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Analysis Dynamics Model Predator-Prey with Holling Type III Response Function and Anti-Predator Behavior

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ABSTRACT

Understanding predator-prey dynamics is essential for maintaining ecological balance and biodiversity. Classical models often fail to capture complex biological behaviors such as prey defense mechanisms and nonlinear predation effects, which are vital for accurately describing real ecosystems. In light of this, there is a growing need to incorporate behavioral and functional complexity into mathematical models to better understand species interactions and their long-term ecological outcomes. This study aims to develop and analyze a predator-prey model that integrates two key ecological features: a Holling type III functional response and the anti-predator behavior exhibited by prey. The model assumes a habitat with limited carrying capacity to reflect environmental constraints. We formulate a nonlinear system of differential equations representing the interaction between prey and predator populations. The model is examined analytically by identifying equilibrium points and analyzing their local stability using the Routh-Hurwitz criteria. A literature-based theoretical analysis is supplemented with numerical simulations to validate and illustrate population dynamics. The model exhibits three equilibrium points: a trivial solution (extinction), a predator-free equilibrium, and a non-trivial saddle point representing coexistence. The non-trivial equilibrium best reflects ecological reality, indicating stable coexistence where prey consumption is balanced by reproduction, and predator mortality aligns with energy intake. Numerical simulations show that prey populations initially grow rapidly, then decline as they reach carrying capacity, while predator populations grow after a time lag and eventually stabilize. The results are further supported by the eigenvalue analysis, confirming local asymptotic stability. The proposed model realistically captures predator-prey dynamics, demonstrating that the inclusion of anti-predator behavior and a Holling type III response significantly affects population trajectories and system stability. This framework provides a more ecologically valid approach for studying long-term species coexistence and highlights the importance of incorporating behavioral responses in ecological modeling.

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A. INTRODUCTION

Interactions in nature represent fundamental processes that sustain ecological balance and ensure the continuity of life on Earth. Scientifically, these interactions are not only vital to understand but also serve as the basis for modeling complex dynamics occurring in ecosystems (Pal et al., 2021). Mathematical modeling provides a powerful lens through which these natural interactions can be observed, analyzed, and predicted in a structured and replicable way (Bouderbala et al., 2019; Kumar et al., 2021). In various scientific domains, differential equations are employed to represent dynamic changes over time or space, capturing the essence of evolving systems. For instance, in epidemiology, the spread of infectious diseases is frequently modeled using the Susceptible-Infected-Recovered (SIR) framework to predict disease outbreaks (Kortchemski, 2015; Pastor et al., 2021; Tuerxun et al., 2021).

Likewise, physics and chemistry utilize partial differential equations to model phenomena such as heat conduction and chemical kinetics (Wang et al., 2018). This cross-disciplinary utility highlights how mathematical modeling transcends specific scientific fields, including ecology. Within ecological systems, predator-prey interactions are a classical example of interspecies dynamics that can be described through mathematical models. The foundational Lotka–Volterra model serves as the basis for understanding the nonlinear interdependence between predators and their prey (Antwi-Fordjour et al., 2020; Luo & Wang, 2021; Vishwakarma & Sen, 2021). However, its linear functional response oversimplifies predation mechanisms. Modern ecological modeling has progressed to adopt more biologically accurate formulations, such as the Holling Type III response, which introduces a nonlinear predation term that captures predator learning and prey refuge effects (Turkyilmazoglu, 2021). These adjustments better reflect the sigmoidal nature of predation and enhance model accuracy in representing real-world ecological systems (Al-Salti et al., 2021). Incorporating functional response complexity is essential to depict saturation effects and adaptive predator behavior.

The Holling Type III response introduces three phases of predation: an initial slow phase when prey density is low, an acceleration phase when predators effectively capture prey, and a saturation phase when predation approaches a biological limit due to handling time constraints (Dai et al., 2019; Xie et al., 2020). These stages introduce realistic mechanisms into predator-prey models, significantly improving the representation of ecological interactions. Importantly, this nonlinear response adjusts predator efficiency depending on prey availability, thus aligning better with empirical observations. The transition from traditional linear assumptions to nonlinear formulations allows for capturing threshold effects, predator satiation, and other complexities observed in field studies (Antwi-Fordjour et al., 2020; Dubey et al., 2021; Purnomo et al., 2025; Sen et al., 2021). Consequently, Holling Type III functions form a cornerstone in modern ecological modeling.

