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Analyzing Marine Predator–Prey Dynamics through the Lotka–Volterra Equations

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Abstract
Predator–prey interaction is a key factor for understanding the stability of marine ecosystems. In this study, we have investigated the relationship between phytoplankton (prey) and zooplankton (predator) using the classical Lotka–Volterra model. The model parameters were defined as prey growth rate (α), predation rate (β), predator mortality rate (γ), and conversion efficiency (δ), consistent with the predator-prey model. Numerical simulations were carried out in MATLAB using ODE solvers to observe the effects of varying initial population levels. The results show regular oscillations in predator and prey populations that eventually reach a stable limit cycle. Sensitivity analysis indicates that small changes in prey growth and predation rates can significantly influence population behavior and system stability. Furthermore, the damped behavior describes the oscillatory dynamics of the predator–prey populations, with their amplitudes gradually decreasing over time. Though the model is simple, it provides an important understanding of marine plankton dynamics.

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Keywords: Phytoplankton (Prey), Zooplankton (Predator), Carrying Capacity, Phytoplankton_Zooplankton (PZ), Lotka-Volterra

1. Introduction

The dynamic interplay between predator and prey populations is a foundational aspect of ecological systems, shaping their structure, function, and long-term stability. Understanding these interactions is essential for predicting population trends, assessing ecosystem resilience, and guiding conservation strategies. Mathematical modeling provides a powerful framework for analyzing these dynamics, particularly through the classical Lotka-Volterra equations, which have long served as a cornerstone in ecological theory. Originally developed by Lotka and Volterra in the 1920s to model predator-prey systems, the equations describe how predator and prey populations influence each other's growth over time. These nonlinear differential equations have since been widely applied and extended to analyze real-world ecological systems, including fishery management, invasive species control, and interspecies competition [1-4]. In this study, we apply the Lotka-Volterra model to a marine ecological context, focusing on the interaction between phytoplankton and zooplankton. Phytoplankton acts as primary producers and prey, while zooplankton serves as primary consumers and predators [5].

To explore the system's behavior under different ecological conditions, we employ numerical simulations using MATLAB's ODE solvers (ODE45, ODE15s, and ODE23), consistent with standard approaches in ecological modeling [6]. Both short-term and long-term dynamics are analyzed under varying initial population conditions. Results demonstrate the classical oscillatory cycles typical of predator-prey systems, highlighting delayed feedback effects and the sensitivity of the system to initial values and parameter selection.

This research contributes to a deeper understanding of the dynamic relationships between marine species and offers insights into the conditions that foster ecosystem resilience or lead to instability. Moreover, it emphasizes the importance of mathematical modeling in ecological research, particularly in the face of growing environmental challenges and anthropogenic pressures.

2. Literature Review

The Lotka-Volterra model is a classical mathematical framework used to describe the dynamics of interacting biological species, such as competition or predator–prey relationships. Originally introduced to study ecological competition and predation, the model provides a theoretical foundation for understanding population interactions in ecosystems with limited resources.

2.1. Background

Understanding population dynamics begins with two core ecological concepts: habitat and niche. A habitat is the specific physical environment an organism occupies, which may be shared by many species. In contrast, a niche refers to the functional role a species plays within its ecosystem, including its feeding habits, reproductive strategy, and interactions with other organisms. Typically, a niche is exclusive to one species, whereas multiple species can coexist within the same habitat [7]. As shown in Table 1, habitat and niche differ in several important ways.

According to the competitive exclusion principle (also called the *Gause Hypothesis*), when two species occupy the same niche, one will eventually outcompete the other, leading to extinction or niche differentiation. This principle helps explain species distribution and biodiversity and motivates the use of mathematical models to predict outcomes of interspecific competition. In Figure 1, consider two competing species, X and Y. The impact of species X on Y is defined by the competition coefficient α_{yx}, and vice versa α_{xy}. These coefficients quantify the inhibitory effect of one species on the growth of the other due to competition for shared resources [8].

Table 1: Differences between habitat & niche.

