JOMTA
Journal of Mathematics: Theory and Applications
Vol. 7, No. 2, 2025, pp. 115 - 128
P-ISSN: 2685-9653 e-ISSN: 2722-2705
DOI: 10.31605/jomta.v7i2.5626

Optimal Strategy and Cost Effectiveness Analysis for Conservation of The Endangered Maleo: A Mathematical Approach

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Abstract

Maleo is a large megapod found on the island of Sulawesi and surrounding islands and is an endangered species due to illegal hunting and habitat conversion. In this article, we propose a mathematical model for Maleo conservation. The model that is constructed is expressed as a system of ordinary differential equations consisting of six equations. To study the optimal strategy, we use optimal control theory. In our model there are three control parameters related to guarding Maleo nests, monitoring Maleo habitats, and transferring Maleo eggs to captivity. To measure the impact and the consequences of each intervention scheme, we determine the percentage increase in the Maleo population and the average cost-effectiveness ratio. Our results show that the most effective intervention scheme to increase Maleo populations is a combination of guarding Maleo nests, monitoring Maleo habitats, and transferring Maleo eggs to captivity. Meanwhile, the intervention scheme that has the best cost-effectiveness is the intervention scheme which is a combination of guarding Maleo nests and monitoring Maleo habitats.

Keywords: *conservation, cost-effectiveness analysis, Maleo, optimal control*

Received :01-10-2025 Revised :11-10-2025 Accepted :14-10-2025 Published :17-10-2025

1. Introduction

Maleo (Macrocephalon maleo) is one type of bird that makes burrows as place for egg incubation [1] and is a typical megapod that is often found on the island of Sulawesi, Indonesia [2]. Maleo body size is almost similar to the size of a rooster and is believed to be monogamous [1].

The uniqueness of the Maleo is the method of its egg incubation and the size of its eggs. Maleo eggs are four times the size of duck eggs and five times of chicken eggs. The average egg weight is about 230 grams and the contents are dominated by egg yolks [3]. The location of the egg burrow is chosen by the female bird while the male is in charge of observing the surroundings. Maleo usually look for locations that have high temperatures to make a nest for laying eggs. To trick their egg predators, Maleo usually build camouflage burrows [1]. When the Maleo egg hatched, Maleo chicks come out of their burrows and can immediately engage in activities such as flying and looking for their own food without the need for parental care [2].

Currently the Maleo is an endangered bird species [4], [5].There are several reasons why the Maleo population has decreased, including eggs poaching and exploitation of habitat for human purposes [3], [6]. There are also several community groups that hunt Maleo for Maleo meat [7]. However, the main problem is egg hunting. In some cases, Maleo eggs are hunted for social and ceremonial purposes [6].Several methods have been tried to increase the Maleo population including to collecting Maleo eggs and then hatching them in captivity and monitoring the nesting area of Maleo [2]. In addition, Maulany [5] stated that noted that regular monitoring of nesting areas can reduce the risk of nest predation, while establishing a hatchery and relocating the eggs may enhance hatching and emergence success when in situ protection is unsuccessful.

In this article, we propose a Maleo conservation model considering several interventions, namely guarding Maleo nests, monitoring Maleo habitats, and transferring Maleo eggs into captivity. Guarding

Maleo nests refers to on-site protection activities focused specifically on the nesting grounds, where conservation staff or local communities safeguard the nests and eggs from poachers, predators, or physical disturbances. This activity is preventive and direct, aiming to secure the reproductive output of Maleo.

Monitoring Maleo habitats, on the other hand, involves collecting data and assessing the broader environmental conditions of the areas where Maleo live, such as vegetation cover, soil temperature, human presence, or predator populations. Unlike guarding, monitoring does not involve direct interference or protection but focuses on understanding habitat quality and long-term ecological changes that affect Maleo populations. We combined these interventions to produce seven intervention schemes (strategies). We investigated the impact and the consequence of each intervention scheme by calculating the percentage increase in the Maleo population and the average cost-effectiveness ratio (ACER).

2. Research Methods

a. This research is accomplished by performing the following steps:
b. Formulate a mathematical model of Maleo conservation incorporating poaching and captivity activity.
c. Identify the invariant set of the model that has been constructed.
d. Formulate optimal control problems by specifying time dependent control parameters and objective function and determine the solution of optimal control problem using the Pontryagin maximum principle as conducted in the articles discussing optimal control problem [8]–[10].
e. Study the impact and consequences of each intervention scheme by calculating the percentage increase in the Maleo population and the average cost-effectiveness ratio as conducted in [10], [11].

3. Results

3.1 Model Formulation

In this subsection, we explain the model formulation process, description of parameters, and definition of variables. The model constructed consisted of six variables, namely male adult Maleo(M_m), female adult Maleo(M_f), male Maleo chick(C_m), female Maleo chick(C_f), Maleo egg in the wild(T_w), and Maleo egg in captivity(T_p).

The number of male adult Maleos and the number of female adult Maleos increased due to the presence of male maleo chicks and female maleo chicks that had just entered adulthood, respectively. In contrast, we assume that the two groups of adult Maleo are decreasing due to natural deaths and poaching activities.

We assume that when Maleo eggs in captivity hatch, conservation officers immediately release the Maleo chicks into the wild. Consequently, the number of male Maleo chicks and female maleo chicks rises because Maleo eggs in the wild and Maleo eggs in captivity hatch. On the other hand, the reduction in the number of Maleo chicks in the wild is assumed to be due to natural deaths and prohibited hunting.

It should be noted that the eggs that have the potential to hatch are eggs fertilized by an adult male Maleo. In this article, we consider only the eggs produced by an adult female Maleo that have mated with an adult male Maleo. Thus, Maleo eggs in the wild increase due to the existence of new eggs produced by adult Maleo pairs. In contrast, the decrease of Maleo eggs in the wild is assumed to occur due to natural damage of the eggs , Maleo egg poaching, hatched eggs, and the process of transferring eggs from the wild to captivity. Unlike Maleo eggs in the wild, Maleo eggs in captivity are only reduced due to natural damage of the eggs and hatched eggs. In addition, the Maleo egg in captivity are increasing due to new eggs taken from the wild. Therefore, the dynamic of Maleo population is illustrated in the following schematic diagram.

