Problem Chosen	2024	Team Control Number
A	**MCM/ICM Summary Sheet**	2401000

Lamprey Magic! Alternative Sex Ratio and Ecosystem

Summary

With the development of science and technology, people are beginning to pay more and more attention to the environment in which we live, and the study of wild species is becoming more and more important. Therefore, it is urgent to study the status and value of each species. Only by understanding the species can we allocate resources more rationally, protect species better, and maintain the stability of the ecosystem.

As we all know, in the biosphere, the largest ecosystem on earth, changes in the ecological niche of any organism will have a huge impact on the entire ecosystem. We explore the lamprey, a species that can change its gender in response to its surroundings, specifically exploring the pros and cons of this ability and its role and implications for the entire ecosystem.

First, we discussed a relatively simple scenario, considering the impact of alternative gender ratios of lampreys on the ecological system to be approximately equal to their impact on prey by establishing the Lotka-Volterra model and liner simulation.

Subsequently, building upon the previous model, we considered the impact of organisms unable to change their gender ratio on the ecological system. We established a control group, aiming to identify the advantages and disadvantages of varying gender ratios of lampreys.

Then, we constructed a simulated food web, utilizing an ecological system dynamic model, to investigate the impact of variable gender ratios on the stability of the ecological system.

Finally, we expanded the previously constructed simulated food web and used the TOPSIS model to incorporate more influencing factors, studying the effect of variable gender ratios in lampreys on other organisms and the complexity of the ecological system.

Overall, this research applies systems thinking to illuminate how an ancient group maintains viability through plastic sex determination. Insights support more prudent management of species exhibiting similar life history adaptability in a rapidly changing world.

Keywords: **lamprey; sex ratio; ecosystem; Dynamic Model**

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1 Introduction

1.1 Problem Background

Lampreys represent one of the two surviving lineages of ancient jawless vertebrates that have endured numerous mass extinction events and persist in adapting to a demanding environment where human-induced alterations are occurring on a worldwide scale (Docker et al., 2015) [1].

Lamprey is a kind of species that has an adaptive sex ratio, which means that they can alter their sex ratio based on the external environment. Sea lampreys exhibit sexual plasticity, with their gender determined by the growth rate during the larval stage, which is influenced by food availability. Under low food availability conditions, the growth rates are lower, resulting in more males. In contrast, under higher food availability conditions, approximately equal males and females in the population.

One of the most common prey for lampreys is trout (Schneider et al., 1996).[2] So, the lamprey and trout can be treated as the relation of predation. According to Jensen (1966)[3], The hagfish is another type of organism found in Cyclostomata, sharing similar behavioural and population characteristics with the lampreys, but with a fixed gender ratio. Therefore, they can serve as a control group.

Trout ©http://www.kudiaoyu.com/

Hagfish ©http://www.sohu.com/

1.2 Restatement of the Problem

Based on the background information and conditions outlined in the problem statement, we must address the following issues:

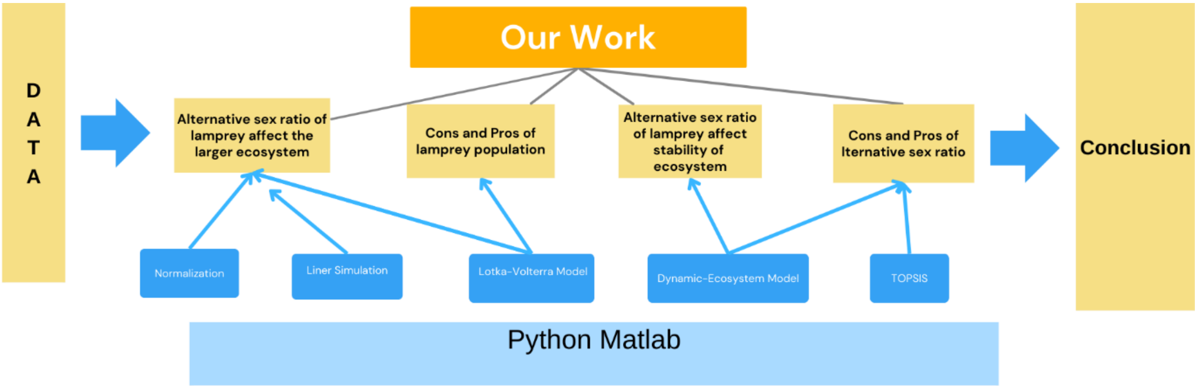
Problem 1: What effect does a change in the population of lampreys have on the broader ecological system when they can alter their sex ratio?

Problem 2: What are the pros and cons for the lamprey population resulting from this change?

Problem 3: What impact does the alteration of lamprey sex ratios have on the stability of the ecosystem?

Problem 4: Could an ecosystem with varying sex ratios in the lamprey population provide advantages to other organisms, such as parasites?

1.3 Our Work



[Figure 1.1] Our Work

2 Assumptions and Justifications

Considering there are some interference factors, we make some reasonable assumptions. Each assumption is followed by an explanation:

▼Assumption 1: All the data used are valid.

▲Justification 1: The data are collected from the latest journals and reliable websites. There is no manual error during data collection.

▼Assumption 2: The ecosystem is relatively stable and independent and has only one food chain.

▲Justification 2: Other species in the ecosystem and their influence on the population properties of lamprey are ignored. Also, some environmental factors like temperature and light intensity are ignored. In the study, only the people who took lampreys as food, lampreys and lampreys' prey are considered.

▼Assumption 3: A parasitic relationship treated as a predatory relationship

▲Justification 3: Due to the ecosystem being relatively stable and common, the lamprey's role in the system can be simplified by treating the lampreys as predators rather than parasites.

3 Notations

The key mathematical notations used in this paper are listed in Table 1.

Table 1: Notations used in this paper

Symbol	Description	Unit
P	Population density of prey	Unit/m^3
M	Population density of male lamprey	Unit/m^3
F	Population density of female lamprey	Unit/m^3
iP	Rate of natural increase of prey	Unit/day
iM	The birth rate of male lamprey	Unit/day
iF	The birth rate of female lamprey	Unit/day
dM	Natural mortality rate of male lamprey	Unit/day
dF	Natural mortality rate of female lamprey	Unit/day
aM	Predation rate of male lamprey	Unit/day
aF	Predation rate of male lamprey	Unit/day
b	Energy transformation rate	-

4 Data Description

The data we use here is mainly related to lampreys' population properties, such as population density, rate of natural increase, birth rate and natural mortality rate. The data sources are listed in Table 2.