S.N.	Habitat	Niche
1	A specific physical space occupied by an organism.	A functional space occupied by an organism in the same ecosystem
2	The same habitat may be shared by many organisms	A single niche is occupied by a single species
3	Habitat specificity is exhibited by organisms	Organisms may change their niche with time and season

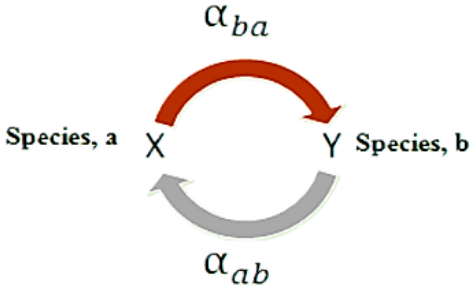


Fig 1: Impact of interactions between two species.

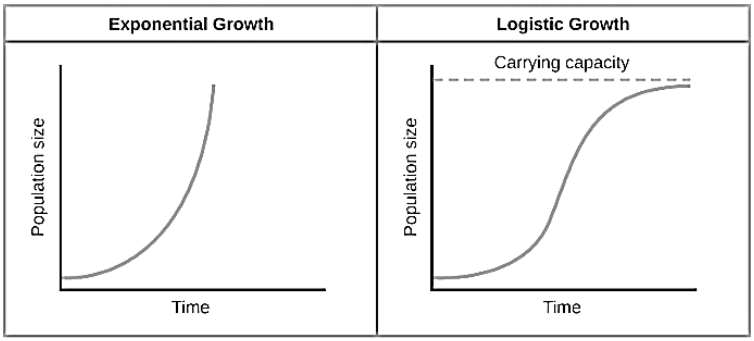


Fig 2: Exponential growth curve vs. logistic growth curve.

As shown in Figure 2,when resources are unlimited, populations exhibit exponential growth, resulting in a J-shaped curve. This can be expressed using the exponential growth equation:$\frac{dN}{dt} = rN$,where, t represents the time, N denotes the population size, and r is the intrinsic growth rate of the population. Under limited resource conditions, populations exhibit logistic growth. In logistic growth, population expansion decreases as resources become scarce, and it levels off when the carrying capacity of the environment is reached, resulting in an S-shaped curve. This leads to the logistic growth equation$\frac{dN}{dt} = rN(\frac{K-N}{K})$,$K =$ carrying capacity.This equation generates an S-shaped (sigmoidal) growth curve, reflecting how population growth slows as it approaches environmental limits.

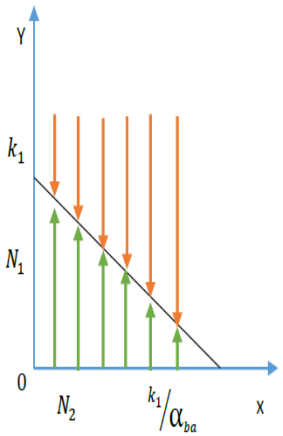


Figure- 1.4.1: *Figure shows the relations between: population of two species, interactions & Carrying Capacity (k_1).*

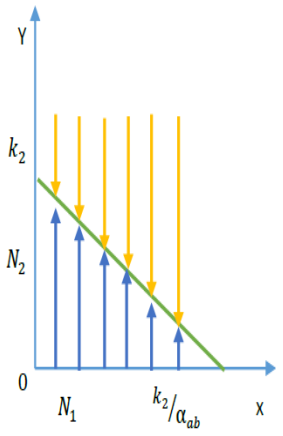


Figure- 1.4.2: *Figure shows the relations between: population of two species, interactions & Carrying Capacity (k_2).*

Fig 3: Figure shows the relations between population of two species, interactions and carrying capacity k_1.

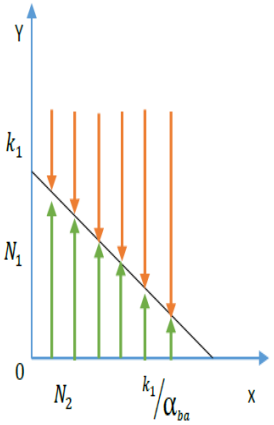


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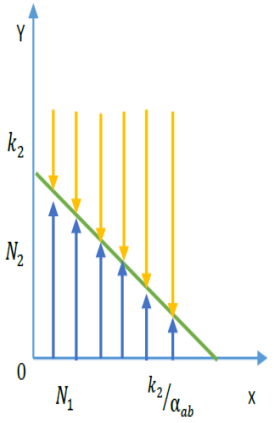


Figure- 1.4.2: *Figure shows the relations between: population of two species, interactions & Carrying Capacity (k_2).*

Fig 4: Figure shows the relations between population of two species, interactions and carrying capacity k_2.

