MODELLING THE IMPACT OF CLIMATE CHANGE ON PLANT-POLLINATOR MUTUALISMS AND ECOSYSTEM RESILIENCE

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by

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CANDIDATE'S DECLARATION

I Swati Suman hereby certify that the work which is being presented in the thesis entitled "Modelling the Impact of Climate Change on Plant-Pollinator Mutualisms and Ecosystem Resilience" in partial fulfilment of the requirements for the award of the Degree of Master of Mathematics, submitted in the Department of Applied Mathematics, Delhi Technological University is an authentic record of my own carried out during the period from August 2023 to May 2024 under the supervision of Dr. Nilam, Assistant Professor, Department of Applied Mathematics.

The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other Institute.

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This is to certify that the student has incorporated all the corrections suggested by the examiners in the thesis and the statement made by the candidate is correct to the best of our knowledge.

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CERTIFICATE

Certified that Swati Suman (2K22/MSCMAT/51) has carried out their search work presented in this thesis entitled "Modelling the Impact of Climate Change on Plant-Pollinator Mutualisms and Ecosystem Resilience" for the award of Master of Science from Department of Applied Mathematics, Delhi Technological University, Delhi, under my supervision. The thesis embodies results of original work, and studies are carried out by the student herself and the contents of the thesis do not form the basis for the award of any other degree to the candidate or to anybody else from this or any other University/Institution.

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ABSTRACT

Climate change poses significant challenges to the intricate dynamics of plant-pollinator interactions, with potential implications for ecosystem resilience. This study investigates the impact of phenological mismatches-discrepancies in the timing of life cycle events-between plants and pollinators on the stability and sustainability of ecosystems. We utilize a mathematical model based on the framework proposed by Fagan et al. (2014). The model is parameterized using historical phenological data for butterfly species Vanessa atalanta and plant species Syringa vulgaris. Through a series of simulations, we investigate the dynamics of pollinator and plant populations under decreasing visitation and pollination rates. The results reveal that as these rates decline, significant changes occur in the population dynamics. These findings highlight the critical role of synchrony in plant-pollinator interactions for ecosystem resilience. Phenological mismatches driven by climate change can lead to reduced pollinator services and compromised plant reproduction, ultimately affecting ecosystem functions. The study underscores the need for adaptive conservation strategies to mitigate the adverse effects of climate-induced phenological shifts on plant-pollinator mutualisms. Future research should aim to incorporate multi-species interaction, spatial variability, and socio-economic factors to develop more comprehensive models of ecosystem resilience in a changing climate. This study contributes to the existing literature by providing a detailed mathematical analysis of plant-pollinator dynamics under climate change scenarios, offering critical insights into the mechanisms driving ecosystem resilience. It emphasizes the need for an integrated approach to conservation that considers the complex interplay between biological, environmental, and socio-economic factors.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbol/Abbreviations	Description
α	Constant death rate of plants
β	Rate at which pollen is removed from a pollinator
γ	Visitation rate of pollinators to flowering plants
$g_s(t, \theta)$	Rate at which pollinators arrive, based on gamma distribution
$g_p(t, \theta)$	Flower opening rate
Q	Population of pollinators without pollen
R	Population of pollinators with pollen
S	Total pollinator population size
U	Abundance of unpollinated flowering plants
P	Abundance of pollinated flowering plants
S_0	Initial total pollinator population size
μ	Death rate for flowers
U_0	Initial number of unpollinated flowers
t	Time variable
λ	Inverse scale parameter of gamma distribution
ζ	Shape parameter of gamma distribution
PDF	Probability Distribution Function