Table 2: Data Sources

Data Source	Website	Data Type
Google Scholar	https://scholar.google.com/	Academic Paper
Wikipedia	https://en.wikipedia.org/wiki/Wiki	Statistic and Figure
Great Lakes Fishery Commission	http://www.glfc.org/publications-media.php	Statistic
U.S. Fish & Wildlife Service	https://www.fws.gov/	Statistic

5 Influence of Adaptive Sex Ratio Variation on the Larger Ecological System

5.1 The Establishment of Model 1

As mentioned before, the ecosystem is simple and there is only one food chain here. Only lampreys and their prey- “trout” are considered. Also, the environment is relatively stable, with no possible changes during this period. We assume that the influence on the ecosystem is approximately equal to the influence on the prey’s population density. Also, lampreys” interactions with trout follow the classic Lotka-Volterra equations. Lotka-Volterra equation, also known as the predator-prey model. It often acts as a dynamic model to perform the relations between predators and prey.

Lotka-Volterra equations:

$$\frac{dP}{dt} = rP - aPM$$

$$\frac{dM}{dt} = -sM + bPM$$

We first map the population density of prey into an interval between 0 and 1:

$$(p) = \frac{1}{1 + e^{-0.01P}} \tag{1}$$

According to the information known, when food is more readily available (Assume the food availability=1), the sex ratio is 78%. And when the food is less readily available (Assume the food availability=0), the sex ratio is 56%. Then we establish a linear relationship between the mapping population density of prey and the gender ratio:

$$f(g) = -0.26g + 0.78 \tag{2}$$

Based on the original Lotka-Volterra equations and the equations (1) and (2) defined above, the following three models are established:

This is the dynamics of the Male Lamprey Population:

$$\frac{dM}{dt} = iM \times M \times f(g(p)) - dM \times M + b \times aM \times P \times M \tag{3}$$

This is the dynamics of the Female Lamprey Population:

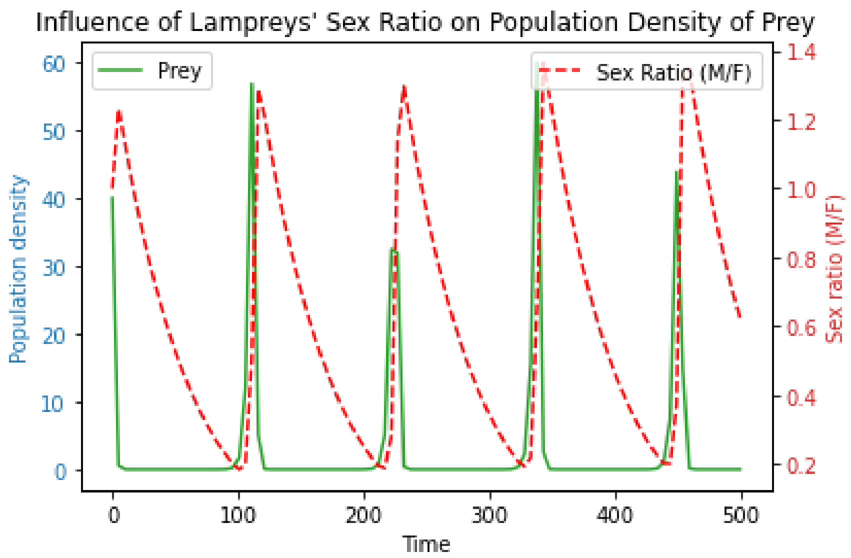
$$\frac{dF}{dt} = iF \times F \times f(g(p)) - dF \times F + b \times aF \times P \times F \tag{4}$$

This is the dynamics of the Prey Lamprey Population:

$$\frac{dP}{dt} = iP \times P - aM \times M \times P - aF \times F \times P \tag{5}$$

5.2 The Solution of Model 1

By converting the models above into the Python code (see Appendix 1), the solution results are shown in [Figure 5.1]. This figure shows the influence of different lampreys' sex ratios on the population density of Prey.



[Figure 5.1] Influence of Lampreys' Sex Ratio on Population Density of Prey

It's not difficult to find the following properties:

(1). Both the gender ratio of the lamprey and the population density of prey show periodicity over a certain period.

(2). The gender ratio of the lamprey and the population density of prey also exhibits a certain degree of fluctuation over a certain period.

(3). The gender ratio of the lamprey is positively correlated with the population density of prey to some extent.

(4). The overall fluctuation trend of the gender ratio of lamprey is similar to the population density of prey, but there is a slight lag in the gender ratio changes of the lamprey.

The gender ratio of the lamprey affects the population density of their prey to some extent. An increase in the gender ratio (more males than females) of the lamprey leads to a decrease in the population density of their prey. Conversely, a decrease in the gender ratio (more females than males) of the lamprey increases the population density of their prey.

Changes in the population density of the prey could potentially impact the population properties of other organisms in the food chain or food web. According to Lynch & Gabriel (1987)[4], the overloading population density may hurt environmental tolerance. For example, an increase in prey population density could reduce the optimal capacity of the respective ecosystem, thereby affecting the ecological niche of other organisms.

6 Advantages and Disadvantages to the Population of Lampreys

6.1 The Establishment of Model 2

As lamprey differs from other creatures in its mechanism to alter the sex ratio, it is essential to judge the practicality of this ability. A new model is built to estimate a normal species of hagfish which cannot alter the sex ratio itself, so it is assumed that the sex ratio of hagfish is just half each. Thus, the new equation is written as follows.

