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# A Study on Future Population Dynamics of Indigenous Earthworm Species in Golaghat District of Assam, India

**Himangshu Barman [a], Amir Barhoi [b*], Apurba Saikia [c] and Pavitra Chutia [c]**

*[a] Department of Mathematics, NIT Meghalaya, India.*
*[b] Department of Mathematics, Duliajan College, India.*
*[c] P.G. Department of Life Sciences, Debraj Roy College, Golaghat-785621, Assam, India.*

***Authors' contributions***

*This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.*

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## ABSTRACT

This study presents a pioneering exploration into the population dynamics of indigenous earthworm species in the Golaghat district of Assam, India, through the lens of mathematical modeling. Recognizing the integral role of earthworms in enhancing soil productivity and ecosystem health, we embarked on a detailed longitudinal analysis spanning from 2018 to 2023 to assess their population

**Corresponding author: Email: barhoiamir@gmail.com;*

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trends across different seasons and subdivisions within the district. Utilizing the principles of Mathematical Biology, we employed the Malthus Growth model and the Logistic Growth model to estimate future population trajectories of earthworm species, integrating biological insights with mathematical rigor. Our methodology, combining extensive field data collection with sophisticated mathematical modeling, provides a replicable framework for similar ecological studies. This study contributes to the growing field of Mathematical Biology, offering a novel approach to understanding the complex interactions within ecosystems and the impact of environmental changes on key species. The outcomes offer valuable insights into sustainable agricultural practices and biodiversity conservation in tropical and subtropical regions, emphasizing the critical role of indigenous earthworm species in maintaining soil health and ecosystem services. Our findings reveal significant seasonal variations and highlight the resilience of these species in the face of ecological changes. The models suggest distinct population growth patterns, with the Logistic model providing a more realistic projection considering environmental constraints and resource availability. The bifurcation diagram is drawn for the Logistic map that presents the phenomena inside the chaotic region.

*Keywords: Earthworm; mathematical modeling; population density; growth rate; carrying capacity.*

## 1. INTRODUCTION

Earthworms which are considered night crawlers are important biological organisms that have tremendous potential in agro-ecosystems. It can enhance the productivity of the soil. Generally, the fertility status of Indian soil is low which directly affects the productivity of crops. Earthworms are broadly scattered all over the world mostly in the temperate and tropical regions and their population contributes about 80% of the total biomass of the topsoil. In India large number of indigenous earthworms is reported by many investigators which constitute about 89% of total earthworm diversity in the country (Paliwal & Julka, 2005). Earthworm consumes soil litter so they increase the amount of plant nutrients in their caste (Brown et al., 2004). In agro-ecosystems, earthworms play a vital role so it is called natural cultivators of the soil. The population of different earthworms always maintains soil sustainability (Ebanasar, Swaminathan, & Pathmavathy, 2015). Earthworms co-operate in a key position in water infiltration and nutrient cycling for the growth of plants including soil fertility (Don et al., 2008; Lavelle, Decaens, & Aubert, 2006). Earthworms always process the soil, and they are highly concerned with the regulation of soil formation, so it is considered as soil engineers (Singh, Singh, & Vig, 2016). The quality of soil, biomass, and macrofauna depends on earthworm species diversity, and its population density (Lavelle, Decaens, & Aubert, 2006; Goswami & Mondal, 2015) because they recycle the organic waste into valuable products. Earthworms can reduce the number of chemical substances by producing earth cast, locally available earthworm species can be used in the production of earth cast, and different soil sampling methods are used such as handling of a soil monolith, combined with an ethological method such as mustard extraction (Jeffery et al., 2010; Rombke et al., 2006).

Mathematical Biology or Biomathematics is one of the popular disciplines that study biological phenomena by formulating mathematical models. It gives us the capacity to study from the DNA molecule of an organism to the whole ecosystem, environment, human health, population, and even microorganisms. The involvement of mathematics in biology started in the $13^{th}$ century through the description of a growing population of rabbits which was given by Fibonacci, an Italian mathematician. In the $18^{th}$ century, a Swiss mathematician Daniel Bernoulli introduced mathematics in the description of smallpox in the human population. In 1798, Thomas Robert Malthus (Malthus, 1798) proposed a classic model of population growth in the book "*An Essay on the Principle of Population"*. After that, in 1836 Pierre Francois Verhulst (Verhulst, 1838), a Belgian Mathematician improved the Malthus model by introducing a new model named the Logistic growth model. Later Hutchinson (1948); Zhang (2022) introduced a Logistic model with time delay and Zhang (2022) and Smith (1963) improved the model by linking the population to the use of food. By differentiating the equilibrium state and environmental capacity of population development, Zhang (2022) and Hallam and Clark (1981) improved the model. After that Cui and G. J. Lawson proposed another model named as Cui-Lawson model (Zhang, 2022; Cui & Lawson, 1982). The Logistic model is mostly used in statistics, economics, physics, chemistry, etc (Omer, 2018; Bani-Yaghoub & Amundsen, 2008; Bani-Yaghoub, 2017). Now we are going to discuss two simple models namely Malthus or Exponential model and Logistic growth model in mathematical approach. Next, we try to estimate the future population with the help of these two models.

Earthworm have been recognized since long time to recycling of the organic waste into eco-friendly product. Earthworm and different microorganisms considered as the main biological organism which help the nature for maintaining and minimization of environmental degradation (Suthar, 2007). Earthworms bears different microorganisms in their gut which produces many enzymes for nutrients for the plants. These enzymes are available in vermicompost (Arancon et al., 2006). The technology of vermicomposting of different organic waste modifies many substances into organic forms (Lazcano, Brandon, & Dominguez, 2008). Throughout the process of vermicomposting earthworms make fragments of organic substances for the microbes by which all microbes can synthesize important enzymes (Aira et al., 2002). Microbes are also found in the vermicast. During the process of vermicompost all earthworms degrade organic wastes in valuable cast. This cast contains high amount of nutrients and useful substances such as vitamin, minerals, hormones, enzymes etc. (Prabha et al., 2007).

## 2. SAMPLING OF EARTHWORM POPULATION

The Earthworms were collected by the digging method (Paliwal & Julka, 2005) from the soil. The earthworms were collected from the sampling area in the morning time because during then they were found more active. Collected earthworms were washed in fresh water and stored in plastic container in the field, then used narcotising solution as ethyl alcohol. Live worms were placed in flat bottomed container with little fresh water. Ethyl alcohol was gradually added to the water till the worms became motionless. When the worms showed no longer respond to probing they are removed from the water and placed on a piece of blotting paper. They were then transferred to a flat dish containing a solution of 5% formalin for fixation for a period of at least 6-8 hours. The worms after fixation were stored in suitable sized bottles filled with 70% ethyl alcohol for further identification. All specimens were serially numbered and important field data such as habitat, locality, soil $p^H$, moisture content, occurrence was recorded.