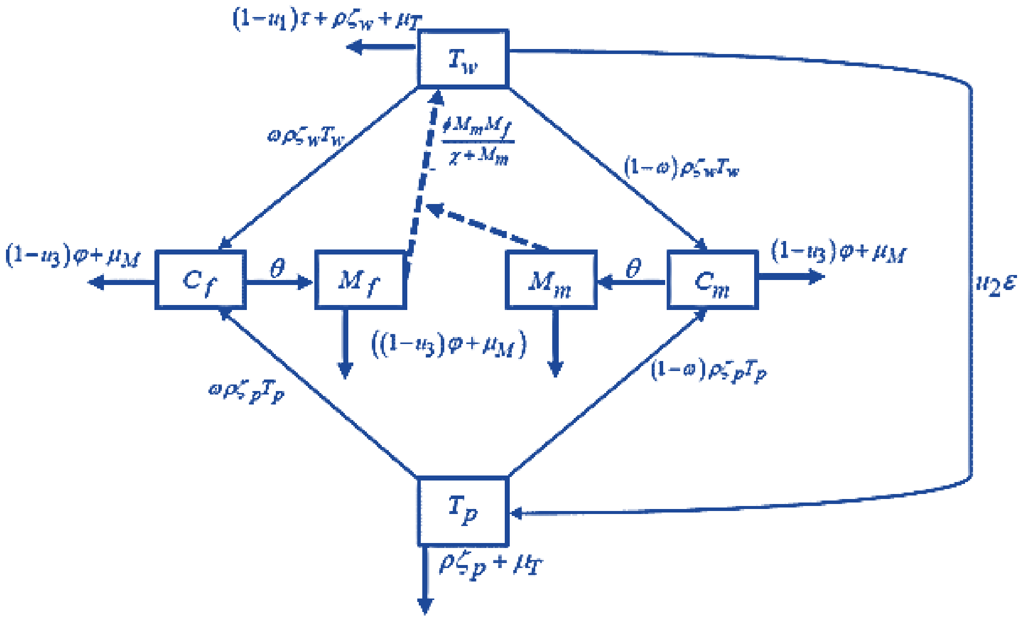


Figure 1. Schematic diagram

Based on the schematic diagram shown in Figure 1, a mathematical model for the conservation of the Maleo, that consists of six ordinary differential equations, is obtained.

$$
\begin{aligned}
\frac{dM_m}{dt} &= \theta C_m - \left(\left(1-u_3\right)\varphi + \mu_M\right)M_m, \\
\frac{dM_f}{dt} &= \theta C_f - \left(\left(1-u_3\right)\varphi + \mu_M\right)M_f, \\
\frac{dC_m}{dt} &= \left(1-\omega\right)\rho\left(\zeta_w T_w + \zeta_p T_p\right) - \left(\left(1-u_3\right)\varphi + \theta + \mu_M\right)C_m, \\
\frac{dC_f}{dt} &= \omega\rho\left(\zeta_w T_w + \zeta_p T_p\right) - \left(\left(1-u_3\right)\varphi + \theta + \mu_M\right)C_f, \\
\frac{dT_w}{dt} &= \frac{\phi M_m M_f}{\chi + M_m} - \left(\left(1-u_1\right)\tau + \rho\zeta_w + u_2\varepsilon + \mu_T\right)T_w, \\
\frac{dT_p}{dt} &= u_2\varepsilon T_w - \left(\rho\zeta_p + \mu_T\right)T_p,
\end{aligned}
\qquad (1)
$$

where $u_i \in [0,1]$ for $i = 1,2,3$ are parameters related to guarding Maleo nests, transferring Maleo eggs to captivity, monitoring Maleo habitat, respectively. The description of the other parameters can be seen in Table 1.

Table 1. Description of parameters

Par.	Description	Values	Unit	Source
θ	The rate of transition from Maleo chicks to adult Maleo	$\frac{1}{3\times 365}$	day^{-1}	[2]
μ_M	The natural death rate of Maleo	$\frac{1}{37\times 365}$	day^{-1}	[2]
ϕ	The number of eggs produced by each adult female Maleo per day	$30/365$	$\text{egg}\times\text{maleo}^{-1}\times\text{day}^{-1}$	[3]

ρ	The hatching rate of Maleo eggs	$1/85$	day^{-1}	[6]
ζ_p	The probability the Maleo egg hatching in captivity	0.65	$\text{maleo chick} \times \text{egg}^{-1}$	[6]
ω	The probability that the eggs that hatches is female Maleo chicks	$1/2$	-	Estimation
ζ_w	The probability of Maleo egg hatching in the wild	$1/2$	$\text{maleo chick} \times \text{egg}^{-1}$	Assumption
τ	The rate of Maleo egg poaching	$1/7$	day^{-1}	Assumption
ε	The rate of egg collection in the wild	$1/7$	day^{-1}	Assumption
φ	The rate of poaching	$\dfrac{1}{6\times 30}$	day^{-1}	Assumption
χ	The saturation constant	1	maleo	Assumption
μ_T	The rate of egg damage	$1/85$	day^{-1}	Estimation

3.2 Invariant Set of The Model

We use similar method used in [12] to study the invariant set of system(1). From system(1), we get

$$
\begin{aligned}
\left.\frac{dM_m}{dt}\right|_{M_f,C_m,C_f,T_w,T_p\geq 0,M_m=0} &= \theta C_m \geq 0,\\
\left.\frac{dM_f}{dt}\right|_{M_m,C_m,C_f,T_w,T_p\geq 0,M_f=0} &= \theta C_f \geq 0,\\
\left.\frac{dC_m}{dt}\right|_{M_m,M_f,C_f,T_w,T_p\geq 0,C_m=0} &= (1-\omega)\rho\left(\zeta_w T_w + \zeta_p T_p\right) \geq 0,\\
\left.\frac{dC_f}{dt}\right|_{M_m,M_f,C_m,T_w,T_p\geq 0,C_f=0} &= \omega\rho\left(\zeta_w T_w + \zeta_p T_p\right) \geq 0,\\
\left.\frac{dT_w}{dt}\right|_{M_m,M_f,C_m,C_f,T_p\geq 0,T_w=0} &= \frac{\phi M_m M_f}{\chi + M_m} \geq 0,\\
\left.\frac{dT_p}{dt}\right|_{M_m,M_f,C_m,C_f,T_w\geq 0,T_p=0} &= u_2 \varepsilon T_w \geq 0.
\end{aligned}
$$

According to Lemma 2 in [13],   is invariant set for system(1). Therefore, the solutions of system (1) are non-negative if initial values given are non-negative.

3.3 Optimal Control Problem

The aim of this study is to investigate the optimal strategy for Maleo conservation by considering the activity of guarding Maleo nests, monitoring Maleo habitats, and transferring Maleo eggs to captivity. Therefore, three control parameters were selected, namely u_1, u_2, and u_3. We want to identify an intervention scheme that can maximize the number of adult Maleo, Maleo chicks and Maleo eggs in the wild but at minimum cost. Therefore, the objective function to be maximized is as follows

$$\begin{aligned} J &= \int_0^{t_f} \left(A_1 M_m + A_2 M_f + A_3 C_m + A_4 C_f \right) dt \\ &\quad - \int_0^{t_f} \left(A_5 {u_1}^2 + A_6 {u_2}^2 + A_7 {u_3}^2 \right) dt, \end{aligned} \tag{2}$$

where A_i for $i = 1,2,...,7$ are balancing cost weights and t_f is the final time. Note that $\left(A_5 {u_1}^2 + A_6 {u_2}^2 + A_7 {u_3}^2 \right)$ represents the cost of control effort. Based on the model **Error! Reference source not found.** and objective function **Error! Reference source not found.**, the following Hamiltonian function (3) is obtained.