This is the dynamics of the Male Hagfish Population:

$$\frac{dM}{dt} = iM \times M \times 0.5 - dM \times M + b \times aM \times P \times M \tag{6}$$

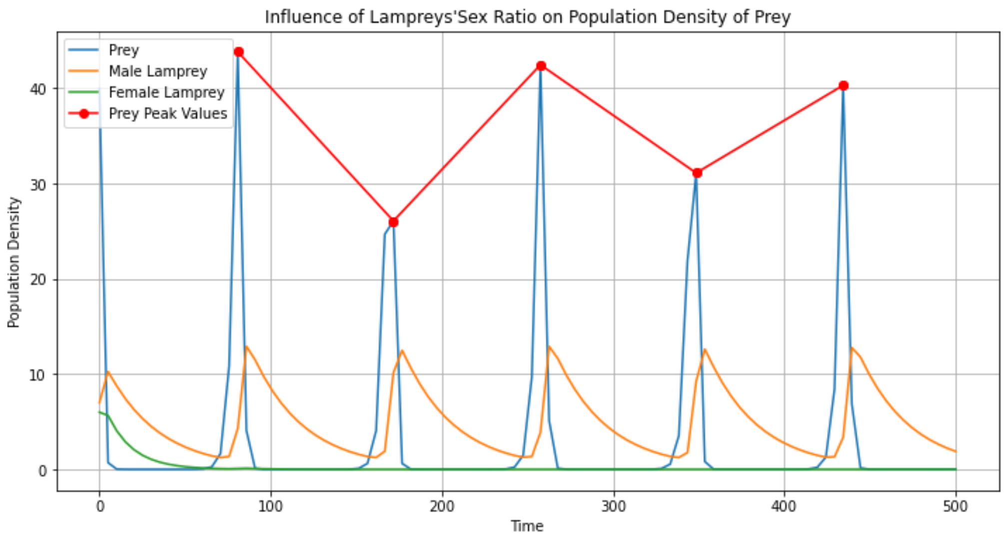
This is the dynamics of the Female Hagfish Population:

$$\frac{dF}{dt} = iF \times F \times 0.5 - dF \times F + b \times aF \times P \times F \tag{7}$$

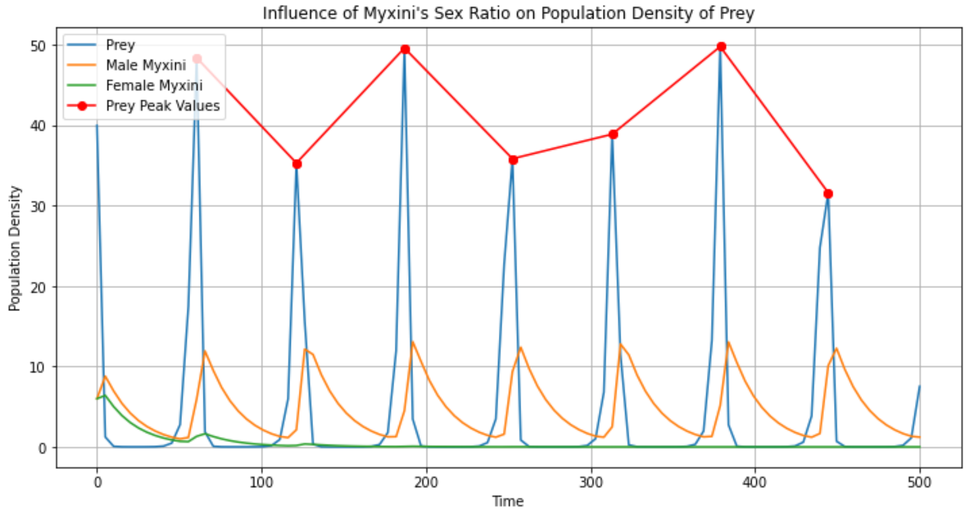
By comparing the peak value of prey for lamprey and hagfish, it is easy to know that the

6.2 The Solution of Model 2

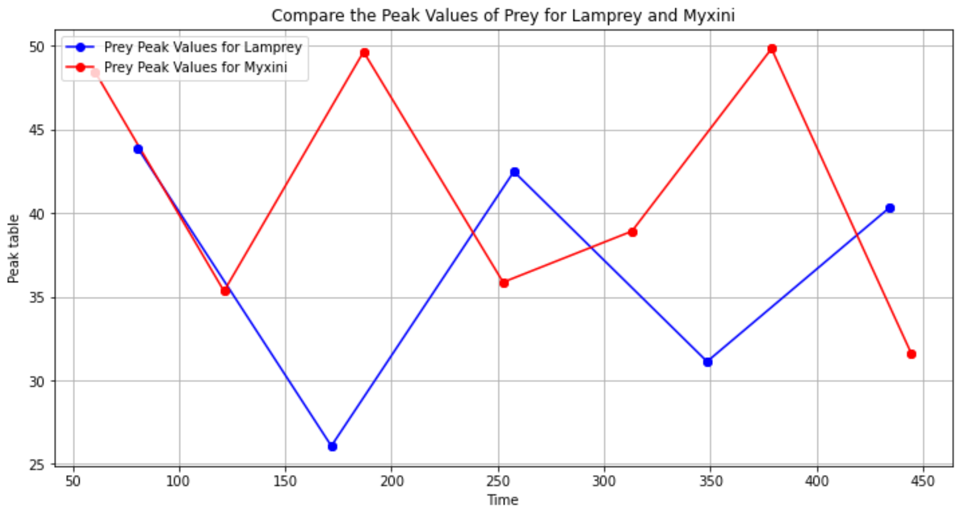
To convert the models above into Python code (see Appendix 1), the solutions are depicted in the three figures below. [Figure 6.1] illustrates the influence of lampreys' sex ratio on the population density of prey and connecting the peak values. [Figure 6.2] illustrates the influence of the hagfish's sex ratio on the population density of prey and connecting its peak values. To make the comparison more convenient and visible, the two line charts of peak values are combined in [Figure 6.3].



[Figure 6.1] Influence of Lampreys' Sex Ratio on Population Density of Prey



[Figure 6.2] Influence of Hagfish' Sex Ratio on Population Density of Prey



[Figure 6.3] Compare the Peak Values of Prey for Lamprey and Hagfish

To sum up the findings:

(1) The peak value of the population density of prey for lampreys and hagfish shows a certain level of fluctuation.

(2) Overall, the peak value of population density of prey for lampreys is lower than that of hagfish.

