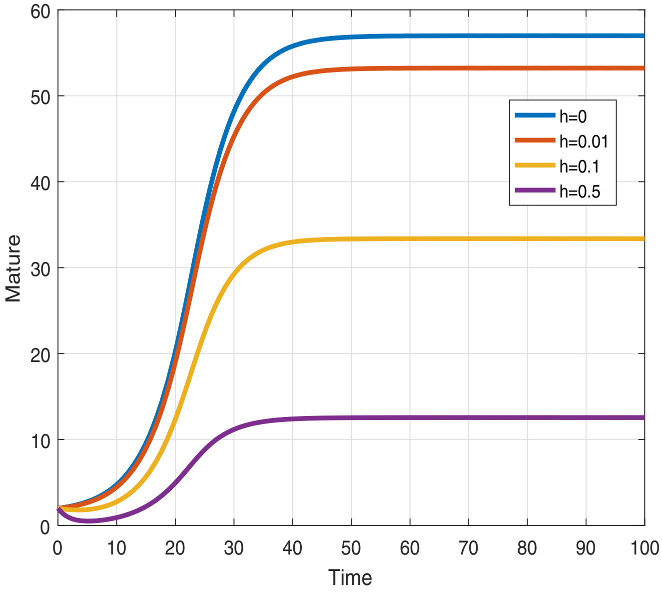

Figure 7. Harvesting effect if $\theta = 0$.

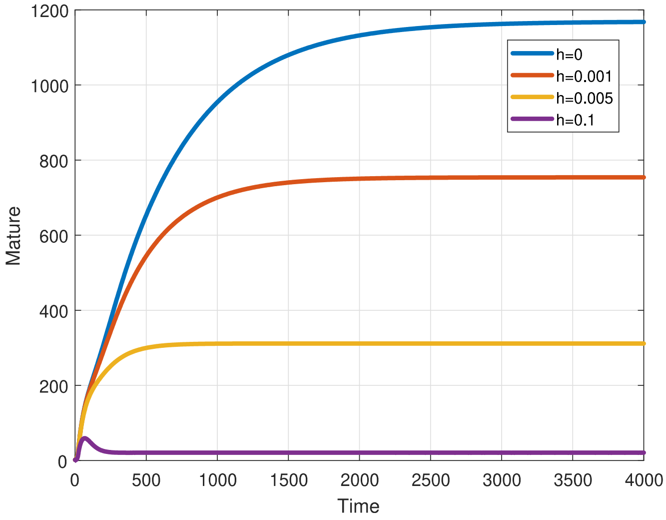

Figure 8. Harvesting effect if $\theta = 0.0025$.

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 using high depletion chemical pesticides will trigger devastating crop losses, causing Desert Locust impacts similar to those obtained during 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 are 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 susceptibility 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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No data was used for the research described in the article.

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] Stephen J. Simpson, Alan R. McCaffery, Bernd F. Hägele, A behavioural analysis of phase change in the desert locust, Biol. Rev. 74 (4) (1999) 461–480.

[2] Abubakr AM. Salih, Marta Baraibar, Kenneth Kemucie Mwangi, Guleid Artan, Climate change and locust outbreak in East Africa, Nat. Clim. Change 10 (7) (2020) 584–585.

[3] FAO, Desert Locust Crisis: Appeal for Rapid Response and Anticipatory Action in the Greater Horn of Africa (January (December 2020), 2020, http://www.fao.org/emergencies/resources/documents/resources-detail/en/c/1263633/.

[4] FAO, Desert Locust, 2020. http://www.fao.org/locusts/en/.

[5] Sharmila Devi, Locust swarms in east Africa could be “a catastrophe”, Lancet 395 (10224) (2020) 547.

[6] FAO, Latest Desert Locust Bulletin (no. 507, December 2020), 2020, http://www.fao.org/ag/locusts/common/ecg/562/en/DL507e.pdf.

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

[8] FSNWG, East Africa Regional Desert Locust Impact Monitoring - Round 2 (12 January 2021), 2021, https://reliefweb.int/report/ethiopia/east-africa-regional-desert-locust-impact-monitoring-round-2-12-january-2021.

[9] Kimathi, Emily, Henri EZ. Tonnang, Sevgan Subramanian, Keith Cressman, Elfatih M. Abdel-Rahman, Mehari Tesfayohannes, Saliou Niassy, et al., Prediction of breeding regions for the desert locust Schistocerca gregaria in East Africa, Sci. Rep. 10 (1) (2020) 1–10.

[10] David Dent, Richard H. Binks, Insect pest management, Cabi (2020).

[11] Hans M. Dobson, Desert Locust Guidelines: Control, 2001.

[12] J.I. Magor, Michel Lecoq, D.M. Hunter, Preventive control and Desert locust plagues, Crop Protect. 27 (12) (2008) 1527–1533.

[13] Allan T. Showler, Mohammed Abdallahi Ould Babah Ebbe, Michel Lecoq, Koutaro O. Maeno, Early intervention against desert locusts: current proactive approach and the prospect of sustainable outbreak prevention, Agronomy 11 (2) (2021) 312.

[14] Michel Lecoq, Recent progress in Desert and Migratory Locust management in Africa. Are preventative actions possible? J. Orthoptera Res. 10 (2) (2001) 277–291.

[15] Arnold Van Huis, Keith Cressman, Joyce I. Magor, Preventing desert locust plagues: optimizing management interventions, Entomol. Exp. Appl. 122 (3) (2007) 191–214.

[16] Lata Rani, Komal Thapa, Neha Kanojia, Neelam Sharma, Sukhbir Singh, Ajmer Singh Grewal, Arun Lal Srivastav, Jyotsna Kaushal, An extensive review on the consequences of chemical pesticides on human health and environment, J. Clean. Prod. (2020) 124657.