In marine ecosystems, such as those involving phytoplankton (prey) and zooplankton (predator), predator-prey dynamics resemble interspecific competition in that both species affect each other's growth and persistence. Oscillatory patterns emerge from delayed feedback loops, where predator growth lags behind prey abundance. Such interactions can be modeled by extending the Lotka-Volterra equations to include predation terms and interaction rates. The figures 1, 2 and 3 illustrate interspecific competition between two species using the Lotka–Volterra competition model. The two axes represent the population sizes N_1 and N_2, while k_1 and k_2 are their carring capacities when each species occurs alone. Here, α_{ab} represents the effect of species b on species a, while α_{ba} represents the effect of species a on species b.

This study employs numerical simulations to explore these dynamics under different ecological scenarios. By analyzing predator-prey interactions and stability conditions, we aim to understand how initial population sizes and interaction coefficients influence long-term coexistence or extinction.

2.2. Extensions& Real-World Applications

While the basic model provides useful insight, its assumptions limit ecological realism (e.g., unlimited prey resources, no age or spatial structure). Researchers have therefore extended the model to incorporate stochasticity, time delays, functional responses beyond the mass-action form, multiple interacting species and competition effects. For example, the generalized Lotka-Volterra framework allows for multiple species communities and non-exponential growth terms. These extensions enable better modelling of ecosystem stability, complex interactions and human-influenced systems [9, 10].

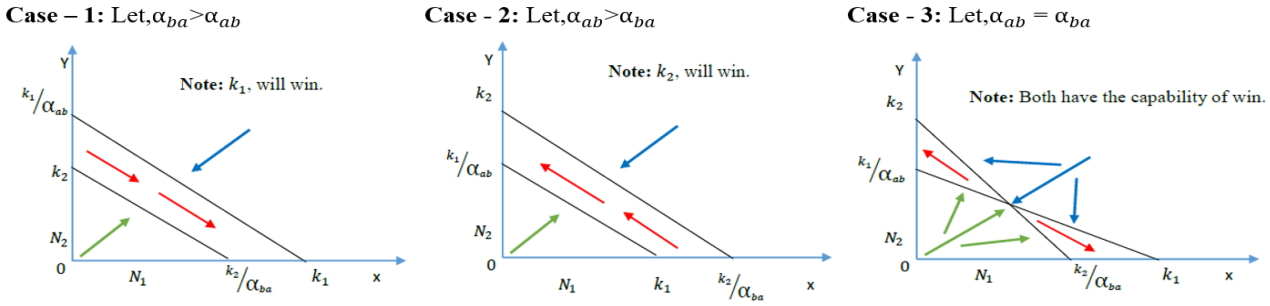


Fig 5: Figure shows the case studies between population of two species, interaction and carrying capacity

2.3. Relevance to Marine Predator System

In marine ecosystems, interactions between phytoplankton (prey) and zooplankton (predator) exhibit characteristic oscillations and are influenced by initial abundances, interaction rates and external drivers. The classic Lotka-Volterra model provides a mathematical baseline for exploring such dynamics, and when combined with numerical simulation, it offers insights into resilience, transient behavior and equilibrium stability under varying conditions [11-14].

3. Methodology

The methodology for this study integrates mathematical formulation, numerical simulation, and ecological interpretation. The goal is to model the predator-prey dynamics between phytoplankton (prey) and zooplankton (predator) using a Lotka-Volterra framework, capturing oscillatory behavior and long-term population stability. While simplified, the model provides insight into fundamental feedback mechanisms in marine ecosystems, consistent with approaches in ecological modeling [15].

3.1. State Variables

The model includes the following state variables:

- Prey population (Phytoplankton), (y_1)
- Predator population (Zooplankton), (y_2)

The model parameters are defined as [5]:

Table 3

Parameter	Description	Value
α	Prey growth rate	0.1
β	Predation rate coefficient	0.4
γ	Predator mortality rate	0.2
δ	Conversion efficiency of prey into predator growth	0.05

These parameters were chosen to reflect general predator-prey interactions in marine systems and are consistent with prior studies.

3.2. Model Assumptions

The classical Lotka–Volterra model relies on several simplifying assumptions:

1. Prey populations grow exponentially in the absence of predators, with unlimited resources.
2. Predator populations decline exponentially in the absence of prey due to starvation.
3. Predator-prey encounters occur proportionally to the product of their populations.
4. The energy gained by predators from consuming prey does not necessarily equal the loss experienced by the prey.