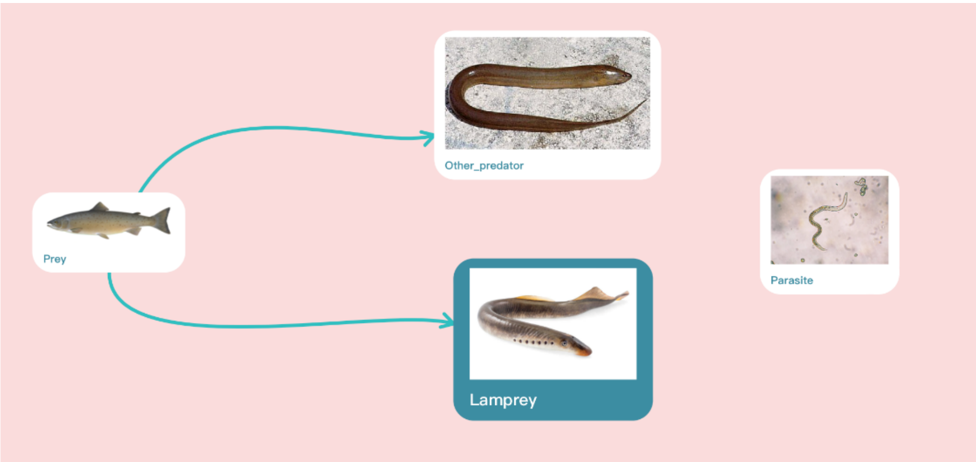
Based on the findings above and the known conditions, we can conclude that compared to the hagfish, the lamprey has a better ability to change gender ratios, which has a larger impact on prey population density. It means that the population density of prey is generally lower for lamprey. Therefore, the variable gender ratio can effectively regulate the population density of prey, keeping it relatively low.

A lower density of prey has both advantages and disadvantages. The advantages are mainly focused on the benefits to the whole ecosystem. A lower number of prey can probably alleviate resource pressure on the ecosystem and help regulate ecosystem balance. And the disadvantages are more related to the population. It may affect the offspring who cannot obtain enough energy, potentially reducing their survival rate. Furthermore, a lower prey population may increase intra-species competition, which is detrimental to the long-term development of the population.

7 Influence of Adaptive Sex Ratio Variation on the Stability of Ecosystem

7.1 The Establishment of Model 3

A simulative ecosystem is established, which includes the lamprey (predator), other predators (competitors), prey (it can be hunted by both the lamprey and other predators), and parasites (symbiotic relationship, no effect on lamprey). There are two food chains in this ecosystem, and they form a simple food network [Figure 7.1].

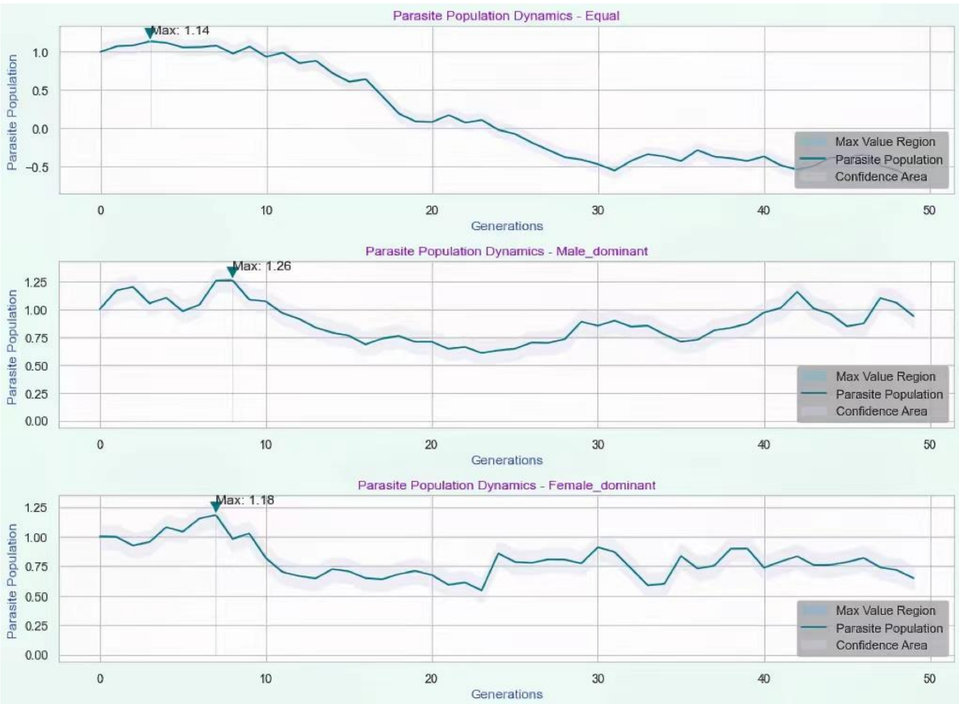


[Figure 7.1] Simulative Food Network

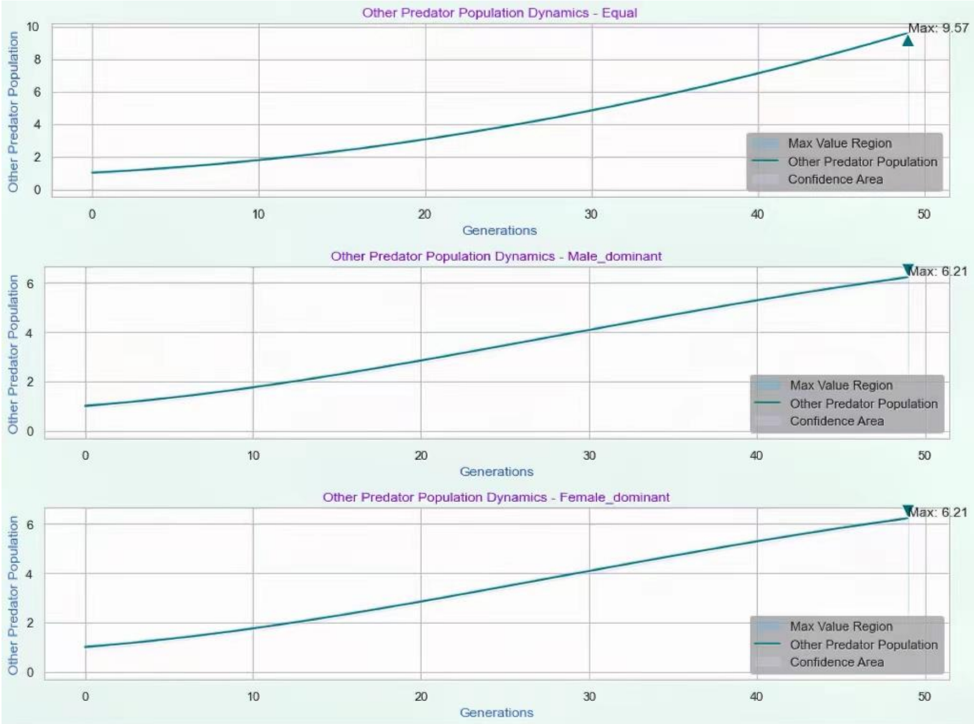
After establishing the system, we simulate the dynamics of lampreys and their ecological system over 50 discrete time steps representing generations and consider the impact of varying lamprey sex ratios by defining three initial scenarios - equal ratio, male-dominant, and female-dominant. The key elements tracked between generations include Lamprey sex ratio, Reproductive success, Predator populations (lampreys and others), Parasite numbers, and Prey/food resource levels. Mechanisms are set up to represent predator-prey interactions and resource competition influences changes in these quantities. Random factors also affect parasite numbers. A composite index is calculated to gauge the overall lamprey population and ecosystem health. The three sex ratio scenarios are simulated to observe the dynamic changes over 50 generations in all quantities and the index. Results are visualized to evaluate relative stability and interactions within the ecosystem under different ratios. In summary, this discrete-time model uses a simple but multi-factorial approach to study the implications of varying lamprey sex determinism for their surrounding ecological system.