$$\begin{aligned} \mathrm{H} &= \left(A_1 M_m + A_2 M_f + A_3 C_m + A_4 C_f \right) \\ &\quad - \left(A_5 {u_1}^2 + A_6 {u_2}^2 + A_7 {u_3}^2 \right) \\ &\quad + \lambda_1 \left(\theta C_m - \left((1-u_3)\varphi + \mu_M \right) M_m \right) \\ &\quad + \lambda_2 \left(\theta C_f - \left((1-u_3)\varphi + \mu_M \right) M_f \right) \\ &\quad + \lambda_3 \left((1-\omega)\rho \left(\zeta_w T_w + \zeta_p T_p \right) - \left((1-u_3)\varphi + \theta + \mu_M \right) C_m \right) \\ &\quad + \lambda_4 \left(\omega\rho \left(\zeta_w T_w + \zeta_p T_p \right) - \left((1-u_3)\varphi + \theta + \mu_M \right) C_f \right) \\ &\quad + \lambda_5 \left(\frac{\phi M_m M_f}{\chi + M_m} - \left((1-u_1)\tau + \rho\zeta_w + u_2\varepsilon + \mu_T \right) T_w \right) \\ &\quad + \lambda_6 \left(u_2 \varepsilon T_w - \left(\rho\zeta_p + \mu_T \right) T_p \right), \end{aligned} \tag{3}$$

where λ_i for $i = 1,2,...,6$ are adjoin variables. From the Hamiltonian function **Error! Reference source not found.**, we get the adjoin system(4).

$$\begin{aligned} \frac{d\lambda_1}{dt} &= -\frac{\partial \mathrm{H}}{\partial M_m} = -\left(A_1 - \lambda_1 \left((1-u_3)\varphi + \mu_M \right) + \lambda_5 \phi \frac{M_f \chi}{(\chi + M_m)^2} \right), \\ \frac{d\lambda_2}{dt} &= -\frac{\partial \mathrm{H}}{\partial M_f} = -\left(A_2 - \lambda_2 \left((1-u_3)\varphi + \mu_M \right) + \lambda_5 \phi \frac{M_m}{(\chi + M_m)} \right), \\ \frac{d\lambda_3}{dt} &= -\frac{\partial \mathrm{H}}{\partial C_m} = -\left(A_3 + \lambda_1 \theta - \lambda_3 \left((1-u_3)\varphi + \theta + \mu_M \right) \right), \\ \frac{d\lambda_4}{dt} &= -\frac{\partial \mathrm{H}}{\partial C_f} = -\left(A_4 + \lambda_2 \theta - \lambda_4 \left((1-u_3)\varphi + \theta + \mu_M \right) \right), \\ \frac{d\lambda_5}{dt} &= -\frac{\partial \mathrm{H}}{\partial T_w} = -\left(\lambda_3 (1-\omega)\rho\zeta_w + \lambda_4 \omega\rho\zeta_w - \lambda_5 \left((1-u_1)\tau + \rho\zeta_w + u_2\varepsilon + \mu_T \right) + \lambda_6 u_2 \varepsilon \right), \\ \frac{d\lambda_6}{dt} &= -\frac{\partial \mathrm{H}}{\partial T_p} = -\left(\lambda_3 (1-\omega)\rho\zeta_p + \lambda_4 \omega\rho\zeta_p - \lambda_6 \left(\rho\zeta_p + \mu_T \right) \right), \end{aligned} \tag{4}$$

where $\lambda_i \left(t_f \right) = 0$ for $i = 1,...,6$. Furthermore, the Hamiltonian function(3) gives

$$\frac{\partial \mathrm{H}}{\partial u_1} = -2A_5u_1 + \lambda_5\tau T_w,$$
$$\frac{\partial \mathrm{H}}{\partial u_2} = -2A_6u_2 - \lambda_5\varepsilon T_w + \lambda_6\varepsilon T_w,$$
$$\frac{\partial \mathrm{H}}{\partial u_3} = -2A_7u_3 + \lambda_1\varphi M_m + \lambda_2\varphi M_f + \lambda_3\varphi C_m + \lambda_4\varphi C_f.$$

Based on the optimal conditions, the control parameters is $\overset{*}{u_1}, \overset{*}{u_2}, \overset{*}{u_3}$ which satisfy $\frac{\partial \mathrm{H}}{\partial u_i} = 0$ and $u_i \in [0,1]$ for $i = 1,2,3$. Therefore, we get

$$u_1^* = \min\left\{\max\left\{0, \frac{\lambda_5\tau T_w}{2A_5}\right\}, 1\right\},$$
$$u_2^* = \min\left\{\max\left\{0, \frac{(\lambda_6 - \lambda_5)\varepsilon T_w}{2A_6}\right\}, 1\right\},$$
$$u_3^* = \min\left\{\max\left\{0, \frac{(\lambda_1 M_m + \lambda_2 M_f + \lambda_3 C_m + \lambda_4 C_f)\varphi}{2A_7}\right\}, 1\right\}.$$

3.4 Cost-Effectiveness Measure

In this subsection, we will explain the formula for measuring the cost-effectiveness of intervention schemes. As previously mentioned, our goal is to maximize the number of Maleo in the wild. Therefore, the increase in the number of Maleo when the intervention is applied can be said to be a benefit of the intervention. On this basis, the benefit (B) can be written as

$$\mathrm{B} = \left(M_m^+ + M_f^+ + C_m^+ + C_f^+\right) - \left(M_m + M_f + C_m + C_f\right),$$

where $\left(M_m^+ + M_f^+ + C_m^+ + C_f^+\right)$ is the number of Maleo when the intervention is implemented and $\left(M_m + M_f + C_m + C_f\right)$ is the number of Maleo without intervention.

According to[14], the average cost-effectiveness ratio (ACER) is the ratio between the costs of an intervention and its benefits. Therefore, we define ACER during t_f period of intervention as follows

$$ACER = \int_0^{t_f} \frac{\left(A_5u_1^2 + A_6u_2^2 + A_7u_3^2\right)}{\left(M_m^+ + M_f^+ + C_m^+ + C_f^+\right) - \left(M_m + M_f + C_m + C_f\right)} dt. \tag{5}$$

To measure the effectiveness of the intervention scheme in increasing the number of Maleo in the wild, we used the percentage increase in Maleo numbers expressed in the following formula

$$P = \left(\int_0^{t_f} \frac{\left(M_m^+ + M_f^+ + C_m^+ + C_f^+\right) - \left(M_m + M_f + C_m + C_f\right)}{\left(M_m + M_f + C_m + C_f\right)} dt\right) \times 100\%.$$

3.5 Numerical Experiments

To perform numerical simulations for the optimal control problem, we use the same method used in [10]. We set $A_1 = 2,\ A_2 = 2,\ A_3 = 2,\ A_4 = 2,\ A_5 = 1,\ A_6 = 1,$ and $A_7 = 2$ .The initial values used is