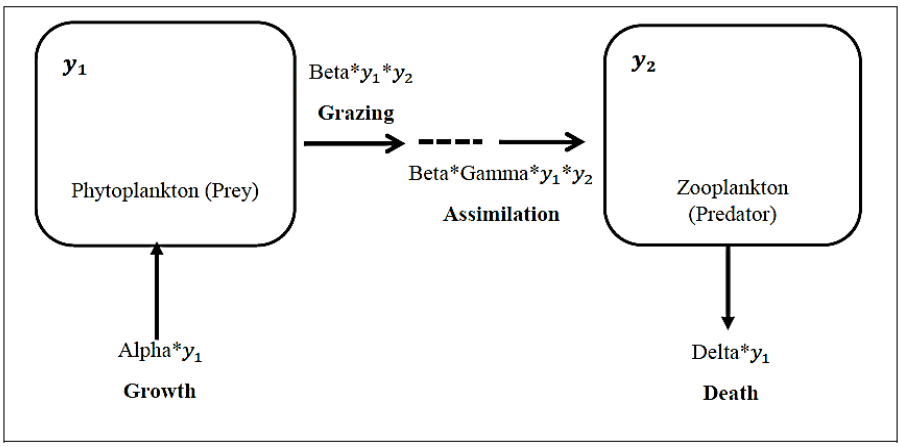


Fig 6: A schematic diagram of our simple Lotka-Volterra, predator-prey (Phytoplankton-Zooplankton) model. Here, the state variables are prey, y_1 and predator, y_2. The arrow from box, y_1 to box, y_2 has a dashed segment to represent the fact that grazing rate does not necessarily need to similar of assimilation rate.

These assumptions provide a first approximation of the dynamic interactions between phytoplankton and zooplankton [16, 17].

3.3. Model Formulation

The dynamics of the system are expressed using two coupled ordinary differential equations (ODEs), representing the change in population densities over time.Thus, itends up with two coupled ordinary differential equations (Figure 6):

$$\frac{dy_1}{dt} = \alpha y_1 - \beta y_1 y_2$$

$$\frac{dy_2}{dt} = \delta y_1 y_2 - \gamma y_2$$

where:

- y_1 and y_2 are prey and predator population densities, respectively.
- (α, β, γ, δ) are positive constants defining growth, predation, mortality, and conversion efficiency.

The first equation models prey growth reduced by predation, while the second describes predator growth fueled by prey consumption and reduced by natural mortality.

3.4. Equilibrium & Phase Plane Dynamics

The system's equilibria are found by setting the time derivatives to zero, which means that the populations are not changing with respect to time. This yields two biologically meaningful equilibria: extinction of both species, and non-zero coexistence, where $y_1 = \frac{\gamma}{\delta}$ and $y_2 = \frac{\alpha}{\beta}$.The equilibrium $E_0 = (0, 0)$ has eigenvalues α and $-\gamma$, indicating a saddle point and hence an unstable state, which means simultaneous extinction of both species is not an attracting condition. In contrast, the coexistence equilibrium $E^* = (\frac{\gamma}{\delta}, \frac{\alpha}{\beta})$ has purely imaginary eigenvalues $\pm i\sqrt{\alpha\gamma}$, making it a neutrally stable center. Ecologically, this suggests that the prey and predator populations can coexist through persistent oscillations around their equilibrium levels [18].

In the classical Lotka–Volterra marine prey–predator model, the phase plane shows the relationship between prey density $y_1$and predator densityy_2. The coexistence equilibrium is surrounded by closed trajectories, indicating continuous oscillations of both populations. When prey abundance increases, predators have more food, and their population subsequently increases. Increased predation then causes the prey population to decline. As prey becomes scarce, predator abundance also decreases, reducing predation pressure and allowing the prey population to recover. This process repeats cyclically. Because the eigenvalues at the coexistence equilibrium are $\pm i\sqrt{\alpha\gamma}$, the equilibrium is neutrally stable. Thus, trajectories neither converge to the equilibrium nor diverge from it. Instead, they form closed periodic orbits, representing persistent prey–predator oscillations.

3.5. Numerical Simulation

Numerical simulations were performed in MATLAB using standard ODE solvers to explore the system's dynamics under varying initial conditions. Phase plane analysis was conducted to identify limit cycles, equilibria, and transient dynamics. Simulation steps included:

1. Setting initial populations, $y_1(0)$ and $y_2(0)$ based on ecological scenarios.
2. Running time-domain simulations for sufficiently long periods to observe oscillatory behavior.
3. Plotting phase planes to identify stability and limit cycles.
4. Comparing results across solvers to ensure numerical accuracy and stability.