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Mutualism is an ecological relationship between two or more species where each species derives a net benefit. This type of interaction is frequently observed in nature. In mutualistic relationship, the individuals involved typically provide resources or services to each other that enhance their survival, reproduction, or overall fitness. It is said to be a type of symbiotic relationship, however as mentioned by Holland & Bronstein (2008) it is not synonymous with symbiosis, cooperation, or facilitation, although ecological and evolutionary parallels do occur among these forms of interaction. Mutualisms can further be classified based on the degree of dependency between the interacting species as facultative vs obligate, and the specificity of the interaction as species-specific and generalized mutualism. In tropical rainforests, the large majority of flowering plants depend on mutualistic pollinators and seed dispersers. Deserts are dominated by nitrogen-fixing legumes, lichens dominate tundra habitats, and most northern hardwood forest and grassland plant species depend on mycorrhizal fungi to survive and persists. In the ocean, both coral and deep-sea vent communities are rich with mutualisms; coral itself is the product of a mutualistic symbiosis (Bronstein, 2001). Mutualism are ubiquitous in nature, provide important ecosystem services, and involve many species of interest for conservation (Hale & Valdovinos, 2021). In this text we will be focusing on one of the most common and vast form of mutualistic interaction, the plant-pollinator mutualism. Pollination interactions play a crucial role in supporting both biodiversity and human needs. A wide variety of plants and animals, including insects, birds, lizards, and mammals, rely on each other for pollination and sustenance. These mutual dependencies can impact the survival of their populations (Hegland et al., 2009). Many models have been made to study mutualism but it has not been easy to take into account all factors governing the phenomena. We will focus on a mutualism model for plant-pollinator interaction and study the population dynamics for pollinators under changing circumstances and its effects on the ecosystem.

1.1.1 OVERVIEW OF PLANT-POLLINATOR MUTUALISMS

Plant-pollinator mutualisms are critical interactions in ecosystems, where plants provide resources such as nectar and pollen to pollinators, which in turn facilitate plant reproduction by transferring pollen. This mutualistic relationship is highly beneficial for both parties, promoting biodiversity and ecosystem stability. Some mutualisms are highly specialized, such as the relationship between globeflower (Trollius europaeus) and its pollinating flies (Chiastocheta spp.). The flies lay their eggs in the flowers, and the larvae consume a portion of the seeds. This relationship balances between the number of seeds fertilized and those consumed, promoting a stable mutualism (Ferdy et al., 2002). Floral scents play a crucial role in nursery pollination mutualisms. These chemical signals attract specific pollinators and ensure the renewal of the mutualistic relationship each generation. The specificity of these signals helps maintain the mutualism by signalling the appropriate phenological stage for pollinator visits (Hossaert-McKey et al., 2010).

Fig. 1.1: A European honey bee extracts nectar from an Aster flower using its proboscis.
Image released into the public domain by John Severns

Fig. 1.2: Mutualism between butterfly and flower.
Image by Marcia Straub// Getty Images.

Mutualisms also play a role in the invasiveness of certain plant species. Introduced plants often rely on mutualistic relationships with local pollinators to establish and spread. Generalist pollinators are particularly effective in facilitating the spread of invasive plants, as they are not limited by the availability of specific pollinators (Richardson et al., 2000). The restoration of pollination mutualisms in degraded ecosystem involves targeted plantings to attract and sustain pollinators. Understanding the ecological requirements of pollinators and integrating this knowledge with plant restoration strategies can help restore these vital interactions and ensure sustainable pollination services (Menz et al., 2011).

Plant-pollinator mutualisms are essential for ecosystem health and stability. They involve complex interactions that can range from highly specialized to more generalized forms, each with mechanisms to maintain balance and mutual benefit. Understanding and restoring these mutualisms is crucial for biodiversity conservation and the resilience of natural ecosystems.

1.1.2 IMPORTANCE OF POLLINATORS IN ECOSYSTEM AND AGRICULTURE

Pollinators, particularly insects such as bees, butterflies, beetles, and flies, play a critical role in maintaining the health of ecosystems and bolstering agricultural productivity. Their contributions extend beyond simple plant reproduction to ensuring biodiversity, ecosystem stability, and food security.