Beyond predation mechanics, another factor shaping prey survival and predator success is the behavioral adaptation of prey species. The concept of anti-predator behavior involves active responses by prey to mitigate predation threats (Bouderbala et al., 2019; Dubey et al., 2021). Distinguishing it from passive defense mechanisms like camouflage or grouping. While group defense assumes that increased population size offers safety in numbers. Anti-predator behavior reflects active resistance, such as counterattacks or strategic escape (Pratama et al., 2023). Mathematical models incorporating these behaviors demonstrate that prey survival strategies influence predator mortality and population stability. For instance, prey that reach maturity may become more aggressive, reducing predator success rates and indirectly affecting overall population dynamics.

Recent advances have also integrated additional ecological stressors into predator-prey models, such as infection and the Allee effect. These components add further depth to dynamic systems by modeling prey populations under simultaneous predation and disease pressures (Luo & Wang, 2021; Vishwakarma & Sen, 2021). The Allee effect, characterized by reduced reproduction or survival at low population densities, can exacerbate population decline when combined with strong predation (Tuerxun et al., 2021). Moreover, when prey are infected, their vulnerability to predation may increase, compounding ecological stress. Studies incorporating both effects reveal nontrivial equilibrium states and potential extinction thresholds (Purnomo et al., 2025; Vishwakarma & Sen, 2021). These comprehensive approaches illustrate the complex interdependence of biological and environmental variables in shaping ecological trajectories. While group defense has received substantial modeling attention, anti-predator behavior remains relatively underexplored in quantitative terms. Recent studies, however, have begun modeling such behavior explicitly, revealing its influence on predator growth and prey survival (Bouderbala et al., 2019; Dubey et al., 2021). For example, anti-predator strategies may reduce the predator's net reproductive rate or shift the functional response threshold required for population maintenance (Huda & Imro'ah, 2024; Rihan & Rajivganthi, 2020). Additional interventions, such as supplemental food for predators, have also been analyzed to prevent predator extinction and stabilize system dynamics (Liu et al., 2019). These factors collectively underscore the need for comprehensive predator-prey models that account for both behavioral responses and ecological constraints.

This study aims to develop a predator-prey model that incorporates Holling Type III functional response and anti-predator behavior, set within an environment with limited carrying capacity. The research seeks to analyze the equilibrium states and local stability of the system through both analytical and numerical methods. By capturing both nonlinear predation dynamics and prey behavioral responses, the model is intended to provide a more ecologically realistic representation of species interactions. The ultimate goal is to contribute a robust mathematical framework capable of informing ecological sustainability and long-term population viability.

B. METHODS

This research is a literature study and analysis. The stages of the research carried out follow several research steps, formulation and testing of basic assumptions of the model, modeling anti-predator properties in the form of Lotka-Voltera and Holling Type III. The assumptions built are based on relevant research. Furthermore, at the model formulation stage, the concept of mathematical linear differential equations is given to find solutions to the equation. The final stage carried out is to conduct equilibrium point analysis, numerical simulations and analysis of population growth model trajectories. This research is an analytical research type with a literature study approach. The model developed in this research adopts the population dynamics model from research (Sirisubtawee et al., 2021). The aim of this research is to analyze the local stable equilibrium point. Apart from that, it will also show the integration of this stable equilibrium point with life in the population ecosystem. Based on the assumptions described, the mathematical model built is as follows:

$$
\begin{aligned}
N(t) &= rN\left(1-\frac{N}{k}\right)-\frac{\beta N^2 V}{a+N^2}, \\
V(t) &= \frac{\beta N^2 V}{a+N^2}-\delta V - c\,NV\,.
\end{aligned}
\tag{2}
$$

with, $N(t)$ and $V(t)$ respectively are the population density of prey and predators. The assumed Holling Type III is a shape $\dfrac{\beta N^2 V}{a+N^2}$ where this model is a model that represents the characteristics of the sigmoid curve. The following are the trajectories of Holling Type III assumed in this study, as shown in Figure 1.

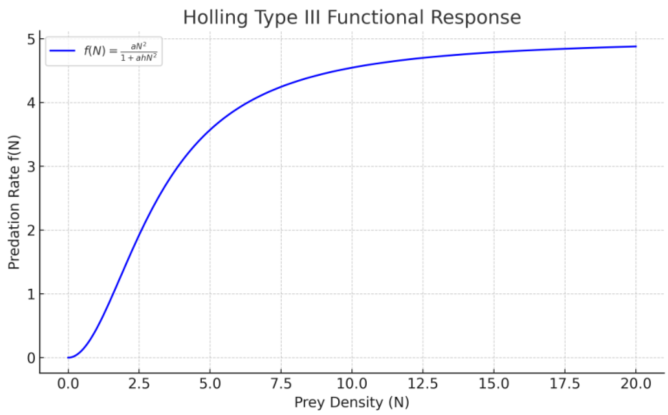

Figure 1. Trajectories Respon Function Holling Type III

All parameters in model (2) are considered realistically by considering the dimensions of these variables. The description of variables and parameters is presented in the following Table 1.