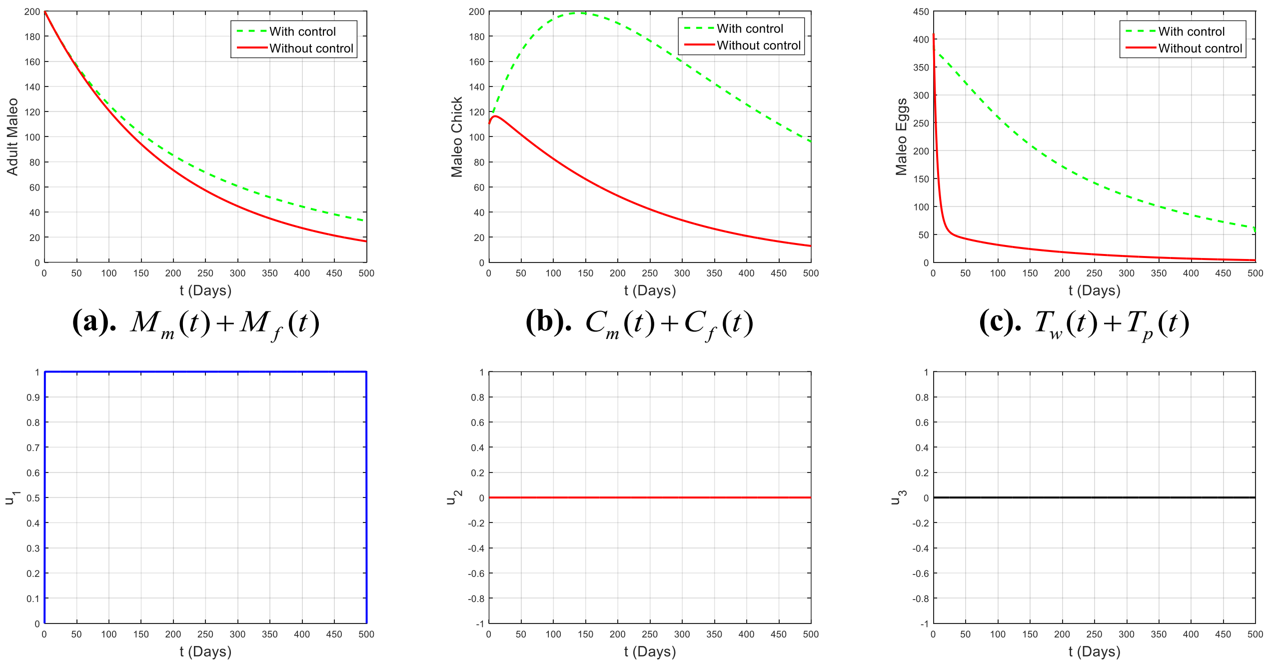
$M_m(0)=100$, $M_f(0)=100$, $C_m(0)=55$, $C_f(0)=55$, $T_w(0)=400$, and $T_p(0)=10$. Meanwhile, the parameter values used are in accordance with those given in Table 1.

It is clear that the three control parameters provide seven intervention schemes, namely

- Strategy 1: Guarding the Maleo nests,
- Strategy 2: Transferring Maleo eggs from the nests and incubate them in captivity,
- Strategy 3: Monitoring Maleo habitats,
- Strategy 4: Guarding Maleo nests and transferring Maleo eggs from the nests then incubate them in captivity,
- Strategy 5: Guarding Maleo nests and monitoring Maleo habitats,
- Strategy 6: Transferring Maleo eggs from the nests and incubate them in captivity and monitoring Maleo habitats,
- Strategy 7: Guarding Maleo nests, monitoring Maleo habitats and transferring Maleo eggs from the nests and incubate them in captivity.

3.5.1. Implementation of Strategy 1

The results of the numerical simulation when strategy 1 is carried out are shown in Figure 2. It is clear that the number of Maleo and their eggs increased dramatically when strategy 1 is applied. When there is no intervention, the number of adult Maleos at day 500 is only about 16. Meanwhile, when strategy 1 is applied, the number of adult Maleos on the same day is 33. These results are shown in Figure 2(a). Figure 2(b) shows a significant increase in the number of Maleo chicks, i.e., 13 to 94. In addition, the number of eggs also increases from 4 to 51 as shown in Figure 2(c). Figure 2(d)-(f) shows that when control u_2 and u_3 are zero, control u_1 should be at its upper bound.



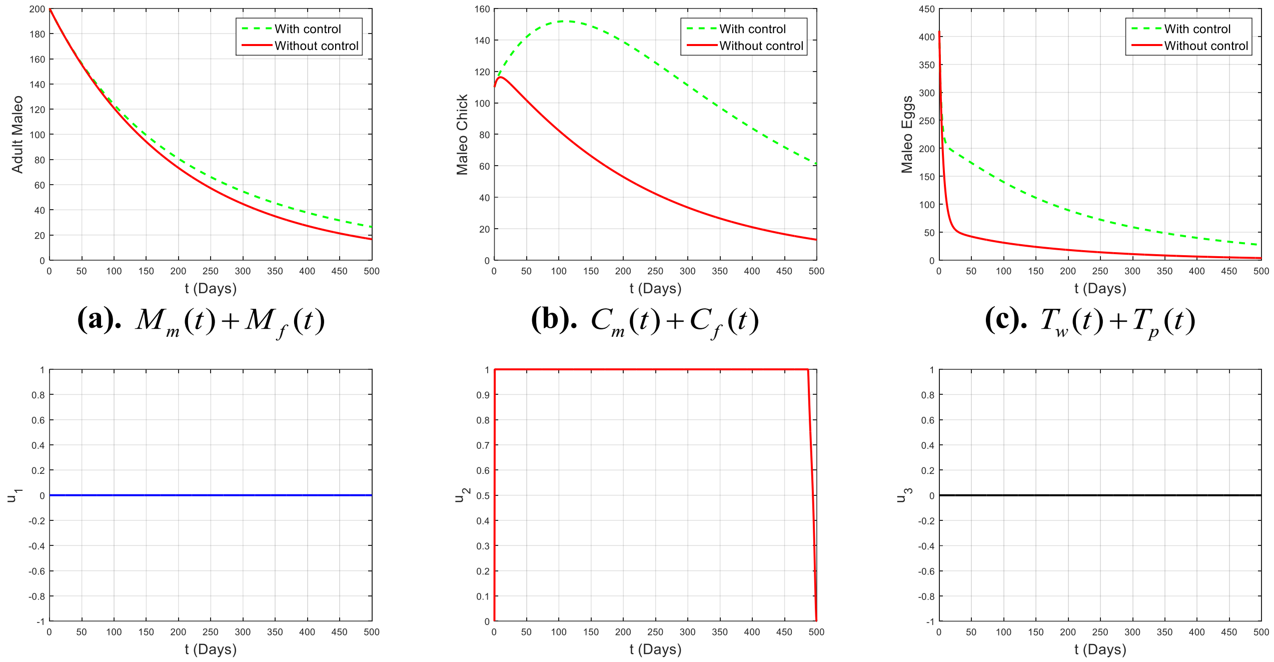
(a). $M_m(t)+M_f(t)$ **(b).** $C_m(t)+C_f(t)$ **(c).** $T_w(t)+T_p(t)$

(d). $u_1(t)$ **(e).** $u_2(t)$ **(f).** $u_3(t)$

Figure 2. Dynamics of Maleo population, Maleo eggs, and control profile when strategy 1 is applied

3.5.2. Implementation of Strategy 2

Figure 3 shows the results of the numerical simulation of the optimal control problem when strategy 2 is implemented. Figure 3(a) and Figure 3(b) show that the number of adult Maleos and the number of maleo chicks is 26 and 60, respectively. These numbers are lower than when strategy 1 was applied. It is clear that when u_1 and u_3 are zero, u_2 should be at its upper bound until day 490 and then gradually lowered to zero as shown in Figure 3(d)-(f).