This approach allows the exploration of feedback mechanisms between phytoplankton and zooplankton populations and the evaluation of initial population effects on long-term dynamics, consistent with ecological theory.

3.6. Model Limitations

While informative, the model is simplified and assumes:

- Homogeneous environment with no spatial structure.
- No age structure or size variation within populations.
- No external forcing such as nutrient pulses, temperature changes, or human impacts.

Future extensions could include carrying capacities, Holling-type functional responses, stochasticity, and multiple interacting species to better reflect marine ecosystem complexity [19-21].

4. Result & Discussion

4.1. Predator–Prey Dynamics

So, the Lotka–Volterra model shows typical oscillation between phytoplankton and zooplankton. In Figure 7-a, with initial condition, y_0 = [1.0,0.1], we see that prey grows first, then predator grows after some lag, then prey decreases,predator decreases, and this cycle continues. Typical, yes, very classical predator-prey feedback. Phase-plane (Figure 7-b) shows a nice closed-loop limit cycle. Meaning, the system reaches a stable rhythm over time.

4.2. Influence of Initial Conditions

If we start with y_0 = [0.62,0.25] over 1100 days, initial oscillations are bigger, then slowly spiral into a limit cycle (Figure 8). Even when initial conditions deviate slightly, the system can self-organize and converge toward a stable state, reflecting the natural tendency of systems to maintain balance and stability.

4.3. Solver Comparison

The model was solved using ODE45, ODE15s, and ODE23, with the results showing close agreement across all three solvers (Figure 9). Minor differences arise from variations in their adaptive step-size procedures; however, these differences do not affect the overall stability of the system.

4.4. Sensitivity to Model Parameters

The sensitivity analysis presented in Table 2 demonstrates that variations in the growth rate (α) and grazing rate (β) substantially affect the simulated prey (P) and predator (Z) populations. As α increases from 150 to 240, the maximum prey population generally increases, indicating that a higher prey growth rate allows the prey population to reach higher peaks. However, the minimum prey population generally decreases with increasing α, suggesting that stronger prey growth also supports a larger predator population and consequently greater fluctuations in prey abundance.

The effect of β is also evident in the population dynamics. Increasing β generally increases the minimum prey population (P_{min}) while reducing the maximum predator population (Z_{max}) for a given α. This indicates that changes in

the grazing rate alter the balance between prey availability and predator abundance. The predator population is particularly sensitive to α, with $Z_{max}250$, Z_{max} increases from 280.38 at α = 150 to 532.91 at α = 240 (Figure 10).

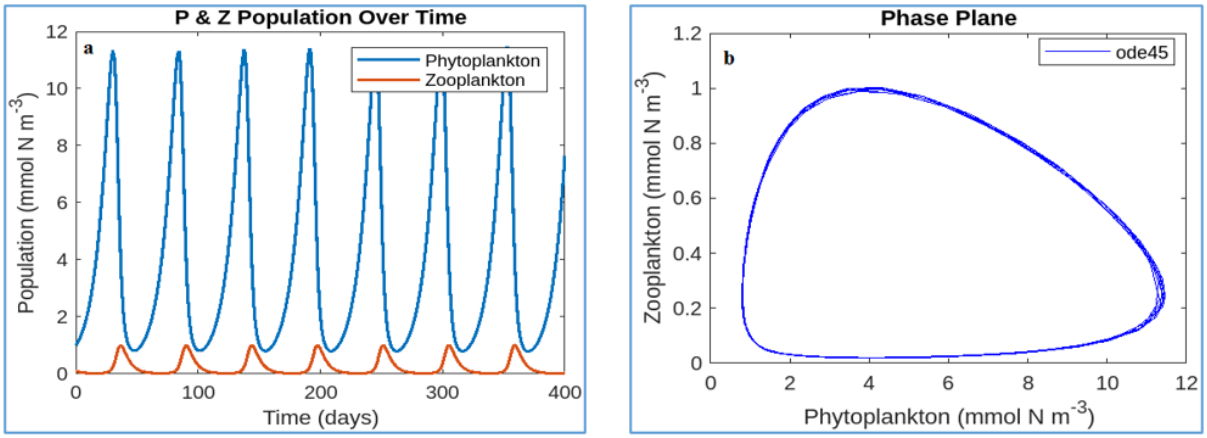


Fig 7: Time series (a) and phase-plane diagram (b) of phytoplankton (blue) and zooplankton (red) populations for y_0 = [1.0, 0.1] over 400 days. The phase-plane plot shows a stable limit cycle.