Pollinators are vital for the reproduction of many plant species, contributing to the genetic diversity and resilience of ecosystems. Approximately 80% of all flowering plants rely on animal pollinators for reproduction (Reddy et al., 2013). This relationship ensures the production of fruits and seeds, which are essential for the survival of numerous wildlife species. Pollinators contribute to the maintenance of plant biodiversity by enabling cross-pollination, which promotes genetic variation and resilience in plant populations. This genetic diversity is crucial for plants to adapt to changing environmental conditions and resist diseases (Sahani et al., 2023). Pollinators are integral nodes in food webs, acting as prey for various species. This position them as critical components in maintaining the balance and health of ecosystems (Kevan, 1999). Beyond pollination, these insects aid in seed dispersal and soil health. They contribute to the decomposition of plant matter, enriching soil fertility and structure, which supports plant growth and ecosystem productivity (Patrício-Roberto & Campos, 2014).

Pollinators are indispensable for agricultural productivity, directly influencing the yield and quantity of many crops. Their role extends to ensuring food security and economic stability globally. Many agricultural sectors, such as fruits (e.g., apples and berries) and nuts (e.g., almonds), heavily depend on insect pollinators for successful yields. Pollination increases both the quantity and quality of produce, which is crucial for market value (Sahani et al., 2023). The economic contribution of pollinators is substantial. The decline of pollinator populations can lead to significant economic losses. For instance, pollination services are estimated to contribute around $361 billion annually to global crop production (Khan & Yogi, 2017). Pollinators are essential for the production of nutrient-rich foods, such as fruits, vegetables, and nuts, which are critical for human diets. Ensuring the health of pollinator populations is therefore directly linked to food security (Sharma & Abrol, 2014). Pollinators are essential for the health of ecosystems and the productivity of agriculture. Their role in maintaining biodiversity, supporting food webs, and ensuring food security underscores the need for concerted conservation efforts.

1.2 RESEARCH PROBLEM

The research problem for this thesis revolves around understanding the impact of climate change on plant-pollinator mutualisms, with a specific focus on phenological mismatches. Phenological mismatches occur when the timing of biological events such as flowering in plants and emergence of pollinators, are out of sync due to changes in environmental conditions. This can have significant consequences for ecosystem resilience and the stability of mutualistic relationships between plants and pollinators.

1.2.1 IMPACT OF CLIMATE CHANGE ON PLANT-POLLINATOR INTERACTIONS

Climate change is altering the timing of seasonal occurrences. It is significantly altering ecosystems worldwide, with profound impacts on plant-pollinator interactions. These mutualistic relationships are crucial for the reproduction of many flowering plants and the survival of pollinator species.

Climate warming affects the timing of life events in both plants and pollinators, often leading to mismatched phenologies. This can result in reduced pollination success and altered ecosystem dynamics (Hegland et al., 2009; Scaven & Rafferty, 2013). Studies have shown that while some plants and pollinators adjust their phenologies in parallel, there is considerable variation, leading to mismatches in some cases (J. R. K. Forrest, 2015). Changes in temperature and precipitation patterns are driving shifts in the geographic ranges of both plants and pollinators. This can lead to new interactions and the loss of established ones, potentially disrupting ecosystem services (Harrison & Winfree, 2015; Memmott et al., 2007). High-altitude and latitude regions are particularly vulnerable to these shifts, with many species moving to higher elevations or latitudes in search of suitable habitats (Benadi et al., 2014). The physiological responses of plants and pollinators to warming temperatures can alter their interactions. For example, changes in flower morphology, nectar composition, and pollinator foraging behaviour can impact pollination success (Hoover et al., 2012; Scaven & Rafferty, 2013).

The overall structure of pollination networks may remain robust despite perturbations caused by climate change. However, specific interactions within these networks can be highly sensitive to changes in temperature and precipitation (Hegland et al., 2009; Rafferty, 2017). Biodiversity within pollination networks can buffer against some negative effects,

maintaining overall pollination function despite species-specific phenological shifts (Bartomeus et al., 2013).
Climate change poses significant challenges to plant-pollinator interactions through phenological mismatches, distributional shifts, and physiological changes. While some pollination networks may exhibit resilience, the potential for disrupted interactions and reduced pollination success remains a critical concern. Ongoing research is essential to predict and mitigate these impacts, ensuring the preservation of these vital ecological relationships.