**Sampling Methods:**

a) **Musturd Extraction Method:**

The mustard acts as an irritant to skin of the earthworm, but it does not harm them.

1. Added 20 gm of mustard powder to 2 L of water and mixed well.
2. Poured half of the mustard solution on the ground of sampling site.
3. The time was set for 5 min, by this time the earthworms come out from the soil.
4. After half an hour again poured mustard water in the plot and it was set timer for another 5 min.
5. Collected all earthworm in the pot.

**b) Digging methods:**

A small hole of 15-30 cm deep in the Soil was made.

- Gently braked clumps of soil into small pieces
- After than all earthworm was collected.

**c) Hand Sorting Methods (Lee, 1985)**:

- A 10 cm hole was made and picked up a handful of soil
- Kept the earthworm and discarded the soil after lookingthe earthworm.

**d) Onion extraction Method:**

50 g of onion was taken and made paste, mixed with 1 lit water and poured in randomly selected places.

- after half an hour earthworm came out due to pungent smell
- After than all earthworm was collected.

**e) Identification of Earthworm:**

All the collected earthworms were identified in Zoological Survey of India, Northern Regional Center (NRC), Dehradun, India.

**Image 1. *Metaphira posthuma***

**Image 2. *Drawdia nepelensis***

## 3. MALTHUS OR EXPONENTIAL MODEL

In this model, Malthus (Malthus, 1798) assumed that the population growth is controlled only by the birth and death of the individual and there is no emigration or immigration in the whole process. Let $N(t)$ be the size of the population and $\frac{1}{N}\frac{dN}{dt}$ is the per capita growth rate of the population density (Chasnov, 2016). So, if b is the per capita birth rate and d is the per capita death rate, then the population (Malthus, 1798) was described by following the differential equation

$\frac{1}{N}\frac{dN}{dt} = b - d$ (Paliwal & Julka, 2005; Malthus, 1798)

$$\Rightarrow \frac{dN}{N} = sdt, \ \ s = b - d$$

$$\Rightarrow \int \frac{dN}{N} = \int sdt$$

$\Rightarrow \ logN = st + c,$ Where c is an arbitrary constant (1)

We can obtain that c by applying an initial condition. Let that be $N(0) = N_0$

$$logN_0 = c \qquad (2)$$

Substituting (2) in equation (1),

$$\Rightarrow logN = st + logN_0$$

$$\Rightarrow N(t) = N_0 e^{st} \qquad (3)$$

The solution to the differential equation shows that population dynamics can be modeled as either exponential growth or exponential decay, depending on whether the net growth rate is positive or negative.

(i) If $s > 0$, then $N(t) \to +\infty$ (growth). In this case, the net growth rate is positive, meaning the birth rate exceeds the death rate. As a result, the population grows exponentially over time, theoretically towards infinity.

(ii) If $s < 0$, then $N(t) \to 0$ (decay). In this case, the net growth rate is negative, indicating the death rate exceeds the birth rate. In this scenario, the population size decreases over time, tending towards zero. Graphically, it can be interpreted in the following way-

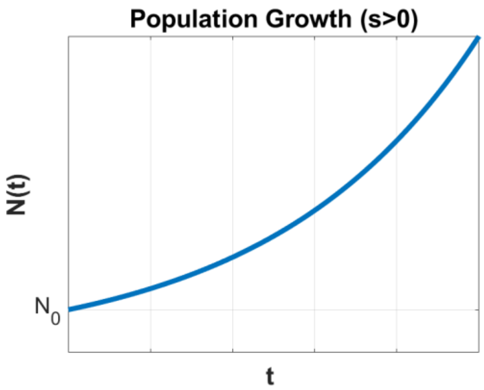


**Fig. 1(a). Population growth when $s > 0$**


**Fig. 1(b). Population decay when $s < 0$**

## 4. LOGISTIC GROWTH MODEL

In this enhanced framework, an advancement over the Malthusian model is presented, where Pierre Francois Verhulst introduces a refined perspective by proposing that the per capita growth rate directly correlates with the population density, denoted as $N(t)$, while explicitly assuming the absence of emigration and immigration throughout the process (Verhulst, 1838). The population dynamics are characterized by the following differential equation:

$\frac{1}{N}\frac{dN}{dt} = s(1 - \frac{N}{K})$, Where s and K are positive constants (Verhulst, 1838; Chasnov, 2016)

If $N > K$, then $\frac{N}{K} > 1$

$\Rightarrow s(1 - \frac{N}{K}) < 0$ as $s > 0$

$$\Rightarrow \frac{1}{N}\frac{dN}{dt} < 0$$

Therefore, if $N > K$, then $\frac{1}{N}\frac{dN}{dt} < 0$

Similarly, if $N < K$, then $\frac{1}{N}\frac{dN}{dt} > 0$

This K is called a measure of threshold or carrying capacity.

Now, $\frac{dN}{N(1-\frac{N}{K})} = s\,dt$

$\Rightarrow \int \frac{dN}{N} + \int \frac{dN}{K(1-\frac{N}{K})} = \int sdt$

$\Rightarrow logN - \log(K - N) = st + c$, where c is an arbitrary constant

$\Rightarrow \frac{N}{K-N} = e^{st}.b$, where we assume $b = e^{c}$ (4)

$\Rightarrow N = \frac{K}{1+be^{-st}}$, by using the initial condition $N(0) = N_0$, we can find that $b = \frac{K}{N_0} - 1$

Hence the population in the Logistic Growth model is $\frac{K}{1+\left(\frac{K}{N_0}-1\right)e^{-st}}$ where s is the growth rate and K is the measure of threshold or carrying capacity (Malthus, 1798). So, the solution mainly depends on three parameters, s (growth rate), $N_0$ (Initial population), K (Carrying Capacity or measure of threshold).