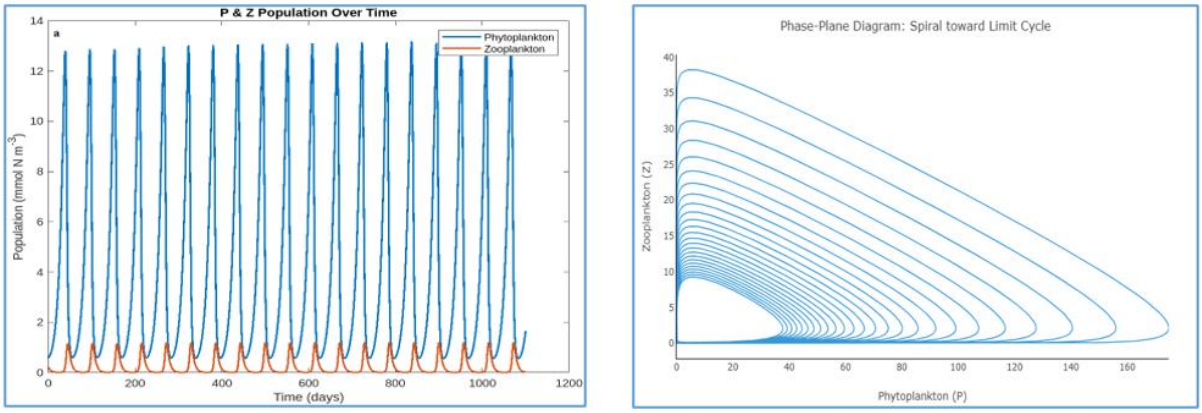


Fig 8: Time series (a) and phase-plane diagram (b) for y_0 = [0.62, 0.25] over 1100 days. Oscillation amplitude initially increases before spiraling toward the limit cycle.

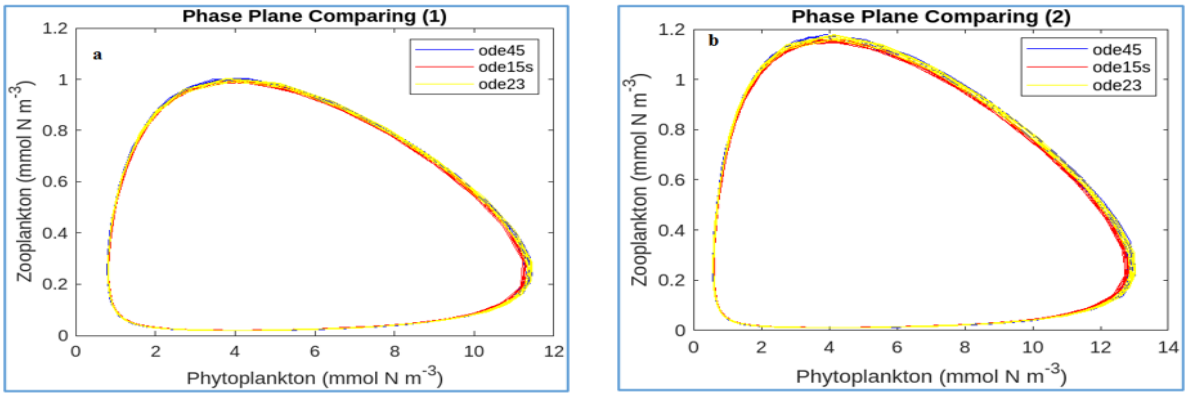


Fig 9: Comparison of phase-plane trajectories obtained using different ODE solvers for two distinct initial conditions. Solvers show overlapping results.

- For clarity in understanding the applied problem, the notations y_1 = P(Prey-Phytoplankton) and y_2 = Z(Predator-Zooplankton) are used in some places.