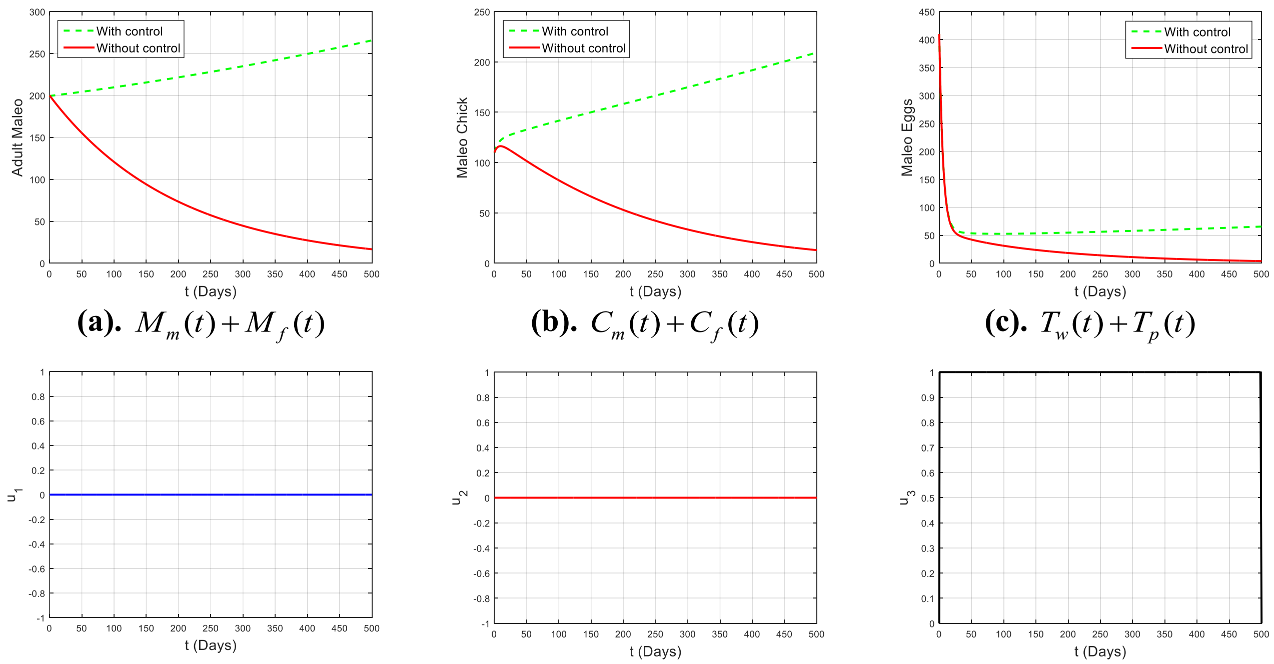
(a). $M_m(t)+M_f(t)$ **(b).** $C_m(t)+C_f(t)$ **(c).** $T_w(t)+T_p(t)$

(d). $u_1(t)$ **(e).** $u_2(t)$ **(f).** $u_3(t)$

Figure 3. Dynamics of Maleo population, Maleo eggs, and control profile when strategy 2 is applied

3.5.3. Implementation of Strategy 3

When strategy 3 is applied, there is an increase in the number of Maleos and in the number of Maleo eggs which are much larger than the two previous strategies. This can be seen in the numerical simulation results as shown in Figure 4. It is clear that Figure 4(a) shows that the number of adult Maleos on day 500 reaches 265. In addition, Figures 4(b) and 4(c) show that the number of Maleo chicks and the number of Maleo eggs are 208 and 65, respectively. Control u_3 should be at its upper bound during simulation period if u_1 and u_2 are equal to zero as shown in Figure 4(d)-(f).



(a). $M_m(t)+M_f(t)$ **(b).** $C_m(t)+C_f(t)$ **(c).** $T_w(t)+T_p(t)$

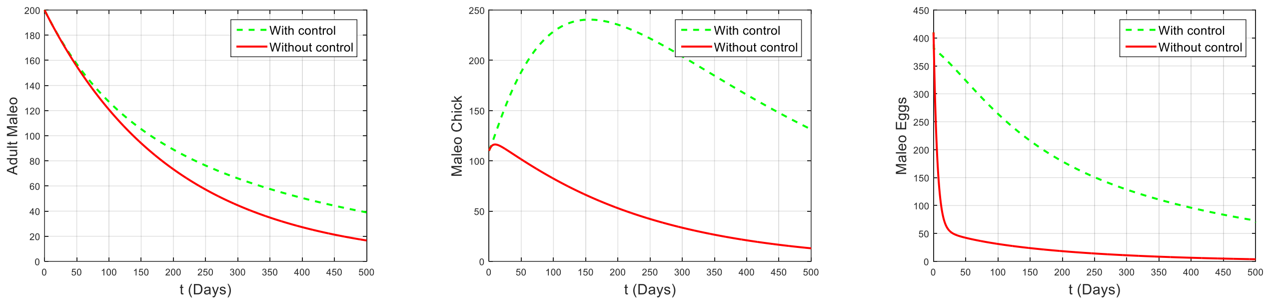
(d). $u_1(t)$ **(e).** $u_2(t)$ **(f).** $u_3(t)$

Figure 4. Dynamics of Maleo population, Maleo eggs, and control profile when strategy 3 is applied

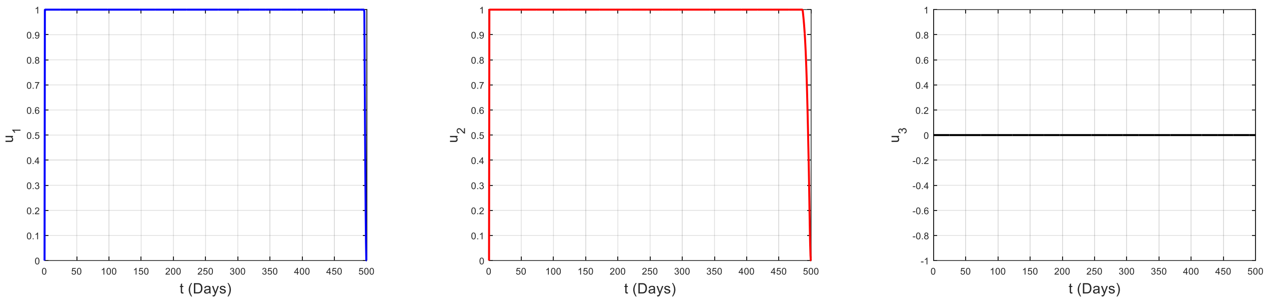
3.5.4. Implementation of Strategy 4

The number of adult Maleos on day 500 is 39 while the number of Maleo chicks and the number of Maleo eggs reach 131 and 69, respectively as shown in Figure 5(a)-(c). It is clear that the increase in the number of Maleos and their eggs is not very significant when compared to the strategy 3. However, the implementation of strategy 4 increased the Maleo population and its eggs better than strategy 1.