Table 1. Descriptive List of Variables and Parameters

Parameters	Dimensions	Description
N	biomass	Prey population time dependent,
V	biomass	Predator population time dependent,
r	times^{-1}	Prey intrinsic growth rate,
k	biomass	Prey environmental carrying capacity,
β	biomass.time^{-1}	Capturerate the predator
a	biomass	The reciprocal of group defense of predator
δ	times^{-1}	The density-independent death rate of predator
c	biomass^{-1}.time^{-1}	The frequency of prey defense behaviors per unit time

C. RESULT AND DISCUSSION

1. Equilibrium Stability

In this section, equilibrium analysis is conducted through linearization of the differential equations. The proposed model (2) employs linearized differential operators, yielding the following form:

$$\begin{aligned} N(t) &= rN\left(1-\frac{N}{k}\right)-\frac{\beta N^2 V}{a+N^2}=0, \\ V(t) &= \frac{\beta N^2 V}{a+N^2}-\delta V - cNV = 0, \end{aligned} \tag{3}$$

From the analysis carried out, there are three equilibrium points that are associated and realistic to consider carrying out a stability test. The equilibrium points are as follows:

a. Trivial equilibrium $E_0(0,0)$,
b. Equilibrium point $E_1(k,0)$ in the absence of growth in predators or under other conditions the growth of the species grows exponentially. This condition can occur if the prey growth rate is balanced with other factors, for example searching capacity or other factors that support the ecosystem. It is clear that stability analysis cannot be carried out at this equilibrium point, because only prey species grow.
c. Non-trivial equilibrium $E_2\left(N_2^*,V_2^*\right)$, this saddle point is an equilibrium point solution that represents stable population growth of prey and predator populations. This condition usually shows the population growth rate is zero. The prey population grows as much as the prey and the predator population dies as much as the prey population grows. Such a system is in dynamic equilibrium. Even though predator-prey interactions are still ongoing, the overall population of both has not changed.

The equilibrium point $E_2\left(N_2^*,V_2^*\right)$ represents a biologically significant state for species sustainability in the ecosystem. We analyze this equilibrium using the Routh-Hurwitz stability criterion to evaluate population dynamics. Further characterization is performed through Jacobian matrix analysis and eigenvalue computation to determine the system's stability properties. Linearizing the system about equilibrium $E_2\left(N_2^*,V_2^*\right)$ yields the Jacobian matrix:

$$J_{cob}(E_2)=\begin{bmatrix} j_{11} & j_{12} \\ j_{21} & j_{22} \end{bmatrix} \tag{4}$$

where,

$$j_{11}=r\left(1-\frac{N^*}{k}\right)-\frac{rN^*}{k}-\frac{2\beta NV}{a+N^2}+\frac{2\beta N^3V}{\left(a+N^2\right)^2},$$

$$j_{12}=-\frac{\beta N^2}{a+N^2},$$

$$j_{21}=\frac{2\beta NV}{a+N^2}-\frac{2\beta N^3V}{\left(a+N^2\right)^2}-Vc,$$

$$j_{22}=\frac{\beta N^2}{a+N^2}-\delta-cN.$$

From the Jacobian matrix structure, we obtain the characteristic equation for system (3):

$$c\lambda^3+(-\beta+\delta)\lambda^2+ac\lambda+a\delta=0, \tag{5}$$

Mathematically, the value of testing the equilibrium point value is very dependent on the solution of the characteristic equation (5). This characteristic equation is a cubic equation or commonly referred to as a third order algebraic equation. The solution set is highly dependent on the discriminant value Δ. The discriminant of the characteristic equation determines the solution set is fundamental. On $\Delta > 0$ So there are 3 different real roots. On $\Delta = 0$ then there are 3 real roots with at least 2 twin roots. While in condition $\Delta < 0$ then there is 1 real root and 2 complex conjugate roots $\lambda_1 = x + iy$ and $\lambda_2 = x - iy$. Where Δ which is associated with characteristic equation (5) is as follows;

$$\Delta = a - 4a^2c^2 - 27ac^2\delta^2 - 18ac^2\delta(\beta - \delta) + ac^2(\beta - \delta)^2 + 4\delta(\beta - \delta)^3, \tag{6}$$

From equation (6) it is clear that what provides meaningful values is the parameter a, c, δ dan β. The next analysis of the equilibrium point is given certain parameters to provide simulation values for model (2).