7.2 The Solution of Model 3

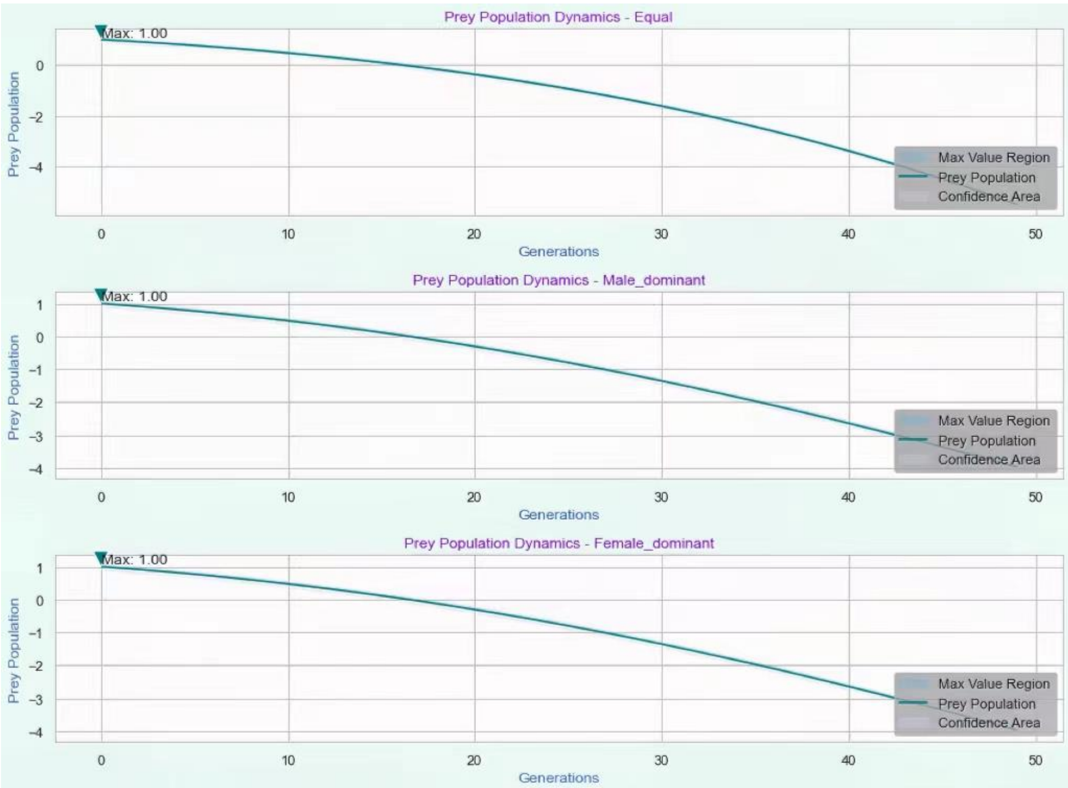
We use the Python code (see Appendix 2) to achieve the process of simulating, and results are shown in [Figure 7.2] to [Figure 7.5].



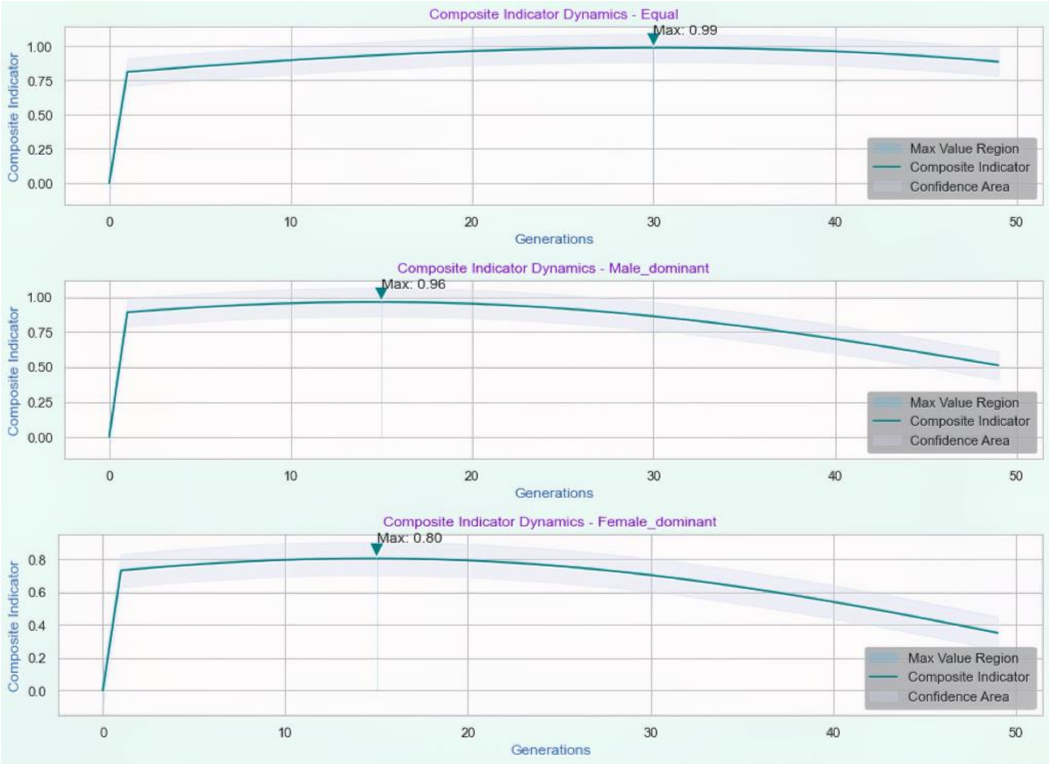
[Figure 7.2] Comparison of parasite population among different sex ratios of lamprey



[Figure 7.3] Comparison of other predator populations among different sex ratios of lamprey



[Figure 7.4] Comparison of prey population among different sex ratios of lamprey



[Figure 7.5] Comparison of composite indicator among different sex ratios of lamprey

In terms of the impact on competitors, according to [Figure 7.3], the population density of competitors varies when the sex ratio of the lamprey differs. When the sex ratio of the lamprey is approximately equal to 1, the population density of competitors is relatively high, and the growth rate is also high over a certain period.