Notice that control u_1 should be at its upper bound while control u_2 is at its upper bound until day 490 if control u_3 is zero as shown in Figure 5(d)-(f).



(a). $M_m(t)+M_f(t)$ **(b).** $C_m(t)+C_f(t)$ **(c).** $T_w(t)+T_p(t)$

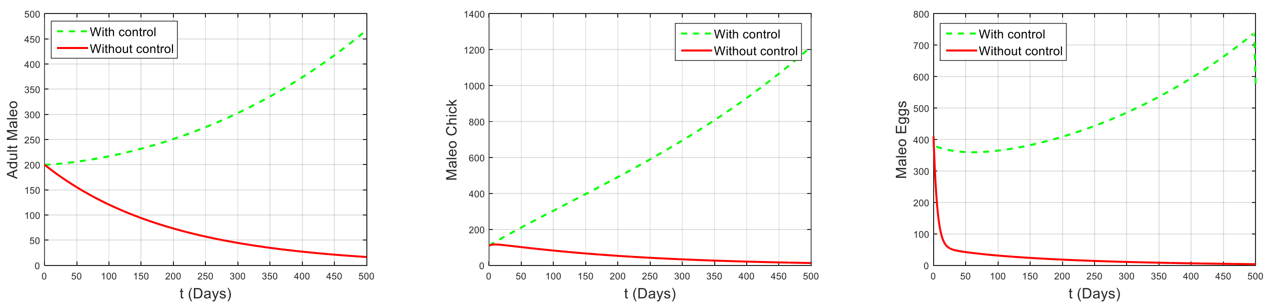


(d). $u_1(t)$ **(e).** $u_2(t)$ **(f).** $u_3(t)$

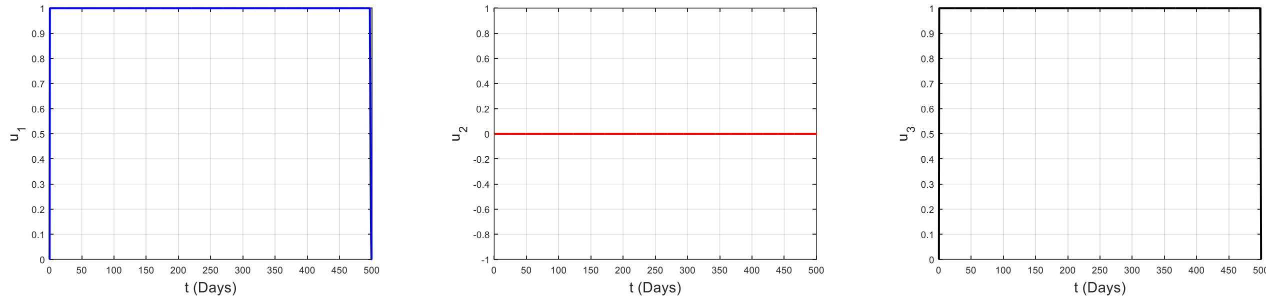
Figure 5. Dynamics of Maleo population, Maleo eggs, and control profile when strategy 4 is applied

3.5.5. Implementation of Strategy 5

On day 500, the number of adult Maleos reached 467 as shown in Figure 6(a). This number is clearly far above when compared to the number of adult Maleos when strategies 1, 2, 3, or 4 is used. In addition, the number of Maleo chicks and Maleo eggs also increased dramatically as shown in Figure 6(b) and Figure 6(c). It is clear that controls u_1 and u_3 must be at their upper bound when control u_2 is zero as shown in Figure 6(d)-(f).



(a). $M_m(t)+M_f(t)$ **(b).** $C_m(t)+C_f(t)$ **(c).** $T_w(t)+T_p(t)$



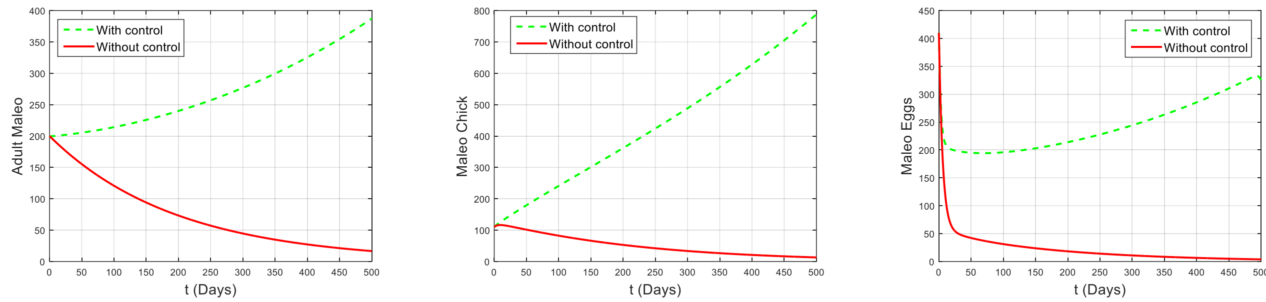
(d). $u_1(t)$ **(e).** $u_2(t)$ **(f).** $u_3(t)$

Figure 6. Dynamics of Maleo population, Maleo eggs, and control profile when strategy 5 is applied

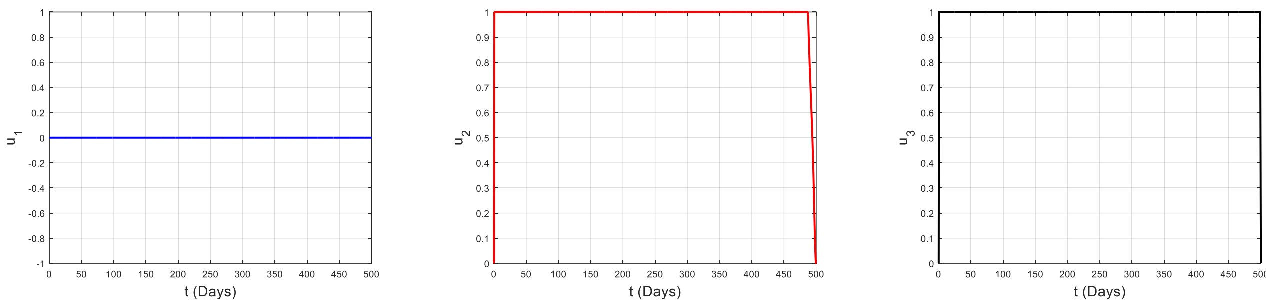
3.5.6. Implementation of Strategy 6

Figure 7(a) shows that on day 500, the number of adult Maleos was 386 when strategy 6 was applied. This number is less than when strategy 5 was carried out. Meanwhile, the number of Maleo chicks is only 384 as shown in

Figure 7(b) while the number of Maleo eggs was 325 as shown in Figure 7(c). It is clear that when control u_1 is zero, control u_2 is mostly at its upper bound while control u_3 must be at its upper bound during the simulation period as seen in Figure 7(d)-(f).