1.2.2 SIGNIFICANCE OF STUDYING PHENOLOGICAL MISMATCHES

Phenological mismatches, where the timing of life cycle events between interacting species becomes desynchronized, are increasingly recognized as critical consequences of climate change. These mismatches can disrupt ecological interactions, affect individual fitness, and alter ecosystem dynamics. Understanding and studying phenological mismatches is essential for predicting and mitigating the impacts of climate change on biodiversity and ecosystem services.

Phenological mismatches affect not only individual species but also the broader ecological communities. Asynchronous shifts among species can disrupt tropic cascades, competitive hierarchies, and species coexistence, impacting overall community dynamics (Nakazawa & Doi, 2012). The mismatch between flowering plants and their pollinators can reduce pollination success, affecting plant reproduction and food availability for pollinators (Morellato et al., 2016). Mismatches can lead to disruptions in ecosystem processes such as nutrient cycling. The timing of resource availability and consumer demand is critical for maintaining ecosystem functions (Beard et al., 2019). For example, studies have highlighted that shifts in the phenology of key species in estuarine ecosystems can affect the nursery function for juvenile fish, with potential implications for fisheries (Chevillot et al., 2017).

Understanding phenological mismatches is vital for conservation biology. Phenological data can help in predicting the impacts of climate change on species interactions and guiding conservation efforts to mitigate these affects (Morellato et al., 2016). Studying phenological mismatches is crucial for understanding the impacts of climate change on ecological interactions and ecosystem functioning. These mismatches have significant evolutionary, demographic, and community-level consequences. Addressing phenological mismatches in conservation and management strategies is essential to mitigate the negative effects of climate change on biodiversity and ecosystem services.

1.3 OBJECTIVES

The main objective is to quantify the extent of phenological mismatches and their impact on the mutualistic relationships between plants and pollinators. Additionally, the study aims to provide insights into the potential long-term consequences of these mismatches on ecosystem resilience and biodiversity conservation.

1.3.1 GOALS OF THE RESEARCH

The research aims to use mathematical models to simulate the dynamics of plant-pollinator interactions under different climate change scenarios. Measure the extent of shifts in the timing of biological events (phenology) for both plants and pollinators due to climate change. By modelling these interactions, the study seeks to predict the potential impacts of phenological mismatches on pollinator populations and plant reproduction. The ultimate goal is to predict the potential long-term effects of these mismatches on ecosystem resilience and biodiversity. To provide insights that can help in formulating strategies for biodiversity conservation and ecosystem management in the face of climate change.

1.3.2 SPECIFIC QUESTIONS ADDRESSED BY THE STUDY

How significantly are the phenological events of plants and pollinators shifting due to climate change? What is the variation in these shifts across different species and geographic locations? How do these phenological mismatches impact the reproductive success of plants and pollinators? What are the broader ecological consequences of disrupted plant-pollinator interactions? How accurately can mathematical models predict the dynamics of plant-pollinator interactions under changing climate conditions? What are the predicted outcomes of continued climate change on these interactions and overall ecosystem health? How do phenological mismatches influence the resilience of ecosystems to environmental changes? What strategies can be developed to mitigate the negative impacts of phenological mismatches? How can conservation efforts be optimized to enhance the resilience of mutualistic relationships in ecosystems?

By addressing these questions, the study aims to provide a comprehensive understanding of the intricate ways in which climate change is altering plant-pollinator mutualisms and to propose informed strategies for mitigating these impacts. This research is crucial for developing effective conservation policies and ensuring the long-term sustainability of ecosystems.

1.4 STRUCTURE OF THE THESIS

In the first chapter, we will be introduced to the concept of plant-pollinator mutualism and its crucial role in both ecosystems and agriculture. This chapter will outline our research problem and highlight the significance of studying phenological mismatches induced by climate change. We will also define the goals of our research and the specific questions the study aims to answer.