In order to reduce the number of parameters, we can non-dimensionalized the above equation which is of the following form

$$\frac{dx}{dt} = sx(1 - x) = f(x)$$

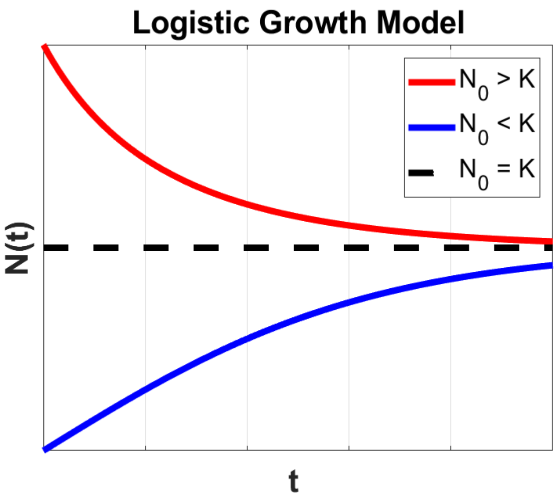


**Fig. 2. Logistic Growth Model: Depicting population adjustment over time, this graph illustrates three scenarios-where the initial population ($N_0$) is above (red line), below (blue line), and at (black dashed line) the carrying capacity (K). Each line shows how the population converges towards the equilibrium, highlighting the model's predictive ability across different starting conditions**

The map $f(x) = sx(1-x)$ is called a logistic map which has two fixed points $x_1 = 0$ and $x_2 = 1 - \frac{1}{s}$. For stability, we will first find the derivative of $f(x)$ which is $f'(x) = s(1-2x)$. Now, $f'(x)|_{x=0} = s < 1$ for $s < 1$ i.e. the fixed point 0 is a stable fixed point for $s < 1$ and an unstable fixed point for $s > 1$. And $f'(x)|_{x=1-\frac{1}{s}} = 2 - s$. Using the stability theorem, $x_2$ is stable if $|2-s| < 1$ which implies $1 < s < 3$ and unstable if $|2-s| > 1$ which implies $s < 1\ and\ s > 3$ which we tabulated in the following way.

**Table 1. Consisting of all the fixed points of logistic map along with their stability**

| Fixed Points | Stable | Unstable |
|---|---|---|
| $\boldsymbol{x_1 = 0}$ | $0 < s < 1$ | $s > 1$ |
| $\boldsymbol{x_2 = 1 - \frac{1}{s}}$ | $x_2 = 1 - \frac{1}{s}$ | $s < 1\ \&\ s > 3$ |

We can illustrate the long-time behavior of the logistic map with the help of a bifurcation diagram where we plot trajectories between fixed points and parameter s (Hilborn, 1994).

As we move from $s < 1$ to $s > 1$, the table shows that both the fixed points exchange their stability and hence transcritical bifurcation occurs at $s = 1$. The fixed point $1 - \frac{1}{s}$ is stable for $s < 3$ and unstable for $s > 3$. At $s = 3$, $f'(x)|_{x=1-\frac{1}{s}} = -1$ which implies that the first bifurcation occurs at $s = 3$ or $s = 3$ is the bifurcation point. As $s > 3$, the attractor is a period-2 cycle, which is indicated by two branches in the bifurcation diagram. As $s$ increases, both branches split simultaneously, creating a period 4 cycle which is nothing but period-doubling bifurcation and further increasing the value of the parameter s create period-8, period-16, and so on. Later if we zoom in again and again at $s = s_\infty = 3.57$, the map becomes chaotic. For $s > s_\infty$ the orbit diagram shows a mixture of order and chaos.

## 5. SEASONAL POPULATION DYNAMICS OF EARTHWORM SPECIES

This section presents a comprehensive dataset detailing the population dynamics of various earthworm species across multiple sub-divisions (Golaghat, Bokakhat, and Dhansiri) over a period spanning from 2018 to 2023. The data, systematically arranged in Tables 2 to 20, comprehensively captures seasonal population fluctuations: Pre-Monsoon, Monsoon, Post-Monsoon, and Winter-highlighting the ecological resilience and variability inherent within these species. This longitudinal study serves not only as a crucial baseline for understanding biodiversity within the specified regions but also as a foundation for assessing the impacts of environmental changes on earthworm populations. The subsequent analysis and discussion are aimed at exploring the complex interplay between these species and their habitats, thereby contributing to a broader understanding of soil health and ecosystem services in the Golaghat district. This introduction sets the stage for a detailed examination of the data, situating it within the broader context of our research objectives, and highlighting its importance for both specific ecological studies and general environmental conservation efforts.

**Table 2. Population of different Earthworm species in Golaghat sub-division**

| **2018, Golaghat Sub-Division** | | | | | |
|---|---|---|---|---|---|
| **Earthworm Species** | **Pre-Monsoon** | **Monsoon** | **Post-Monsoon** | **Winter** | **Total Population** |
| *Amyathas diffringens* | 8 | 14 | 12 | 4 | 38 |
| *Drawida nepelensis* | 11 | 69 | 58 | 9 | 147 |
| *Eutyphoeus kempi* | 10 | 28 | 17 | 5 | 60 |
| *Lampito maruitii* | 11 | 30 | 27 | 5 | 73 |
| *Metaphire posthuma* | 8 | 19 | 17 | 3 | 47 |
| *Octolasion tyrtaeum* | 11 | 20 | 15 | 4 | 50 |
| *Perionyx excavates* | 11 | 31 | 24 | 7 | 73 |
| *Perionyx pulvinnatus* | 23 | 49 | 32 | 9 | 113 |
| **Total Population** | 93 | 260 | 202 | 46 | 601 |

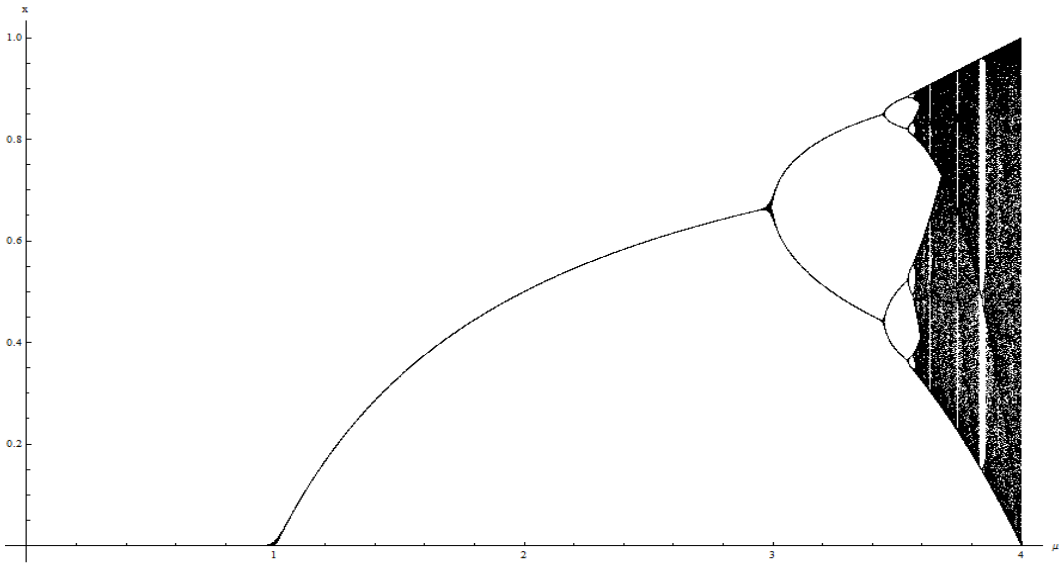


**Fig. 3. Bifurcation diagram: presenting the phenomena inside the chaotic region of the logistic map with an initial point of 0.1**