2. Numerical Simulation

In this section the model simulation with parameter composition is given. Further analysis will show the equilibrium values and eigenvalues. Numerical simulations are also provided to see the population growth trajectories of each species. The parameters taken are based on valid, relevant and updated assumptions and references which are used as the main research reference. The parameters given are as follows,

$$r = 1.5,\ k = 100,\ c = 0.0008,\ \delta = 0.025, \beta = 0.4, \text{ and } a = 2.$$

Using the specified parameter values, Model (2) takes the following form:;

$$\begin{aligned} N(t) &= 1.5N\left(1 - \frac{N}{100}\right) - \frac{0.4N^2V}{2 + N^2}, \\ V(t) &= \frac{0.4N^2V}{2 + N^2} - 0.025V - 0.0008NV. \end{aligned} \tag{6}$$

We derive the following non-trivial equilibrium point from model equation (6):

$$E_0 = (0,0) \tag{7}$$
$$E_1 = (100,0,0) \tag{8}$$
$$E_2 = (0.36743281\,39, 21.7097052\,5) \tag{9}$$

The three equilibrium points show non-negative results, this confirms that the proposed model (2) can be studied more deeply in stability analysis. Equilibrium point $E_2(N_2^*, V_2^*)$ analyzed to see the growth rate of both populations. The analysis was carried out using the Jacobian matrix stages and the Routh-Hurwitz criteria. At the equilibrium point $E_2(N_2^*, V_2^*)$ we obtain the form of the Jacobian matrix as follows;

$$J_{cob}\left(E_2\right)=\begin{bmatrix}-1.310992439 & -0.02529394624\\ 2.782601691 & -1.11\times 10^{-11}\end{bmatrix} \tag{10}$$

From Jacobian matrix (10), we obtain the characteristic polynomial determining local stability:

$$\lambda^3+1.310992439\ \lambda^2+0.07038297759 \tag{11}$$

The Routh-Hurwitz stability conditions are satisfied if and only if all roots of the characteristic polynomial have negative real parts $\lambda<0$, that's is;

$$\lambda_1 = -1.254906192889 \text{ and } \lambda_2 = -0.0560862461216989$$

The system satisfies both the necessary and sufficient conditions of the Routh-Hurwitz stability criterion. Equilibrium $E_2\left(N_2^*,V_2^*\right)$ meet local stability criteria, so that both populations can exist in an ecosystem. Conditions like this in an ecosystem are ideal, because the presence or absence of disturbances will not affect the rate of population growth. This condition also shows the stability of the ecosystem resilience. We are aware of the lack of analysis to examine global stability in the proposed model. Local stable conditions can already describe the rate of population growth. Moreover, the basic assumptions of model (2) are prepared from simple and small ecosystem assumptions. We also provide trajectory analysis in the research discussion analysis to answer the research objectives. The following is an illustration of the equilibrium point of model (2), as shown in Figure 2.