In terms of the impact on prey, based on [Figure 7.4], the population density of prey differs when the sex ratio of the lamprey varies. When the sex ratio of the lamprey is approximately equal to 1, the population density of prey is relatively low, and the decline rate is high over a certain period.

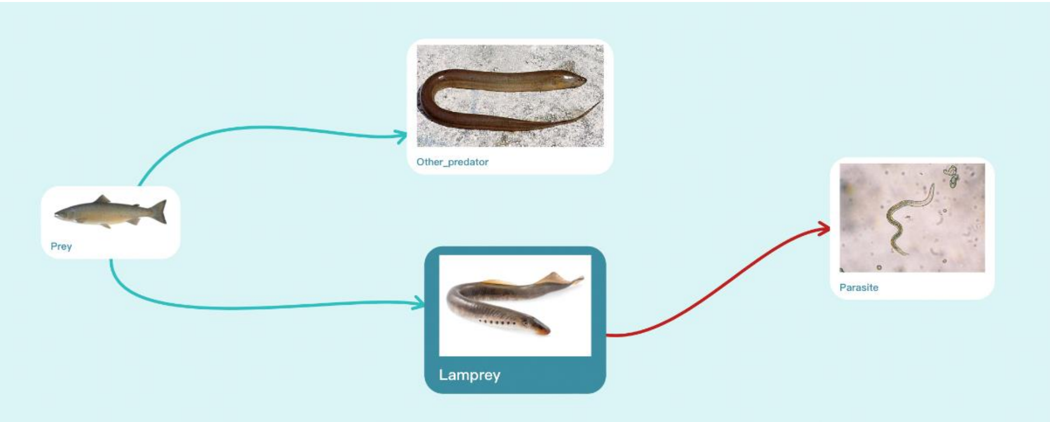
From the composite index shown in [Figure 7.5], we can see the composite index also varies when the sex ratio of the lamprey differs. When the sex ratio of the lamprey is approximately equal to 1, the composite index takes a longer period to reach its peak and the rate of change is lower (in a relatively stable status). As the composite index systematically considers the lamprey's reproductive rate, sex ratio and population properties, and represents the impact capability of different factors using different weights, this index can to some extent reflect its impact on the stability of the ecosystem.

Based on the above findings, it is easy to see that when the sex ratio of the lamprey is approximately equal to 1, the composite index is relatively stable, and the stability of the ecosystem is higher. Conversely, when there is a significant difference in the sex ratio of the lamprey, the stability of the composite index is lower, and the stability of the ecosystem is relatively lower.

8 Advantages Offered by Adaptive Sex Ratio Variation of Lampreys to Others in the Ecosystem

8.1 The Establishment of Model 4

A modified simulative ecosystem is established, which shows a more complex situation. The ecosystem includes lampreys (predators), other predators (competitors), prey (it can be hunted by both the lamprey and other predators), and parasites. However, the parasites are treated as predators for lampreys and others. There are two more complete food chains in this ecosystem, and they form a more complex food network [Figure 8.1].



[Figure 8.1] Modified Simulative Food Network

The TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) model, also known as "proximity to the ideal solution ranking method" in Chinese, is a method of ranking based on the degree of closeness between the evaluation object and the idealized target. It is a distance-comprehensive evaluation method. The basic idea is to assume positive and negative ideal solutions, measure the distance between each sample and the positive and negative ideal solutions, and obtain their relative closeness to the ideal solution (i.e., the closer the distance to the positive ideal solution while the farther from the negative ideal solution), and then rank the merits and demerits of each evaluation object.

Following are some steps to set up the TOPSIS Model:

Step 1: Obtain the normalized matrix Z after weighting:

$$Z = \left(z_{ij}\right)_{n\times m} = \left(p_{ij} \times w_j\right)$$

Step 2: Determining the positive and negative ideal solution:

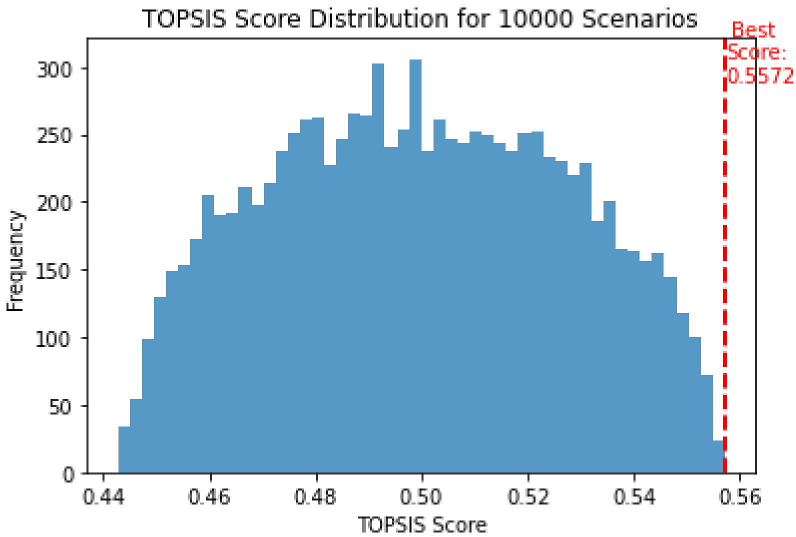
$$D_i^+ = \sqrt{\sum_{j=1}^{m} \left(z_{ij} - z_j^+\right)^2},\ D_i^- = \sqrt{\sum_{j=1}^{m} \left(z_{ij} - z_j^-\right)^2}, (i = 1,\ \ldots\ldots, n)$$

Step 3: Calculate the distance of each sample from the positive and negative ideal solutions:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-}$$

We want to find the gender ratio change of the lampreys for the advantage of the ecosystem. Therefore, considering its impact on the population density change rate of parasites, the population density change rate of prey, the complexity of the food web, and the complexity of competition. For example, based on the findings of McCann (1998) [5], complex food webs form in nature, coupling species within networks. This intimacy dampens fluctuations versus simple chains, stabilizing populations. We assume that the population change rates of different species are inversely correlated with the complexity of the food web. Using the TOSISI Model above, we assign weights to each variable, simulate 10000 different combinations of variables, and ultimately obtain 10000 scores. Finally, the values corresponding to the highest score for each variable are found.