The second chapter will provide a comprehensive literature review, offering an in-depth exploration of plant-pollinator mutualism, phenological changes, and climate change's impact on ecosystem resilience. We will examine relevant studies on plant-pollinator interactions within the context of climate change, drawing insights from existing literature.

In the third chapter, we will detail our data sources and data collection procedures, followed by an analysis of the model used in our study. This chapter will explain the methodologies and frameworks employed to assess the interactions between plants and pollinators.

The fourth chapter will present the results of our model simulations, focusing on the impact of phenological mismatches on plant and pollinator populations. We will analyse the trends and patterns observed in the simulations to understand the broader implications of these mismatches.

The fifth chapter will provide a discussion of our findings, delving into the implications for ecosystem resilience and the limitations of our study. We will interpret the results within the broader context of current ecological research and theory.

Finally, the last chapter will summarize our findings, propose future research directions, and discuss the significance and social impact of the study. This chapter will highlight the study's contributions to the field and its potential implications for conservation and policy-making.

CHAPTER 2

LITERATURE REVIEW

2.1 PLANT-POLLINATOR MUTUALISMS

Plant-pollinator mutualisms are of various types and also differs with various species of pollinators.

1. **Generalist Mutualisms:** Generalist plants are pollinated by a wide variety of pollinators, and generalist pollinators visit a wide variety of plants. Example: Dandelions (Taraxacum spp.) are pollinated by a diverse array of insects, including bees, butterflies, and flies (Herrera, 1987).
2. **Specialist Mutualisms:** Specialist plants are pollinated by one or a few species of pollinators, and specialist pollinators rely on one or a few species of plants. Example: The Yucca plant (Yucca spp.) is pollinated by Yucca moths (Tegeticula spp.), which lay their eggs in the flowers. The larvae feed on some of the developing seeds, but enough seeds remain to ensure plant reproduction (Pellmyr & Huth, 1994).
3. **Obligate Mutualisms:** In obligate mutualisms, both the plant and the pollinator are highly specialized and depend entirely on each other for reproduction and survival. Example: Fig trees (Ficus spp.) and their associated fig wasps (Agaonidae family). Each species of fig tree is typically pollinated by one species of fig wasp (Herre et al., 2008).
4. **Facultative Mutualisms:** Facultative mutualisms are interactions where the plant and the pollinator benefit from each other but are not completely dependent on the relationship for survival. Example: The common sunflower (Helianthus annuus) is pollinated by bees, such as the bumblebee (Bombus spp.), but can also self-pollinate if necessary (Mallinger & Prasifka, 2017).

These examples illustrate the diversity of plant-pollinator mutualisms and highlight the complexity of these ecological interactions. Each type of mutualism plays a significant role in maintaining biodiversity and ecosystem stability.

We will look at some examples in Table 2.1 to highlight the diverse and essential mutualistic relationships between butterflies, bees, and their plant partners, which play a significant role in maintaining ecosystem health and biodiversity.

Table 2.1: Mutualism in different species of butterflies and bees.

Species	Type of Mutualism	Mutualistic Partner	Details	Reference
Monarch Butterfly	Pollination, Host-Plant	Milkweed (Asclepias spp.)	Monarch lay eggs on milkweed; larvae feed on leaves; adults pollinate flowers.	(Fischer et al., 2015)
Pipevine Swallowtail	Host-Plant	Pipevine (Aristolochia spp.)	Larvae feed on toxic leaves; toxins provide defense against predators.	(Fordyce & Agrawal, 2001)
Lycaena rubidus	Ant-Butterfly	Ants (Formica spp.)	Larvae produce sugary secretions; ants provide protection from predators.	(Pierce & Mead, 1981)
Cabbage White Butterfly	Pollination	Mustard Plants (Brassica spp.)	Pollinate mustard plants while feeding on nectar, aiding in plant reproduction.	(Heinrich, 1975)
Long-Tailed Skipper	Pollination	Lantana (Lantana camara)	Visit lantana flowers for nectar, facilitating cross-pollination and seed set.	(Núñez-Farfán et al., 1988)
Honeybee	Pollination	Apple Trees (Malus domestica)	Pollinate flowers while collecting nectar and pollen; crucial for fruit production.	(Delaplane & Mayer, 2000)
Bumblebee	Pollination	Red Clover (Trifolium pratense)	Effective pollinators for seed production; obtain nectar from flowers.	(Mill, 1993)
Carpenter Bee	Pollination	Passion flower (Passiflora spp.)	Pollinate as they feed on nectar; large size makes them effective for these flowers.	(Kearns & Inouye, 1993)