**Table 3. Population of different Earthworm species in Bokakhat sub-division**

| **2018 Bokakhat Sub-Division** | | | | | |
|---|---|---|---|---|---|
| **Earthworm Species** | **Pre-Monsoon** | **Monsoon** | **Post-Monsoon** | **Winter** | **Total Population** |
| *Amyathas diffringens* | 12 | 76 | 61 | 3 | 152 |
| *Drawida nepelensis* | 11 | 34 | 23 | 6 | 74 |
| *Eutyphoeus kempi* | 13 | 64 | 40 | 8 | 125 |
| *Lampito maruitii* | 19 | 61 | 55 | 4 | 139 |
| *Metaphire posthuma* | 12 | 31 | 21 | 7 | 71 |
| *Octolasion tyrtaeum* | 18 | 52 | 42 | 6 | 118 |
| *Perionyx excavates* | 16 | 73 | 59 | 5 | 153 |
| *Perionyx pulvinnatus* | 10 | 47 | 37 | 9 | 103 |
| **Total Population** | 111 | 438 | 338 | 48 | 935 |

**Table 4. Population of different Earthworm species in Dhansiri sub-division**

| **2018, Dhansiri Sub-Division** | | | | | |
|---|---|---|---|---|---|
| **Earthworm Species** | **Pre-Monsoon** | **Monsoon** | **Post-Monsoon** | **Winter** | **Total Population** |
| *Amyathas diffringens* | 8 | 15 | 12 | 3 | 38 |
| *Drawida nepelensis* | 17 | 65 | 56 | 6 | 144 |
| *Eutyphoeus kempi* | 8 | 18 | 12 | 4 | 42 |
| *Lampito maruitii* | 5 | 16 | 11 | 7 | 39 |
| *Metaphire posthuma* | 21 | 55 | 37 | 8 | 121 |
| *Octolasion tyrtaeum* | 7 | 17 | 12 | 5 | 41 |
| *Perionyx excavates* | 5 | 11 | 12 | 2 | 30 |
| *Perionyx pulvinnatus* | 9 | 13 | 10 | 4 | 36 |
| **Total Population** | 80 | 210 | 162 | 39 | 491 |

**Table 5. Population of different Earthworm species in Golaghat sub-division**

| 2019, Golaghat Sub-Division | | | | | |
|---|---|---|---|---|---|
| **Earthworm Species** | **Pre-Monsoon** | **Monsoon** | **Post-Monsoon** | **Winter** | **Total Population** |
| *Amyathas diffringens* | 11 | 19 | 17 | 5 | 52 |
| *Drawida nepelensis* | 31 | 69 | 49 | 8 | 157 |
| *Eutyphoeus kempi* | 9 | 29 | 17 | 5 | 60 |
| *Lampito maruitii* | 15 | 33 | 25 | 9 | 82 |
| *Metaphire posthuma* | 13 | 57 | 14 | 3 | 87 |
| *Octolasion tyrtaeum* | 15 | 23 | 19 | 7 | 64 |
| *Perionyx excavates* | 18 | 33 | 23 | 6 | 80 |
| *Perionyx pulvinnatus* | 23 | 79 | 64 | 9 | 175 |
| **Total Population** | 135 | 342 | 228 | 52 | 757 |

**Table 6. Population of different Earthworm species in Bokakhat sub-division**

| 2019, Bokakhat Sub-Division | | | | | |
|---|---|---|---|---|---|
| **Earthworm Species** | **Pre-Monsoon** | **Monsoon** | **Post-Monsoon** | **Winter** | **Total Population** |
| *Amyathas diffringens* | 23 | 93 | 47 | 2 | 165 |
| *Drawida nepelensis* | 18 | 36 | 11 | 7 | 72 |
| *Eutyphoeus kempi* | 10 | 45 | 31 | 4 | 90 |
| *Lampito maruitii* | 12 | 68 | 50 | 9 | 139 |
| *Metaphire posthuma* | 19 | 21 | 11 | 7 | 58 |
| *Octolasion tyrtaeum* | 11 | 57 | 34 | 3 | 105 |
| *Perionyx excavates* | 9 | 69 | 43 | 5 | 126 |
| *Perionyx pulvinnatus* | 19 | 17 | 11 | 6 | 53 |
| **Total Population** | 121 | 406 | 238 | 43 | 808 |

**Table 7. Population of different Earthworm species in Dhansiri sub-division**

| 2019, Dhansiri Sub-Division | | | | | |
|---|---|---|---|---|---|
| **Earthworm Species** | **Pre-Monsoon** | **Monsoon** | **Post-Monsoon** | **Winter** | **Total Population** |
| *Amyathas diffringens* | 7 | 11 | 17 | 4 | 39 |
| *Drawida nepelensis* | 21 | 78 | 69 | 7 | 175 |
| *Eutyphoeus kempi* | 3 | 11 | 17 | 8 | 39 |
| *Lampito maruitii* | 9 | 23 | 13 | 3 | 48 |
| *Metaphire posthuma* | 19 | 59 | 41 | 8 | 127 |
| *Octolasion tyrtaeum* | 6 | 23 | 19 | 7 | 55 |
| *Perionyx excavates* | 9 | 17 | 11 | 5 | 42 |
| *Perionyx pulvinnatus* | 7 | 21 | 17 | 9 | 54 |
| **Total Population** | 81 | 243 | 204 | 51 | 579 |

**Table 8. Population of different Earthworm species in Golaghat sub-division**

| 2020, Golaghat Sub-Division | | | | | |
|---|---|---|---|---|---|
| **Earthworm Species** | **Pre-Monsoon** | **Monsoon** | **Post-Monsoon** | **Winter** | **Total Population** |
| *Amyathas diffringens* | 9 | 21 | 13 | 4 | 47 |
| *Drawida nepelensis* | 29 | 75 | 48 | 12 | 164 |
| *Eutyphoeus kempi* | 15 | 21 | 18 | 9 | 63 |
| *Lampito maruitii* | 10 | 35 | 21 | 7 | 73 |
| *Metaphire posthuma* | 8 | 56 | 13 | 3 | 80 |
| *Octolasion tyrtaeum* | 13 | 29 | 21 | 4 | 67 |
| *Perionyx excavates* | 11 | 35 | 23 | 7 | 76 |
| *Perionyx pulvinnatus* | 31 | 69 | 68 | 3 | 171 |
| **Total Population** | 126 | 341 | 225 | 49 | 741 |