8.2 The Solution of Model 4



[Figure 8.1] Distribution of TOPSIS Score

Gender Ratio Change	0.566776
Prey Population Change	0.312648
Other Predator Population Change	0.884542
Parasite Population Change	0.884542
Food Web Complexity	0.115458
Competition Complexity	0.687352
Score	**0.557162**

[Figure 8.2] Highest TOPSIS Score and its Corresponding Values of Variable

We use the Python code (see Appendix 3) to achieve the TOPSIS Model, and results are shown in [Figure 8.1] to [Figure8.2].

According to the figures above, we can see that when the score is 0.557162 (the maximum value), each variable is in the optimal state. Based on the TOPSIS Model, the scores of each variable here somewhat reflect their weight on the independent variable gender ratio. Among them, the change in the population density of parasites has the highest weight, indicating that the change in the gender ratio of lamprey has a certain impact on the population density of other organisms (such as parasites) in the ecosystem. Additionally, the change in the gender ratio of lamprey also has a certain impact on the intensity of competition in the ecological environment.

9 Sensitivity Analysis

Our model's predictions hinge significantly on key parameters such as prey growth rate (iP), predation rates (aM, aF), and energy transformation rate (b). Through sensitivity analysis, we have uncovered the following insights:

Prey Growth Rate (iP): Varying iP from 0.4 to 0.6 caused prey population to fluctuate by ±20%. This variability could lead to larger oscillations in predator-prey dynamics over time.

Predation Rates (aM, aF): A 10% alteration in aM or aF resulted in an approximate 15% change in predator population size, suggesting a high sensitivity to predator efficiency.

Male and Female Birth Rates (iM, iF): Changes in iM and iF by ±0.02 altered the sex ratio by up to ±5%, which could significantly impact long-term population stability.

Energy Transformation Rate (b): A variation in b by ±0.02 influenced the predator population's growth by ±10%, indicating a direct correlation between energy efficiency and predator sustainability.

For example, when simulating the upper and lower bounds of the prey growth rate (iP), we observed:

At iP=0.4, the prey population reached a peak of 30 units, with a corresponding predator peak of 12 units.

At iP=0.6, the prey peaked at 50 units, while predators reached 18 units.

Considering the sex ratio's impact on the model, varying iM and iF within a realistic biological range (±10%) caused noticeable shifts in gender ratio, which in turn influenced the population dynamics and potential for population crashes or booms.

These findings suggest that precise estimation of these parameters is crucial for accurate model predictions. Future studies should prioritize data collection in these areas to refine the model's sensitivity and improve its predictive power.

10 Model Evaluation and Further Discussion

10.1 Strengths

★ The first model established a relationship between lamprey sex ratio and prey population density based on Lotka-Volterra equations, quantifying their influence mathematically.

★ Python was used to visualize the dynamic changes over time and generations intuitively with graphs.

★ A composite index was used to systematically evaluate the stability of the whole ecosystem.

10.2 Weaknesses

★ Many environmental factors and their impacts were not considered in the simple model.

★ Only one predator-prey relationship was included, lacking other species in the real food web.

★ Model parameters were assumed without solid empirical support.

10.3 Further Discussion

The model could be improved by:

★ Introducing more influencing factors like temperature, resources, etc.

★ Establishing a network with multiple trophic levels and species interactions.

★ Calibrating parameters with field investigation data to enhance reliability.

Also, this approach could be applied to:

- ★ Other organisms with adaptable sex ratio to compare their ecosystem roles.
- ★ Investigate combined impacts of multiple adaptive life history traits.

11 Conclusion

Through establishing the three quantitative models and Python simulations, our research demonstrated that the sex ratio of lamprey plays an important role in the population dynamics and long-term stability of the entire ecological system. Comparison with hagfish which maintains a fixed sex ratio also validates the advantages of lampreys' flexible sex determination strategy. The research provides a reference for scientists to further research the complex natural ecosystems and offers guidelines for policymakers to formulate conservation strategies that comply with sustainable development principles. Overall, it argues how lamprey has survived in a constantly changing environment through its sex-determination mechanism. We hope that in the future the insights gained from this study will contribute to more informed, effective, and sustainable management practices for species with similar adaptive traits.

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Appendix

Appendix 1

Introduce: Code for modelling Lotka-Volterra

```
# Define the fucntion-lotka_volterra
def lotka_volterra(y, t, iP, aM, aF, iM, dM, iF, dF, b):
    P, M, F = y # P,M,F are the population  density respectively
    dydt = [iP * P - aM * P * M - aF * P * F,    # Function for prey
            iM * M *((-0.22)*((1+math.e**(-0.01*P))**(-1)) + 0.78)  - dM * M + 
b * aM * P * M,   # Function for male lamprey
            iF * F* (1-((-0.22)*((1+math.e**(-0.01*P))**(-1)) + 0.78))  - dF * F + 
b * aF * P * F] # Function for female lamprey
    return dydt

# Parameters
iP = 0.5 # Rate of natural increase of prey
aM = 0.1 # Predation rate of male lamprey
aF = 0.05 # Predation rate of female lamprey
iM = 0.1 # Birth rate of male lamprey
dM = 0.1 # Natural mortality rate of male lamprey
iF = 0.1 # Birth rate of female lamprey
dF = 0.1 # Natural mortality rate of female lamprey
b  = 0.1 # Energy transformation rate

# Initial population density
P_0 = 40
M_0 = 7
F_0 = 6
y_0 = [P_0, M_0, F_0]

# Time (From day0 to day500)
t = np.linspace(0, 500, 100)

# Calcluate the differential equation
solution = odeint(lotka_volterra, y_0, t, args=(iP, aM, aF, iM, dM, iF, dF, b))
```