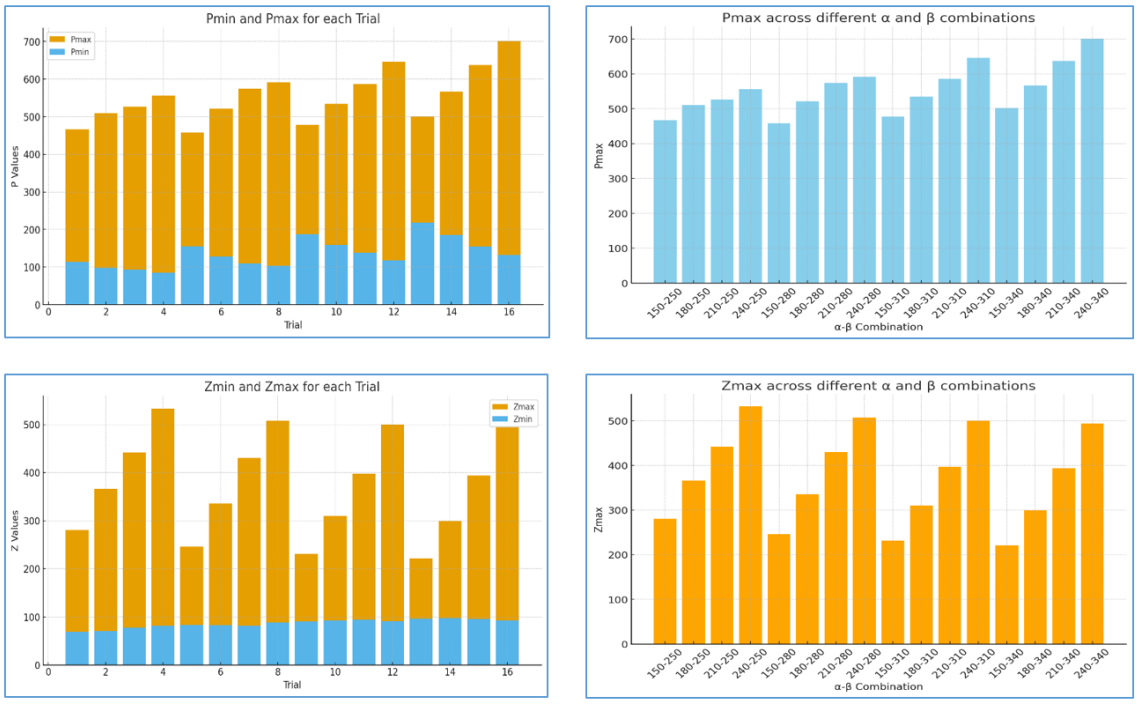


Fig 10: Sensitivity analysis of prey (P) and predator (Z) populations to variations in growth rate (α) and grazing rate (β) over 400 days with initial conditions, y_0 = [400, 100]. The four panels illustrate the minimum and maximum values of P and Z across all trials and α-β combinations, representing the overall system response and stability range.

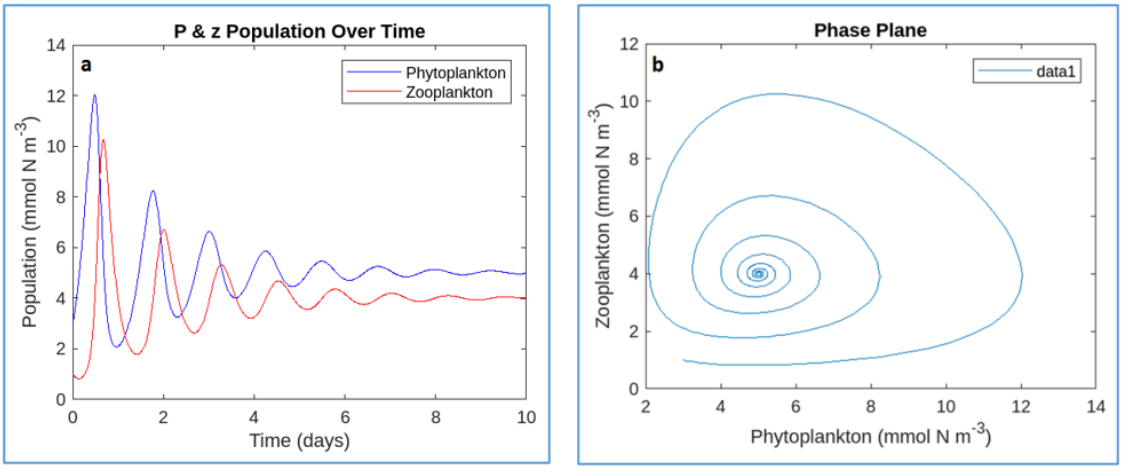


Fig 11: Population dynamics and phase-plane trajectory for the Lotka-Volterra predator-prey model. (a) Time series of phytoplankton (blue) and zooplankton (red) populations showing damped oscillations converging to equilibrium. (b) Phase-plane diagram illustrating the spiraling inward trajectory toward a stable limit cycle, indicating the system's approach to steady-state population levels.