**Table 9. Population of different Earthworm species in Bokakhat sub-division**

| 2020, Bokakhat Sub-Division | | | | | |
|---|---|---|---|---|---|
| **Earthworm Species** | **Pre-Monsoon** | **Monsoon** | **Post-Monsoon** | **Winter** | **Total population** |
| *Amyathas diffringens* | 20 | 100 | 80 | 18 | 218 |
| *Drawida nepelensis* | 11 | 15 | 19 | 7 | 52 |
| *Eutyphoeus kempi* | 20 | 51 | 37 | 8 | 116 |
| *Lampito maruitii* | 15 | 63 | 58 | 9 | 145 |
| *Metaphire posthuma* | 12 | 23 | 15 | 5 | 55 |
| *Octolasion tyrtaeum* | 19 | 69 | 46 | 3 | 137 |
| *Perionyx excavates* | 15 | 58 | 73 | 4 | 150 |
| *Perionyx pulvinnatus* | 9 | 15 | 17 | 7 | 48 |
| **Total Population** | 121 | 394 | 345 | 61 | 921 |

**Table 10. Population of different Earthworm species in Dhansiri sub-division**

| 2020, Dhansiri Sub-Division | | | | | |
|---|---|---|---|---|---|
| **Earthworm Species** | **Pre-Monsoon** | **Monsoon** | **Post-Monsoon** | **Winter** | **Total Population** |
| *Amyathas diffringens* | 14 | 21 | 18 | 5 | 58 |
| *Drawida nepelensis* | 13 | 69 | 54 | 9 | 145 |
| *Eutyphoeus kempi* | 9 | 39 | 20 | 4 | 72 |
| *Lampito maruitii* | 11 | 33 | 37 | 6 | 87 |
| *Metaphire posthuma* | 19 | 81 | 63 | 3 | 166 |
| *Octolasion tyrtaeum* | 9 | 20 | 14 | 7 | 50 |
| *Perionyx excavates* | 17 | 31 | 20 | 5 | 73 |
| *Perionyx pulvinnatus* | 25 | 27 | 21 | 6 | 79 |
| **Total Population** | 117 | 321 | 247 | 45 | 730 |

**Table 11. Population of different Earthworm species in Golaghat sub-division**

| 2021, Golaghat Sub-Division | | | | | |
|---|---|---|---|---|---|
| **Earthworm Species** | **Pre-Monsoon** | **Monsoon** | **Post-Monsoon** | **Winter** | **Total Population** |
| *Amyathas diffringens* | 10 | 20 | 12 | 5 | 47 |
| *Drawida nepelensis* | 30 | 68 | 50 | 10 | 158 |
| *Eutyphoeus kempi* | 11 | 25 | 18 | 8 | 62 |
| *Lampito maruitii* | 15 | 31 | 21 | 7 | 74 |
| *Metaphire posthuma* | 10 | 52 | 13 | 4 | 79 |
| *Octolasion tyrtaeum* | 13 | 23 | 18 | 4 | 58 |
| *Perionyx excavates* | 12 | 30 | 27 | 3 | 72 |
| *Perionyx pulvinnatus* | 25 | 71 | 60 | 6 | 162 |
| **Total Population** | 126 | 320 | 219 | 47 | 712 |

**Table 12. Population of different Earthworm species in Bokakhat sub-division**

| 2021, Bokakhat Sub-Division | | | | | |
|---|---|---|---|---|---|
| **Earthworm Species** | **Pre-Monsoon** | **Monsoon** | **Post-Monsoon** | **Winter** | **Total population** |
| *Amyathas diffringens* | 21 | 118 | 62 | 16 | 217 |
| *Drawida nepelensis* | 11 | 17 | 17 | 7 | 52 |
| *Eutyphoeus kempi* | 18 | 49 | 35 | 8 | 110 |
| *Lampito maruitii* | 16 | 60 | 58 | 8 | 142 |
| *Metaphire posthuma* | 12 | 23 | 15 | 3 | 53 |
| *Octolasion tyrtaeum* | 15 | 63 | 49 | 5 | 132 |
| *Perionyx excavates* | 19 | 68 | 63 | 6 | 156 |
| *Perionyx pulvinnatus* | 9 | 17 | 15 | 4 | 45 |
| **Total Population** | 121 | 415 | 314 | 57 | 906 |

**Table 13. Population of different Earthworm species in Dhansiri sub-division**

| 2021, Dhansiri Sub-Division | | | | | |
|---|---|---|---|---|---|
| **Earthworm Species** | **Pre-Monsoon** | **Monsoon** | **Post-Monsoon** | **Winter** | **Total Population** |
| *Amyathas diffringens* | 14 | 24 | 15 | 5 | 58 |
| *Drawida nepelensis* | 12 | 71 | 53 | 8 | 144 |
| *Eutyphoeus kempi* | 10 | 33 | 23 | 4 | 70 |
| *Lampito maruitii* | 11 | 37 | 28 | 6 | 82 |
| *Metaphire posthuma* | 21 | 77 | 58 | 7 | 163 |
| *Octolasion tyrtaeum* | 9 | 20 | 14 | 3 | 46 |
| *Perionyx excavates* | 13 | 28 | 21 | 5 | 67 |
| *Perionyx pulvinnatus* | 19 | 30 | 20 | 6 | 75 |
| **Total Population** | 109 | 320 | 232 | 44 | 705 |

**Table 14. Population of different Earthworm species in Golaghat sub-division**

| 2022, Golaghat Sub-Division | | | | | |
|---|---|---|---|---|---|
| **Earthworm Species** | **Pre-Monsoon** | **Monsoon** | **Post-Monsoon** | **Winter** | **Total Population** |
| *Amyathas diffringens* | 7 | 25 | 13 | 3 | 48 |
| *Drawida nepelensis* | 29 | 55 | 67 | 13 | 164 |
| *Eutyphoeus kempi* | 13 | 21 | 19 | 7 | 60 |
| *Lampito maruitii* | 18 | 34 | 28 | 2 | 82 |
| *Metaphire posthuma* | 9 | 57 | 15 | 6 | 87 |
| *Octolasion tyrtaeum* | 11 | 29 | 23 | 3 | 66 |
| *Perionyx excavates* | 11 | 35 | 29 | 9 | 84 |
| *Perionyx pulvinnatus* | 39 | 59 | 83 | 4 | 185 |
| **Total Population** | 137 | 315 | 277 | 47 | 776 |

**Table 15. Population of different Earthworm species in Bokakhat sub-division**

| 2022, Bokakhat Sub-Division | | | | | |
|---|---|---|---|---|---|
| **Earthworm Species** | **Pre-Monsoon** | **Monsoon** | **Post-Monsoon** | **Winter** | **Total population** |
| *Amyathas diffringens* | 12 | 88 | 101 | 9 | 210 |
| *Drawida nepelensis* | 11 | 14 | 17 | 6 | 48 |
| *Eutyphoeus kempi* | 22 | 64 | 33 | 8 | 127 |
| *Lampito maruitii* | 15 | 81 | 47 | 5 | 148 |
| *Metaphire posthuma* | 13 | 23 | 15 | 11 | 62 |
| *Octolasion tyrtaeum* | 11 | 84 | 54 | 2 | 151 |
| *Perionyx excavates* | 14 | 73 | 69 | 3 | 159 |
| *Perionyx pulvinnatus* | 9 | 19 | 17 | 8 | 53 |
| **Total Population** | 107 | 446 | 353 | 52 | 958 |