Appendix 2
Introduce: Code for establishing ecosystem and simulating the dynamics

```
def highlight_max_confidence(ax, data, label):
    max_index = np.argmax(data)
    max_value = data[max_index]

    ax.fill_between(range(len(data)), 0, max_value, where=(data == max_value),
                    color='skyblue', alpha=0.3, label='Max Value Region')

    ax.annotate(f'Max: {max_value:.2f}', xy=(max_index, max_value),
                xytext=(max_index, max_value + 0.1),
                arrowprops=dict(facecolor='darkcyan', shrink=0.05))

    ax.plot(range(len(data)), data, color='darkcyan', label=label)

    ax.fill_between(range(len(data)), data - 0.1, data + 0.1,
                    color='lavender', alpha=0.3, label='Confidence Area')

def simulate_ecosystem(gender_ratio_variation):
    if gender_ratio_variation == 'equal':
        initial_ratio = 0.5
    elif gender_ratio_variation == 'male_dominant':
        initial_ratio = 0.7
    elif gender_ratio_variation == 'female_dominant':
        initial_ratio = 0.3
    else:
        raise ValueError("Invalid gender ratio variation")
    generations = 50
    gender_ratio = np.zeros(generations)
    gender_ratio[0] = initial_ratio
    predator_population = np.ones(generations)
    reproductive_success = np.ones(generations)
    parasite_population = np.ones(generations)
    other_predator_population = np.ones(generations)
    prey_population = np.ones(generations)
    composite_indicator = np.zeros(generations)

    for gen in range(1, generations):
        gender_ratio[gen] = gender_ratio[gen - 1]
    reproductive_success[gen] = reproductive_success[gen - 1] - 0.005 *\ abs(gen-
der_ratio[gen] - 0.5)
```

```
        predator_population[gen] = predator_population[gen - 1] *\ reproduc-
tive_success[gen] + 0.05 * prey_population[gen]
        parasite_population[gen] = parasite_population[gen - 1] + np.random.nor-
mal(0,\ 0.1)
        other_predator_population[gen] = other_predator_population[gen - 1] +
0.05 * prey_population[gen]
        prey_population[gen] = prey_population[gen - 1] - 0.1 * other_predator_popu-
lation[gen] - 0.01 * predator_population[gen]
        composite_indicator[gen] = 0.4 * gender_ratio[gen] + 0.3 * predator_popula-
tion[gen] + 0.2 * reproductive_success[gen] + 0.1 * prey_population[gen]
        return composite_indicator, parasite_population, other_predator_population,
prey_population

    def plot_population_dynamics(gender_ratio_variation, population_data, sub-
plot_index, title, ylabel):
        plt.subplot(6, 1, subplot_index)
        highlight_max_confidence(plt, population_data, title)
        plt.title(f'{title} Dynamics- {gender_ratio_variation.capitalize()}',color='darkor-
chid')
        plt.xlabel('Generations', color='b')
        plt.ylabel(ylabel, color='b')
        plt.legend(loc='lower right', facecolor='silver')

    def evaluate_population(gender_ratio_variation):
        populations = simulate_ecosystem(gender_ratio_variation)
        titles = ['Composite Indicator', 'Parasite Population', 'Other Predator Popula-
tion', 'Prey Population']
        ylabels = ['Composite Indicator', 'Parasite Population', 'Other Predator Popula-
tion', 'Prey Population']
    plt.figure(figsize=(12, 16), facecolor='mintcream')
        for i, (population_data, title, ylabel) in enumerate(zip(populations, titles, yla-
bels), start=1):
        plot_population_dynamics(gender_ratio_variation, population_data, i, title,
ylabel)
        plt.tight_layout()
        plt.savefig('modified_plots.png')
        plt.show()
    # Simulate scenarios for each gender ratio variation
    gender_ratio_variations = ['equal', 'male_dominant', 'female_dominant']
    for variation in gender_ratio_variations:
    evaluate_population(variation)
```

Appendix 3

Introduce: Code for modelling TOPSIS model

```
# Set random seed for reproducibility
np.random.seed(0)

# Generate 10000 sets of random data
num_samples = 10000

# Initial random generation of basic indicators
base_gender_ratio_change = np.random.rand(num_samples)
base_prey_population_change = np.random.rand(num_samples)
base_other_predator_population_change = np.random.rand(num_samples)

# GenderRatioChange is inversely proportional to PreyPopulationChange
gender_ratio_change = (-0.22) * base_prey_population_change + 0.78
prey_population_change = 1 - base_gender_ratio_change

# Calculate FoodWebComplexity, which is inversely proportional to multiple indica-
tors
food_web_complexity = (1 - base_gender_ratio_change +
                        1 - base_prey_population_change +
                        1 - base_other_predator_population_change) / 3
food_web_complexity = np.clip(food_web_complexity, 0, 1)  # Ensure values are
between 0 and 1

# Calculate ParasitePopulationChange and OtherPredatorPopulationChange
parasite_population_change = 1 - food_web_complexity
other_predator_population_change = 1 - food_web_complexity

# GenderRatioChange is directly proportional to CompetitionComplexity
competition_complexity = base_gender_ratio_change

# Assemble all indicators
indicators = {
    'GenderRatioChange': gender_ratio_change,
    'PreyPopulationChange': prey_population_change,
    'OtherPredatorPopulationChange': other_predator_population_change,
    'ParasitePopulationChange': parasite_population_change,
    'FoodWebComplexity': food_web_complexity,
    'CompetitionComplexity': competition_complexity
```

```
}

# Create a DataFrame to store indicator data
df = pd.DataFrame(indicators)

# Normalize indicator data
normalized_df = df / np.sqrt((df ** 2).sum())

# Calculate the positive and negative ideal solutions
ideal_positive = normalized_df.max()
ideal_negative = normalized_df.min()

# Calculate the distances to the positive and negative ideal solutions
distance_positive = np.sqrt(((normalized_df - ideal_positive) ** 2).sum(axis=1))
distance_negative = np.sqrt(((normalized_df - ideal_negative) ** 2).sum(axis=1))

# Calculate the composite score
scores = distance_negative / (distance_positive + distance_negative)

# Add the scores to the DataFrame
df['Score'] = scores

# Find the best-scoring scenario
best_scenario = df.loc[df['Score'].idxmax()]
```