Table 2: Parameter values and population outcomes for sensitivity analysis, y_0= [400, 100] and time = 400 days.

Trial	α	β	P_{init}	Z_{init}	P_{min}	P_{max}	Z_{min}	Z_{max}
1	150	250	400	100	114.13	466.98	68.49	280.38
2	180	250	400	100	98.11	510.26	70.72	366.65
3	210	250	400	100	92.64	526.53	77.79	442.26
4	240	250	400	100	84.19	556.06	81.07	532.91
5	150	280	400	100	155.53	457.95	83.19	245.72
6	180	280	400	100	128.34	522.09	82.43	335.74
7	210	280	400	100	109.02	574.54	81.69	430.15
8	240	280	400	100	103.07	592.07	88.34	507.56
9	150	310	400	100	186.93	477.83	90.46	231.08
10	180	310	400	100	159.73	534.20	92.69	309.99
11	210	310	400	100	138.49	586.49	94.26	397.55
12	240	310	400	100	117.24	646.17	90.81	500.23
13	150	340	400	100	217.57	501.46	96.11	221.25
14	180	340	400	100	184.55	567.19	97.76	299.36
15	210	340	400	100	154.47	637.48	95.25	393.93
16	240	340	400	100	131.32	700.91	92.62	494.07

Overall, the sensitivity analysis shows that the choice of model parameters has a significant influence on both the magnitude and range of prey and predator populations. Therefore, appropriate parameter selection is important forobtaining reliable predictions of the predator–prey system and for understanding its stability under different ecological conditions.

4.5. Population Dynamics and Damping

In the classical Lotka–Volterra model, predator and prey populations exhibit continuous oscillations with constant amplitude. This behavior is associated with eigenvalues that are purely imaginary, indicating neutral stability of the coexistence equilibrium. When additional ecological factors, such as prey competition or resource limitation, are incorporated, the eigenvalues may acquire negative real parts while retaining an imaginary component. The negative real part causes the oscillation amplitude to gradually decrease, while the imaginary component represents the oscillatory behavior. Consequently, the system exhibits damped oscillations, with predator and prey populations fluctuating around the equilibrium and eventually approaching a stable coexistence state [22].

Time series (Figure 11-a) shows phytoplankton first bloom, zooplankton follow. Oscillation amplitude slowly decreases. Phase-plane (Figure 11-b) spirals inward-finally, equilibrium. Very nice for ecosystem stability; no crazy boom-bust cycles.

4.6. Ecological Implications

The Model shows marine food web dynamics nicely: prey bloom, predator responds, then both settle down. Even small changes in initial conditions make temporary larger oscillations, but the system always returns to equilibrium.

5. Conclusion

In this study, we see that the classic Lotka–Volterra predator-prey model nicely captures the dynamic relationship between phytoplankton and zooplankton in the marine ecosystem. The numerical results demonstrate that the dynamics of the system are strongly influenced by the initial population densities of both phytoplankton and zooplankton. Variations in the initial population densities of phytoplankton and zooplankton significantly influence the amplitude and phase of the resulting population oscillations. Sensitivity analysis further indicates that the model parameters play an important role in determining the stability and temporal behavior of the plankton populations. Changes in the phytoplankton growth rate, zooplankton predation rate, and other interaction parameters can significantly modify the oscillation characteristics and the balance between prey and predator populations. Finally, the damped oscillatory behavior illustrates a more realistic tendency toward stabilization, in which successive fluctuations in phytoplankton and zooplankton gradually decrease with time. Overall, the analysis highlights the usefulness of mathematical predator–prey models in understanding marine plankton dynamics,

For future work, it will be very beneficial to extend this model by including more trophic levels, nutrient cycling, temperature changes, and human impacts such as overfishing or pollution. Adding randomness to the model could make it more realistic as well. Moreover, validating the model with real data from specific ocean regions will increase its predictive power. Such improvements will make the model a valuable tool for managing and conserving our precious marine ecosystems sustainably.

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