**Table 16. Population of different Earthworm species in Dhansiri sub-division**

| 2022, Dhansiri Sub-Division | | | | | |
|---|---|---|---|---|---|
| **Earthworm Species** | **Pre-Monsoon** | **Monsoon** | **Post-Monsoon** | **Winter** | **Total Population** |
| *Amyathas diffringens* | 9 | 19 | 22 | 3 | 53 |
| *Drawida nepelensis* | 11 | 89 | 56 | 3 | 159 |
| *Eutyphoeus kempi* | 17 | 76 | 17 | 5 | 115 |
| *Lampito maruitii* | 17 | 33 | 45 | 9 | 104 |
| *Metaphire posthuma* | 21 | 93 | 89 | 2 | 205 |
| *Octolasion tyrtaeum* | 9 | 27 | 19 | 7 | 62 |
| *Perionyx excavates* | 16 | 43 | 28 | 7 | 94 |
| *Perionyx pulvinnatus* | 29 | 38 | 29 | 9 | 105 |
| **Total Population** | 129 | 418 | 305 | 45 | 897 |

**Table 17. Population of different Earthworm species in Golaghat sub-division**

| 2023, Golaghat Sub-Division | | | | | |
|---|---|---|---|---|---|
| **Earthworm Species** | **Pre-Monsoon** | **Monsoon** | **Post-Monsoon** | **Winter** | **Total Population** |
| *Amyathas diffringens* | 8 | 22 | 12 | 5 | 47 |
| *Drawida nepelensis* | 29 | 65 | 58 | 11 | 163 |
| *Eutyphoeus kempi* | 15 | 21 | 18 | 7 | 61 |
| *Lampito maruitii* | 18 | 35 | 23 | 3 | 79 |
| *Metaphire posthuma* | 9 | 52 | 17 | 9 | 87 |
| *Octolasion tyrtaeum* | 11 | 29 | 21 | 3 | 64 |
| *Perionyx excavates* | 13 | 35 | 29 | 7 | 84 |
| *Perionyx pulvinnatus* | 31 | 69 | 75 | 4 | 179 |
| **Total Population** | 134 | 328 | 253 | 49 | 764 |

**Table 18. Population of different Earthworm species in Bokakhat sub-division**

| 2023, Bokakhat Sub-Division | | | | | |
|---|---|---|---|---|---|
| **Earthworm Species** | **Pre-Monsoon** | **Monsoon** | **Post-Monsoon** | **Winter** | **Total population** |
| *Amyathas diffringens* | 21 | 88 | 92 | 12 | 213 |
| *Drawida nepelensis* | 11 | 15 | 19 | 7 | 52 |
| *Eutyphoeus kempi* | 20 | 54 | 43 | 8 | 125 |
| *Lampito maruitii* | 15 | 83 | 47 | 5 | 150 |
| *Metaphire posthuma* | 13 | 23 | 15 | 9 | 60 |
| *Octolasion tyrtaeum* | 12 | 71 | 49 | 3 | 135 |
| *Perionyx excavates* | 15 | 75 | 65 | 3 | 158 |
| *Perionyx pulvinnatus* | 9 | 16 | 17 | 9 | 51 |
| **Total Population** | 116 | 425 | 347 | 56 | 944 |

**Table 19. Population of different Earthworm species in Dhansiri sub-division**

| 2023, Dhansiri Sub-Division | | | | | |
|---|---|---|---|---|---|
| **Earthworm Species** | **Pre-Monsoon** | **Monsoon** | **Post-Monsoon** | **Winter** | **Total Population** |
| *Amyathas diffringens* | 13 | 21 | 18 | 5 | 57 |
| *Drawida nepelensis* | 14 | 77 | 47 | 9 | 147 |
| *Eutyphoeus kempi* | 11 | 41 | 20 | 4 | 76 |
| *Lampito maruitii* | 17 | 33 | 46 | 6 | 102 |
| *Metaphire posthuma* | 21 | 117 | 72 | 3 | 213 |
| *Octolasion tyrtaeum* | 9 | 20 | 14 | 7 | 50 |
| *Perionyx excavates* | 16 | 37 | 21 | 5 | 79 |
| *Perionyx pulvinnatus* | 29 | 23 | 26 | 6 | 84 |
| **Total Population** | 130 | 369 | 264 | 45 | 808 |

**Table 20. Estimated Population of Earthworm Species in Golaghat**

| Golaghat District | | |
|---|---|---|
| **Time** | **Year** | **Total Earthworm Population** |
| 0 | 2018 | 2027 |
| 1 | 2019 | 2144 |
| 2 | 2020 | 2392 |
| 3 | 2021 | 2323 |
| 4 | 2022 | 2631 |
| 5 | 2023 | 2516 |

## 6. RESULTS AND DISCUSSION

We have collected populations of different types of earthworm species namely *Amyathas diffringens*, *Drawida nepelensis*, *Eutyphoeus kempi*, *Lampito maruitii*, *Metaphire posthuma*, *Octolasion tyrtaeum*, *Perionyx excavates*, and *Perionyx pulvinatus* in all sub-divisions of Golaghat district namely Golaghat, Bokakhat, and Dhansiri sub-divisions from 2018 to 2023. With the help of these population data, we try to estimate the approximate future population of earthworm species. For this, we take the help of two models namely Malthus (Malthus, 1798), and the Logistic growth model (Verhulst, 1838). To predict the future population, we need the growth rate of the earthworm population. Following we find the approximate growth rate of the earthworm population for both models and try to find the approximate formula for each model to estimate the future population.

**(1) For the case of the Malthus Model:** From the above table, the actual population of earthworms at $t = 0$ and $t = 1$ are 2027 and 2144 respectively. Using the analytical solution of the model,

$$N(1) = N_0 e^s$$

$$\Rightarrow 2144 = 2027e^s$$

$$\Rightarrow s \approx 0.0561$$

This implies that the approximate growth rate of the earthworm population for 2018-2019 is approximately 5.61%.