(a). $M_m(t)+M_f(t)$ **(b).** $C_m(t)+C_f(t)$ **(c).** $T_w(t)+T_p(t)$



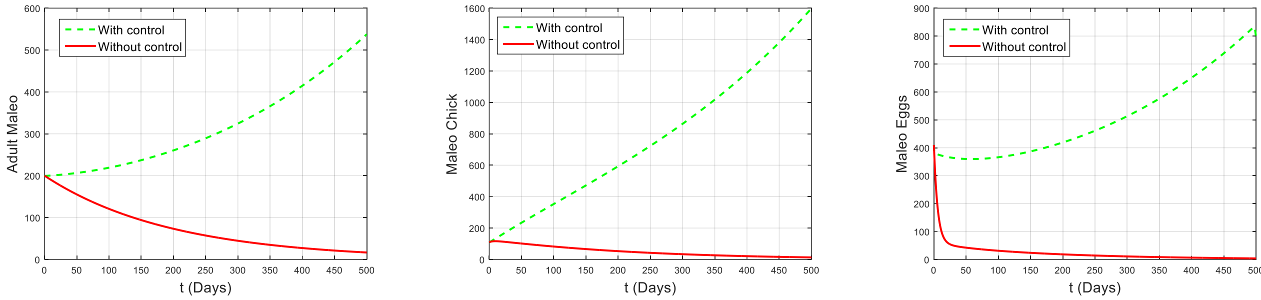
(d). $u_1(t)$ **(e).** $u_2(t)$ **(f).** $u_3(t)$

Figure 7. Dynamics of Maleo population, Maleo eggs, and control profile when strategy 6 is applied

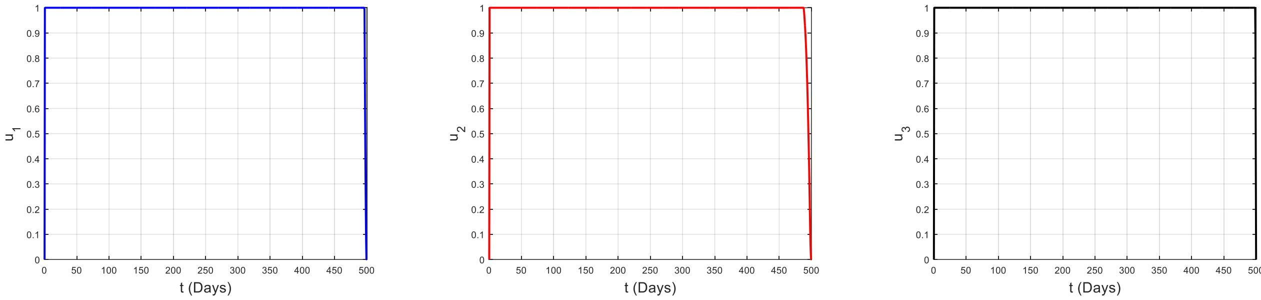
3.5.7. Implementation of Strategy 7

The numerical solution to the optimal control problem when strategy 7 is implemented is presented in Figure 8. On day 500, the number of Maleos and their eggs was far above the number of Maleo birds and their eggs when compared to the impact of implementing strategies 1 to 6. The number of adult Maleos on day 500 was 527 while the number of Maleo chicks and Maleo eggs are 1594 and 792, respectively.

The illustrations can be seen in Figure 8(a)-(c). It is clear that controls u_1 and u_3 should be at their upper bound while control u_2 is at their upper bound until day 490 as shown in Figure 8(d)-(f).



(a). $M_m(t)+M_f(t)$ **(b).** $C_m(t)+C_f(t)$ **(c).** $T_w(t)+T_p(t)$



(d). $u_1(t)$ **(e).** $u_2(t)$ **(f).** $u_3(t)$

Figure 8. Dynamics of Maleo population, Maleo eggs, and control profile when strategy 7 is applied

3.5.8. Percentage increase of Maleo and Cost Effectiveness of Intervention Schemes

To identify the most effective strategy for increasing the Maleo population, we calculate the percentage increase of the Maleo population using the formula (6). In addition, we calculate the ACER of each strategy using formula (5) to study which strategy has the best cost-effectiveness.

The results can be seen in Table 2. Visualization of the percentage increase of the Maleo population can be seen in Figure 9 while Figure 10 shows the comparison of ACER values for each strategy.

Table 2. Percentage increase of Maleo and ACER of each strategy

Strategy	% increase	ACER
1	95.22	0.0084
2	58.39	0.0135
3	219.05	0.0073
4	128.43	0.0124
5	632.68	0.0038
6	466.03	0.0051
7	772.18	0.0041

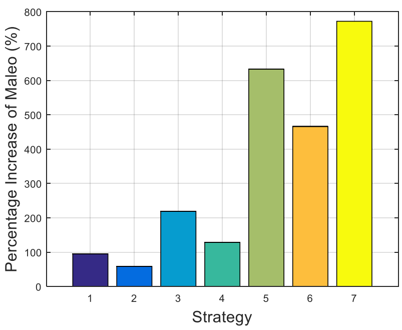


Figure 9. Percentage increase of Maleo population

Table 2 and Figure 9 show that strategy 1 provides a higher percentage increase in the number of Maleo than when strategy 2 is implemented. This indicates that guarding Maleo nests is more effective than transferring and incubating Maleo eggs in captivity. The results are consistent with the results of the study discussed in [2], which states that intervention by protecting Maleo nests from poachers and allowing eggs to hatch naturally is an effective way to increase Maleo populations.

In addition, our results show that strategy 5 is more effective in increasing the number of Maleo than strategy 6. Therefore, a combination of guarding Maleo nests and monitoring Maleo habitats is more effective in increasing Maleo population than a combination of monitoring Maleo habitats and transferring Maleo eggs to captivity.

Furthermore, Table 2 shows that strategy 7 is the most effective way to increase the Maleo population. Although there is a research suggesting that intervention by transferring and incubating eggs in captivity may be unnecessary if poaching can be stopped [2], our results suggest thata combination of guarding Maleo nests, monitoring Maleo habitats, and transferring and incubating Maleo eggs in captivityis the most effective way to increase Maleo population. Therefore, if the available funds are large enough, the policymakers should implement strategy 7 to address the problem of the Maleo population which is on the verge of extinction.