[17] Aktar, Md Wasim, Dwaipayan Sengupta, Ashim Chowdhury, Impact of pesticides use in agriculture: their benefits and hazards, Interdiscipl. Toxicol. 2 (1) (2009) 1.

[18] Harold Van der Valk, Riccardo Del Castello, Keith Cressman, Annie Monard, Helena Eriksson, Mohamed Ammati, Pietro Bartoleschi, Balthazar De Brouwer, Sophia Gazza, James Everts, Fighting the locusts... Safely. Pesticides in Desert Locust Control: Balancing Risks against Benefits, 2006.

[19] Anil Sharma, Locust control management: moving from traditional to new technologies-an empirical analysis, Entomol., Ornithol. Herpetol. 4 (1) (2015) 1.

[20] Allan T. Showler, Desert locust control: the effectiveness of proactive interventions and the goal of outbreak prevention, Am. Entomol. 65 (3) (2019) 180–191.

[21] Sory Cisse, Saïd Ghaout, Ahmed Mazih, Mohamed Abdallahi Ould Babah Ebbe, Ahmed Salem Benahi, Cyril Piou, Effect of vegetation on density thresholds of adult desert locust gregarization from survey data in Mauritania, Entomol. Exp. Appl. 149 (2) (2013) 159–165.

[22] Long Zhang, Michel Lecoq, Alexandre Latchininsky, David Hunter, Locust and grasshopper management, Annu. Rev. Entomol. 64 (2019) 15–34.

[23] Wanxi Peng, Nyuk Ling Ma, Dangquan Zhang, Quan Zhou, Xiaochen Yue, Shing Ching Khoo, Han Yang, et al., A review of historical and recent locust outbreaks: links to global warming, food security and mitigation strategies, Environ. Res. 191 (2020) 110046.

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

[25] Samil, Hadia Mohmmed Osman Ahmed, Annabelle Martin, Arnav Kumar Jain, Susan Amin, Samira Ebrahimi Kahou, Predicting Regional Locust Swarm Distribution with Recurrent Neural Networks, arXiv preprint arXiv:2011.14371, 2020.

[26] Xinzhu Meng, Zhitao Song, Lansun Chen, A new mathematical model for optimal control strategies of integrated pest management, J. Biol. Syst. 15 (2) (2007) 219–234.

[27] Baolin Kang, Mingfeng He, Bing Liu, Optimal control policies of pests for hybrid dynamical systems, Abstr. Appl. Anal. 2013 (2013). Hindawi.

[28] R. Bhattacharyya, B. Mukhopadhyay, Mathematical study of a pest control model incorporating sterile insect technique, Nat. Resour. Model. 27 (1) (2014) 61–79.

[29] Kenneth EF. Watt, Mathematical models for use in insect pest control, Mem. Entomol. Soc. Can. 93 (S19) (1961) 5–62.

[30] Roumen Anguelov, Claire Dufourd, Yves Dumont, Mathematical model for pest–insect control using mating disruption and trapping, Appl. Math. Model. 52 (2017) 437–457.

[31] Donatelli Marcello, Roger D. Magarey, Simone Bregaglio, L. Willocquet, Jérémy PM. Whish, Serge Savary, Modelling the impacts of pests and diseases on agricultural systems, Agric. Syst. 155 (2017) 213–224.

[32] Xia Wang, Youde Tao, Xinyu Song, Mathematical model for the control of a pest population with impulsive perturbations on diseased pest, Appl. Math. Model. 33 (7) (2009) 3099–3106.

[33] Shulin Sun, Lansun Chen, Mathematical modelling to control a pest population by infected pests, Appl. Math. Model. 33 (6) (2009) 2864–2873.

[34] Fahad Al Basir, Arnab Banerjee, Santanu Ray, Role of farming awareness in crop pest management-A mathematical model, J. Theor. Biol. 461 (2019) 59–67.

[35] Nian-Feng Wan, Xiang-Yun Ji, Jie-Xian Jiang, Bo Li, A modelling methodology to assess the effect of insect pest control on agro-ecosystems, Sci. Rep. 5 (1) (2015) 1–7.

[36] Páez Chávez, Joseph, Dirk Jungmann, Stefan Siegmund, Modeling and analysis of integrated pest control strategies via impulsive differential equations, Int. J. Differ. Equ. 2017 (2017).

[37] A.K. Misra, Navnit Jha, Rahul Patel, Modeling the effects of insects and insecticides with external efforts on agricultural crops, Differ. Equ. Dyn. Syst. (2020) 1–18.

[38] A.K. Misra, Navnit Jha, Rahul Patel, Modeling the effects of insects and insecticides on agricultural crops with NSFD method, J. Appl. Math. Comput. 63 (1) (2020) 197–215.

[39] FAO, Desert Locust Standard Operating Procedures, 2021. http://www.fao.org/ag/locusts/common/ecg/359/en/SOPControlE.pdf.

[40] P.M. Symmons, K. Cressman, Desert Locust Guidelines 5. Campaign Organization and Execution, Food and Agriculture Organization, 2001.

[41] J.T. Ritchie, U. Singh, D. Godwin, W.T. Bowen, Cereal growth, development and yield, in: GY Tsuji, G. Hoogenboom, P.K. Thornton (Eds.), Understanding Options for Agricultural Production, 1998, pp. 79–98.

[42] Locust Watch, How Much Food Can a Desert Locust Eat?, 2021. http://www.fao.org/ag/locusts/en/info/info/faq/index.html.

[43] Stephan Krall, Ralf Peveling, B.D. Diallo (Eds.), New Strategies in Locust Control, Birkhäuser, 2012.

[44] H. Ritchie, M. Roser, Crop yields, our world in data. https://ourworldindata.org/crop-yields.