**Table 21. Presents the annual growth rate (percentage) from 2018-2023 for the case of Malthus model**

| Time | Year | Growth Rate |
|---|---|---|
| 0 | 2018 | - |
| 1 | 2019 | 5.611 |
| 2 | 2020 | 8.279 |
| 3 | 2021 | 4.543 |
| 4 | 2022 | 6.520 |
| 5 | 2023 | 4.322 |

The average of all the above growth rates is 5.855 % (Since we want a constant growth rate). We assume this growth rate works for the remaining process. So by putting this in the solution, we can have the following formula for future estimation of the population

$$N(t) = 2027.e^{0.05855t}$$

**(2) For the case of the Logistic Growth Model:** From the analytical solution of the model, we get $N(t) = \frac{K}{1+be^{-st}}$ where K is the carrying capacity, t is the time, s is the intrinsic growth rate, and b is the constant. So firstly, we need to solve both s, and b. We estimated the Carrying Capacity (Malthus, 1798) K to be 5000 (the reason is getting clear observation from the graph). Since the initial Population (at $t = 0$) is 2027

$$b = \frac{K}{N_0} - 1$$

$$\Rightarrow b = \frac{5000}{2027} - 1$$

$$\Rightarrow b \approx 1.467$$

The growth rate, $s = \frac{2516-2027}{2027} \approx 0.2412$

The approximate growth rate of the earthworm population for one year is approximately 24.12 %. Therefore, we can use the following formula for estimating the approximate future population of earthworm species,

$$N(t) \approx \frac{5000}{1 + 1.467e^{-0.2412\,t}}$$

Communicating with electronic machines makes life easier and that's why we communicate with MATLAB software through the following programs which provide answers more accurately in the least period.

### 6.1 Analysis of Population Dynamics Using MATLAB Programs

MATLAB scripts are developed to calculate population estimates using two core models: the Malthus and Logistic growth equations. Each script calculates and plots population trajectories over time according to defined parameters (Hilborn, 1994). Once executed, these programs generate data that is summarized in tabular form for detailed analysis. For ease of access and to maintain the flow of the main text, these MATLAB scripts are included in this paper

**(1) MATLAB Script for Calculating Population Estimates Using the Malthus Growth Model**

```
s = 0.0561;
t = 0:1:32;
N0 = 2027;
N = N0.* exp(s.*t);
plot(t, N, 'k--', 'LineWidth', 4);
xlabel('t'); % x-axis label
ylabel('N(t)'); % y-axis label
title('Population decay (s<0)');
shading interp
xlabel('\bf{t} ');
ylabel('\bf{N(t)}');
title('Logistic Growth Model');
set(gca,'FontSize',18)
grid on;
```

**(2) MATLAB Script for Calculating Population Estimates Using the Malthusian Growth Model**

```
K = 5000;
s = 0.2412;
t = 0:1:32;
N0 = 2027;
b=1.467;
N = K ./ (1+b.* exp(-s*t));
plot(t, N, 'k--', 'LineWidth', 4);
xlabel('t'); % x-axis label
ylabel('N(t)'); % y-axis label
title('Population decay (s<0)');
shading interp
xlabel('\bf{t} ');
ylabel('\bf{N(t)}');
title('Logistic Growth Model');
set(gca,'FontSize',18)
grid on;
```

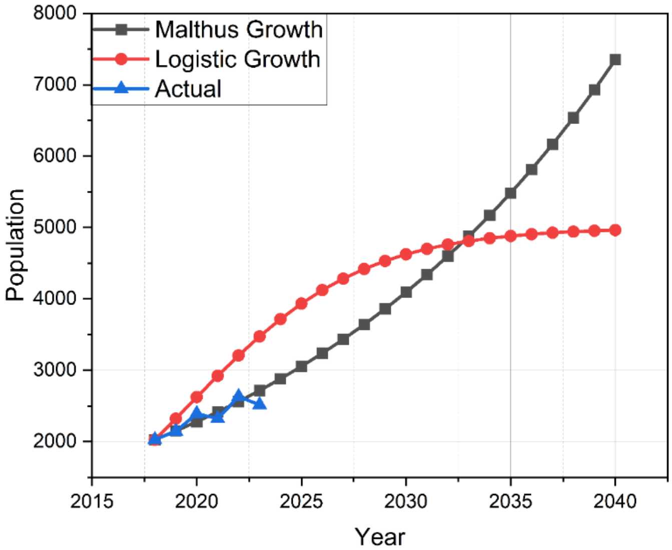


**Fig. 4. Illustrate variation of earthworm population (Actual population from 2018 to 2023; Malthus and Logistic growth from 2018 to 2040)**

**Table 22. Presents a comparison of the actual and projected population growth of earthworms using two different mathematical models: the Malthus growth model and the Logistic growth model**

| Time | Year | Actual Population | Malthus Growth | Logistic Growth |
|---|---|---|---|---|
| 0 | 2018 | 2027 | 2027 | 2026.753 |
| 1 | 2019 | 2144 | 2149.224 | 2322.773 |
| 2 | 2020 | 2392 | 2278.818 | 2623.874 |
| 3 | 2021 | 2323 | 2416.226 | 2921.415 |
| 4 | 2022 | 2631 | 2561.920 | 3207.155 |
| 5 | 2023 | 2516 | 2716.398 | 3474.131 |
| 6 | 2024 | | 2880.191 | 3717.252 |
| 7 | 2025 | | 3053.861 | 3933.528 |
| 8 | 2026 | | 3238.003 | 4121.952 |
| 9 | 2027 | | 3433.248 | 4283.152 |
| 10 | 2028 | | 3640.266 | 4418.929 |
| 11 | 2029 | | 3859.767 | 4531.801 |
| 12 | 2030 | | 4092.503 | 4624.609 |
| 13 | 2031 | | 4339.273 | 4700.238 |
| 14 | 2032 | | 4600.923 | 4761.416 |
| 15 | 2033 | | 4878.349 | 4810.612 |
| 16 | 2034 | | 5172.504 | 4849.983 |
| 17 | 2035 | | 5484.395 | 4881.371 |
| 18 | 2036 | | 5815.094 | 4906.319 |
| 19 | 2037 | | 6165.732 | 4926.099 |
| 20 | 2038 | | 6537.513 | 4941.753 |
| 21 | 2039 | | 6931.712 | 4954.122 |
| 22 | 2040 | | 7349.681 | 4963.883 |

**Malthus Growth (Black Line):**

- The Malthus growth curve, represented by the black line with square markers, shows a steep increase in the population size over time.
- This model predicts that the population will grow exponentially without any limits, which is evident from the steeply rising trend that continues upwards without plateauing.
- The population, according to this model, appears to be increasing towards 7350 by the year 2040.

**Logistic Growth (Red Line):**

- The Logistic growth curve, depicted by the red line with circle markers, also shows an increase in population but at a decelerating rate over time.
- Initially, this curve follows a similar trajectory to the Malthus model but begins to level off as it approaches the carrying capacity of the environment.
- This model accounts for environmental constraints and resource limitations, which cause the population growth to slow down and eventually stabilize.
- The population according to this model appears to plateau just above 4963 by 2040.