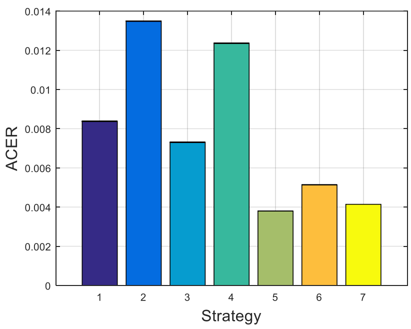


Figure 10. ACER of each strategy

Apart from identifying the most effective strategy to increase the Maleo population, we also investigate the strategy with the best cost-effectiveness. The ACER values shown in Table 2 and Figure 10 indicate that strategy 5 has the lowest ACER value, followed by strategy 7 and strategy 6. According to [10], the strategy with the best cost-effectiveness is the strategy that has the smallest ACER value. Therefore, from Table 2 and Figure 10, it can be concluded that strategy 5, i.e., a combination of guarding Maleo nests and monitoring Maleo habitatsis the most cost-effective strategy. This finding is in accordance with the report [15], which states that guarding program, e.g., guarding Maleo nests is a very efficient method. Thus, if the funds are limited, the policymakers should implement strategy 5 because it is more cost-effective than other strategies.

4. Conclusions

In this article we discuss the Maleo conservation model which is expressed as a system of ordinary differential equations. In our model, there are three control parameters related to the intervention of guarding Maleo nests, monitoring Maleo habitats, and transferring Maleo eggs to captivity. To study the optimal intervention scheme, we used optimal control theory. Our results show that a combination of guarding Maleo nests, monitoring Maleo habitats, and transferring Maleo eggs to captivity is the most-effective intervention scheme when viewed from the percentage increase in Maleo population. However, the intervention scheme that has the best cost effectiveness is a combination of guarding Maleo nests and monitoring Maleo habitats. Therefore, if the amount of available Maleo conservation funds is adequate, the policymakers should implement a combination of guarding Maleo nests, monitoring Maleo habitats, and transferring Maleo eggs to captivity. Meanwhile, if the amount of Maleo conservation funds is insufficient, the policymakers should implement a combination of guarding Maleo nests and monitoring Maleo habitats. As previously explained in the introduction section, guarding Maleo nests involves direct on-site protection of nesting grounds by conservation staff or local communities to prevent egg theft, predation, or disturbance, ensuring successful reproduction. In contrast, monitoring Maleo habitats focuses on collecting and analyzing environmental data—such as vegetation, soil temperature, human activity, and predator presence—to understand habitat quality and long-term ecological changes without direct intervention.

References

[1] A. Santrio, A. Mardiastuti, and D. Perwitasari-Farajallah, "The Characteristics of Maleo Bird (Macrocephalon Maleo) Eggs in the Wildlife Conservation Area, North Buton, Indonesia," 2022. doi: 10.2991/absr.k.220309.092.

[2] J. S. Tasirin *et al.*, "Maleo Macrocephalon maleo population recovery at two Sulawesi nesting grounds after community engagement to prevent egg poaching," *Glob. Ecol. Conserv.*, vol. 28, p. e01699, Aug. 2021, doi: 10.1016/j.gecco.2021.e01699.

[3] L. Saerang, W. Manalu, I. Soesanto, and A. Mardiastuti, "Physical and Chemical Characteristics of Maleo Egg in Bogani Nani Wartabone Park," *Anim. Prod.*, vol. 12, no. 1, pp. 34–38, 2010.

[4] W. P. B. Putra, "PREDICTING THE GROWTH CURVE OF BODY WEIGHT IN MALEO BIRDS (MACROCEPHALON MALEO)," *OISAA J. Indones. Emas*, vol. 4, no. 2, pp. 59–63, Jun. 2021, doi: 10.52162/jie.2021.004.02.4.

[5] R. I. Maulany, M. I. Aliem, Nasri, and Ismail, "A preliminary study of Maleo (Macrocephalon maleo) nesting in Kambunong Cape, West Sulawesi," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 681, no. 1, p. 012124, Mar. 2021, doi: 10.1088/1755-1315/681/1/012124.

[6] Y. Rusiyantono, M. Tanari, and M. I. Mumu, "Conservation of maleo bird (Macrocephalon maleo) through egg hatching modification and ex situ management," *Biodiversitas*, vol. 12, no. 3, pp. 171–176, 2011.

[7] S. Sawaki, D. Taran, F. Taran, R. Bomoi, and M. Rumateray, "Hunting of wild animals by Saubeba Community in Manokwari, West Papua, Indonesia," *Biodiversitas J. Biol. Divers.*, vol. 23, no. 5, Apr. 2022, doi: 10.13057/biodiv/d230519.

[8] R. Viriyapong and W. Ridbamroong, "Global Stability Analysis and Optimal Control of Measles Model with Vaccination and Treatment," *J. Appl. Math. Comput.*, vol. 62, no. 1–2, pp. 207–237, 2020, doi: 10.1007/s12190-019-01282-x.

[9] D. Aldila, M. Z. Ndii, and B. M. Samiadji, "Optimal control on COVID-19 eradication program in Indonesia under the effect of community awareness," *Math. Biosci. Eng.*, vol. 17, no. 6, pp. 6355–6389, 2020, doi: 10.3934/mbe.2020335.

[10] D. Darmawati, M. Musafira, D. Ekawati, W. Nur, M. Muhlis, and S. F. Azzahra, "Sensitivity, Optimal Control, and Cost-Effectiveness Analysis of Intervention Strategies of Filariasis," *Jambura J. Math.*, vol. 4, no. 1, pp. 64–76, Jan. 2022, doi: 10.34312/jjom.v4i1.11766.

[11] D. Aldila, N. Azizah, and B. D. Handari, "Optimal control problem arises from illegal poaching of southern white rhino mathematical model," *Adv. Differ. Equations*, vol. 2020, no. 1, p. 605, Dec. 2020, doi: 10.1186/s13662-020-03062-5.

[12] W. Nur, Trisilowati, A. Suryanto, and W. M. Kusumawinahyu, "Schistosomiasis Model Incorporating Snail Predator as Biological Control Agent," *Mathematics*, vol. 9, no. 16, p. 1858, Aug. 2021, doi: 10.3390/math9161858.

[13] X. Yang, L. Chen, and J. Chen, "Permanence and positive periodic solution for the single-species nonautonomous delay diffusive models," *Comput. Math. with Appl.*, vol. 32, no. 4, pp. 109–116, 1996, doi: 10.1016/0898-1221(96)00129-0.

[14] H. Bang and H. Zhao, "Average Cost-Effectiveness Ratio with Censored Data," *J. Biopharm. Stat.*, vol. 22, no. 2, pp. 401–415, Mar. 2012, doi: 10.1080/10543406.2010.544437.

[15] T. Clements, “Conservation of Sulawesis Endangered Mascot - the Maleo - through Conservation Incentive Agreements,” New York, NY, 2009.