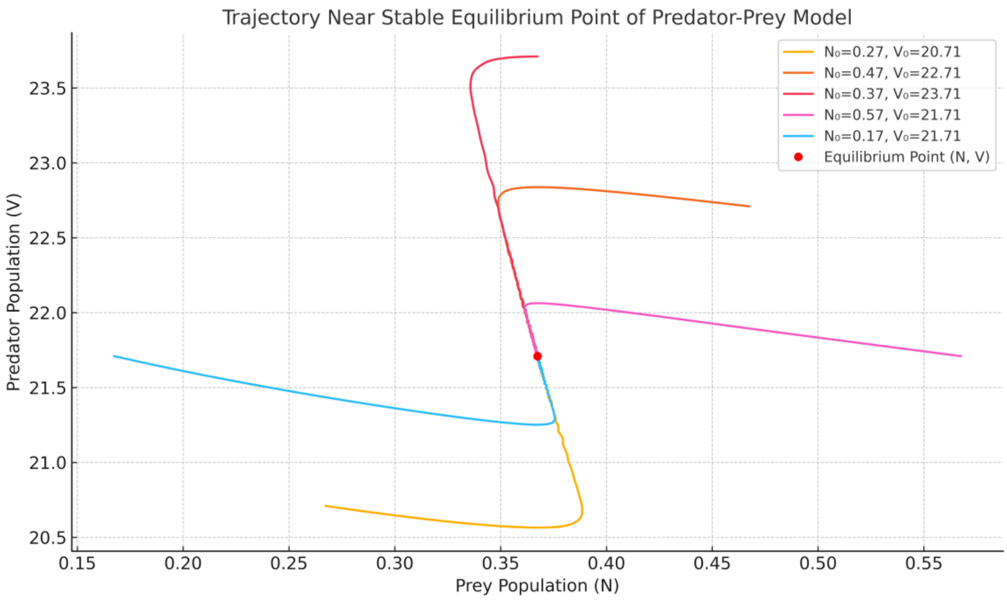

Figure 2. Phase Plane Trajectory

The diagram in Figure 2 shows the system trajectory in state space (N,V), where the horizontal axis indicates the prey population and the vertical axis the predator population. The red point is the equilibrium point (N,V) where the rate of population change is both zero. The trajectory leading to that point indicates that the system is stable: the population will fluctuate and eventually return to the equilibrium value. This illustrates the existence of damping oscillations due to complex interactions between predators and prey. The trajectories of predator-prey population growth in equation (2) are as follows, as shown in Figure 3 dan Figure 4.

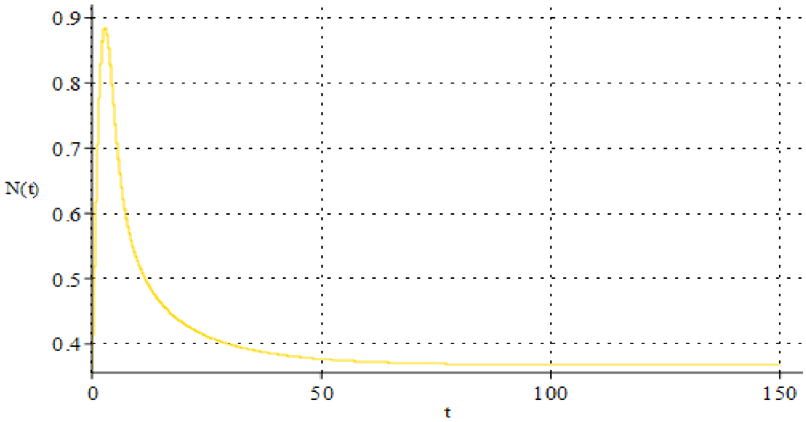

Figure 3. Trajectories prey species

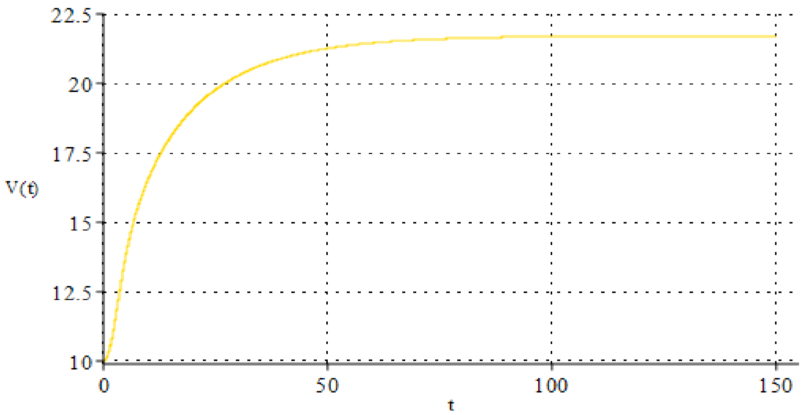

Figure 4. Trajectories predator species

Meanwhile in Figure 3 and Figure 4, it is clear that the time dynamics of the prey and predator populations. Model (2) is in a dynamic system controlled by nonlinear interactions. Initially there are sharp fluctuations (oscillations) indicating initial instability, but the amplitude of the oscillations decreases over time. This is consistent with the phenomenon of self-regulating dynamics in which predator and prey populations adapt to each other's pressures and resource limits. The growth rate of prey is controlled by parameters r and limited by the carrying capacity of the environment k. When prey increases, predator species also begin to increase due to the abundance of food sources. However, because of the direct interaction through the predator's absorption rate of prey (parameter β) and predator mortality (δ) as well as functional competition (c) predator growth is not linear. After reaching a peak, both prey and predator populations show fluctuations in decreasing amplitude (damped oscillation), until finally converging to a fixed point. This indicates that the dynamic system of the predator-prey model reaches ecological balance: the growth rates of prey and predators are equal to zero in the long term. At this point, the population is stable and has not changed significantly, consistent with a predator-prey system model that combines logistic growth and a saturation response function. Both populations reach a steady state which corresponds to the previously calculated equilibrium value.