**Actual Growth (Blue Line):**

- The actual growth curve, illustrated by the blue line with triangle markers, represents the observed population size from 2018 to 2023.
- The trend of actual data points suggests a moderate and steady increase in the earthworm population over these years.
- The curve ends in 2023, which is the last year of actual data available for this study.

The comparison between the actual data and the two models shows that while the Malthus model offers an unrestricted growth prediction, the Logistic model is more aligned with the observed data, providing a more realistic forecast. The Logistic model is likely a better fit for the actual population growth due to its incorporation of the carrying capacity, which is a limit to how many individuals the environment can sustainably support. The discrepancy between the Malthus model and the actual growth highlights the limitations of the former in predicting real-world biological populations that are subject to environmental constraints.

The total population across the district showcased a fluctuating yet generally increasing trend over the study period, with a total population growth from 2027 individuals in 2018 to 2516 individuals in 2023. The predictive modeling using Malthus and Logistic models indicated a continued growth in population, albeit at varying rates, with the Logistic model suggesting a more moderated growth due to the incorporation of carrying capacity (Malthus, 1798) limitations. Drawing from the estimated data on the indigenous earthworm population gathered across various subdivisions of the Golaghat district from 2018 to 2023, we projected the potential future numbers of earthworms using the Malthus and Logistic growth models. The projected figures derived from these models are summarized in the Table 23.

The graph comparing the Malthus and Logistic growth models for indigenous earthworm populations in the Golaghat district until 2050 illustrates the impracticality of the Malthus projection, which predicts an unrealistic exponential growth to nearly 13000, ignoring environmental constraints. In contrast, the Logistic model accounts for these limitations, predicting a plateau in population growth of

**Table 23. Predicted approximate population of Earthworm species through Malthus and Logistic model**

| Year | Malthus Growth | Logistic Growth | Year | Malthus Growth | Logistic Growth |
|---|---|---|---|---|---|
| 2024 | 2880.191 | 3717.252 | 2038 | 6537.513 | 4941.753 |
| 2025 | 3053.861 | 3933.528 | 2039 | 6931.712 | 4954.122 |
| 2026 | 3238.003 | 4121.952 | 2040 | 7349.681 | 4963.883 |
| 2027 | 3433.248 | 4283.152 | 2041 | 7792.852 | 4971.579 |
| 2028 | 3640.266 | 4418.929 | 2042 | 8262.745 | 4977.643 |
| 2029 | 3859.767 | 4531.801 | 2043 | 8760.972 | 4982.418 |
| 2030 | 4092.503 | 4624.609 | 2044 | 9289.241 | 4986.175 |
| 2031 | 4339.273 | 4700.238 | 2045 | 9849.364 | 4989.132 |
| 2032 | 4600.923 | 4761.416 | 2046 | 10443.261 | 4991.457 |
| 2033 | 4878.349 | 4810.612 | 2047 | 11072.968 | 4993.286 |
| 2034 | 5172.504 | 4849.983 | 2048 | 11740.646 | 4994.723 |
| 2035 | 5484.395 | 4881.371 | 2049 | 12448.584 | 4995.853 |
| 2036 | 5815.094 | 4906.319 | 2050 | 13199.209 | 4996.741 |
| 2037 | 6165.732 | 4926.099 | | | |

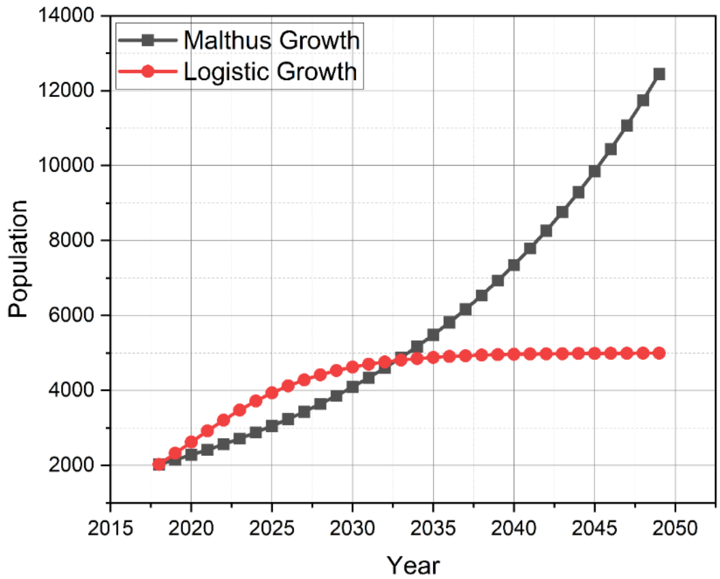


**Fig. 5. The future variation of earthworm species from 2024 to 2050**

around 4997 individuals by 2050, based on a carrying capacity of 5000. This plateau reflects a more sustainable and realistic growth rate of 24.12% annually, considering factors like resource availability and earthworm life spans. Such data is crucial for framing effective conservation and land management policies, emphasizing the importance of ecological balance and the maintenance of soil health for agricultural sustainability.

From the bifurcation diagram for the logistic map, it is clear that for the parameter value $0 < s < 1$, 0 is the only stable point attractor and $1 - \frac{1}{s}$ is the unstable fixed point. We assume for the Logistic model, $s \approx 0.2412$ (24.12%) is the annual growth rate. Therefore, we can conclude that 0 is the only stable fixed point and $(1 - \frac{1}{0.2412}) \approx -3.146$ is the unstable fixed point and no chaotic behavior occurs.

## 7. CONCLUSION

Our study conducted from 2018 to 2023 aimed to understand the population dynamics of various indigenous earthworm species within the Golaghat district, Assam. The application of Malthus and Logistic growth models provided a quantitative framework to forecast earthworm populations. The Malthus model, while simpler, projected an exponential growth that might not be sustainable in real-world scenarios due to environmental constraints. In contrast, the Logistic model, with its consideration for carrying capacity, offered a more realistic projection, acknowledging the limited resources and competitive pressures within the ecosystem.

Our findings underscore the importance of preserving and enhancing earthworm habitats to maintain soil health and agricultural productivity. The disparities between the models highlight the complex interplay of biological, environmental, and anthropogenic factors influencing earthworm populations. Future studies should explore the impacts of land-use changes, climate variability, and conservation practices on these essential soil organisms.

In conclusion, this study not only contributes to the understanding of earthworm population dynamics in the Golaghat district but also emphasizes the critical role of mathematical modeling in ecological research. The predictive insights generated by this study can inform conservation strategies and sustainable agricultural practices, ensuring the preservation of soil health and biodiversity in the region.

## DISCLAIMER (ARTIFICIAL INTELLIGENCE)

We confirm that NO generative AI technologies, such as Large Language Models (e.g., ChatGPT, Copilot), or text-to-image generators, were used during the writing, editing, or preparation of our manuscript.

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## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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