Predator-prey models, a locally stable equilibrium point represents a condition in which the populations of both predator and prey remain at certain levels and will return to this equilibrium in the short term if the ecosystem experiences a disturbance. The findings in the research results indicate that if the prey's growth rate increases slightly, the predator population will also grow to stabilize the prey population back to its original level. This aligns with the study conducted by (Sirisubtawee et al., 2021), which asserts that the predator's growth rate, influenced by anti-predator behavioral interventions, continues to increase in response to the prey's growth rate. This is further supported by the research of (Dubey et al., 2021; Pratama et al., 2023), which demonstrates that anti-predator behavior in prey not only serves to avoid direct predation but also acts as a response to the fear induced by the presence of predators. This anti-predator characteristic is expressed through a reduction in the prey's reproduction rate as a result of stress or heightened vigilance in response to predator threats. A decrease in the prey's growth rate can occur even when predators cease direct predation. Therefore, the anti-predator parameter has a significant influence on the prey's growth rate. As the anti-predator parameter increases, the equilibrium point still moves toward a center of stability. Fluctuations in the prey population's growth occur only during the initial phase of predation.

D. CONCLUSION AND SUGGESTIONS

In the conclusion section of this paper we have discussed the analysis of the predator-prey model with the characteristics of the Holling Type III response function and anti-predator properties. The prey population is represented by $N(t)$, while predator populations by $V(t)$. The proposed predator-prey system, which incorporates density-dependent limitations through carrying capacity terms, is analyzed through: stability analysis of equilibrium points, numerical exploration of parameter space, and phase-space trajectory evaluation. There are three solutions that become equilibrium points, namely solution trivial equilibrium $E_0(0,0)$, the equilibrium point $E_1(k,0)$ in the absence of growth in predators or under other conditions the growth of the species grows exponentially, and in non-trivial equilibrium $E_2(N_2^*,V_2^*)$, saddle point. Of the three equilibrium points, the most realistic one for stability testing is the non-trivial point $E_2(N_2^*,V_2^*)$. The equilibrium point solution represents the stable population growth of the prey and predator populations. This condition usually shows the population growth rate is zero. The prey population grows as much as the prey and the predator population dies as much as the prey population grows. Such a system is in dynamic equilibrium. Even though predator-prey interactions are still ongoing, the overall population of both has not changed. Model (2) employs the Routh-Hurwitz criterion to determine the local asymptotic stability of each population equilibrium. Numerical simulations reveal the eigenvalue spectrum associated with the system's Jacobian matrix, specifically: $\lambda_1 = -1.254906192889$, and $\lambda_2 = -0.0560862461216989$. Trajectory analysis shows the fluctuating growth of each population. In prey populations, the growth rate is very significant at the beginning of the predation process and immediately declines when it has passed its peak point, while this condition is inversely proportional to predator species. However, both conditions are reaching their respective points of stability. A locally stable equilibrium point represents a condition in which the populations of both predator and prey are maintained at certain levels and will return to this point within a short time if a disturbance occurs in the ecosystem. The results presented in this study indicate that if the prey growth rate increases, even slightly, the predator population will also grow to restore the prey population to its original state. The growth of the predator population, influenced by anti-predator behavior intervention, remains capable of adjusting in response to changes in the prey's growth rate. Anti-predator behavior in prey is not solely aimed at avoiding direct predation but also acts as a response to fear triggered by the presence of predators. This anti-predator trait is reflected in a decrease in the prey's reproduction rate, which results from stress or heightened vigilance against predator threats. A reduction in the prey population growth may still occur even when predation ceases. Therefore, the anti-predator parameter significantly influences the prey population growth rate. As the anti-predator parameter increases, the system's equilibrium point continues to move toward a stable condition. Fluctuations in the prey population growth are only observed during the initial phase of predation. This study is currently limited to an analysis of local stability points; thus, further research is needed to explore global stability. The form of the functional response and the influence of anti-predator traits play a critical role in shaping the model. Future studies may also incorporate exploitation behaviors, such as harvesting, into the model. It is possible that the species under consideration could be exploited in ways that generate economic benefits. However, a fundamental requirement in the formulation of such models is ensuring the long-term sustainability of the ecosystem.

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