2.2 PHENOLOGICAL CHANGES

Phenology is the study of the timing of biological events in plants and animals, such as flowering, breeding, and migration, in relation to seasonal and climatic changes. Phenological changes refer to shifts in the timing of these events, which can have significant ecological and evolutionary implications.

2.2.1 CAUSES OF PHENOLOGICAL CHANGES

1. **Climate Change:**

    - **Temperature:** One of the primary drivers of phenological changes. Warmer temperatures can lead to earlier onset of spring events, such as flowering and leaf-out plants, and breeding in animals.
    - **Precipitation:** Changes in rainfall patterns can also affect the timing of phenological events. For instance, plants that rely on specific moisture conditions for germination or flowering may experience shifts in their life cycles.

2. **Photoperiod:**

    The length of day and night influences the timing of many biological processes. While photoperiod remains constant over the years, its interaction with changing temperatures can alter phenological patterns.

3. **Human Activities:**

    Urbanization, agriculture, and other land-use changes can create microclimates, influencing local phenological events. For example, urban heat islands can lead to earlier blooming of plants in cities compared to rural areas.

2.2.2 PHENOLOGICAL CHANGES IN PLANTS AND ANIMALS

Many plant species are blooming earlier in response to rising temperatures. For example, a study on the flowering time of British plants found that 385 species flowered an average of 4.5 days earlier per decade over the last 50 years (Fitter & Fitter, 2002). Trees are also experiencing earlier leaf-out dates. In North America, the onset of spring leaf-out has advanced by several days over the past century (Schwartz et al., 2006).
Migratory birds are reaching their breeding sites earlier. For example, many North American bird species are reaching their destinations earlier by an average of 0.8 days per decade (Butler, 2003). Changes in breeding

timing have been observed in amphibians, mammals, and insects. For instance, European pied flycatchers (Ficedula hypoleuca) are laying eggs earlier, but not always in sync with peak food availability, leading to potential mismatches (Both & Visser, 2001).

Continuous monitoring and research are essential to understand phenological changes and their impacts. Long-term data sets, such as those from the USA National Phenology Network or the European Phenology Network, provide valuable insights into trends and help predict future changes.

The general trend of phenological shifts in various plants and pollinators from different regions around the world can be observed in Tables 2.2 and 2.3.

Table 2.2: Pollinators and change in their first appearance date

Pollinators	**Change in First Appearance (days)**
Bumble bee	-7
Butterfly	-5
Honey bee	-10
Solitary bee	-8
Hoverfly	-6
Mason bee	-9
Carpenter bee	-4
Sweat bee	-7
Leafcutter bee	-6
Mining bee	-5
Beetle	-3
Fly	-2
Wasp	-4
Moth	-1
Ant	-2
Hawk moth	2
Painted lady butterfly	1
Large white butterfly	3
Orchard bee	2
Long-horned bee	1

Table 2.3: Plants and change in their first flowering date

Plants Species	Change in first flowering date (days)
Herb	-32
Snowdrop	-15
Bluebell	-12
Daffodil	-10
Cherry Blossom	-20
Blackthorn	-14
Cowslip	-8
Hawthorn	-13
Lesser Celandine	-10
Primrose	-11
Rose	-7
Common poppy	-9
Common dandelion	-6
Early purple orchid	-12
Common Ivy	-5
Wild garlic	-8
Red clover	-7
Meadow buttercup	-10
Common violet	-9
Foxglove	-11

2.3 CLIMATE CHANGE AND ECOSYSTEM RESILIENCE

Climate change, characterized by rising temperatures, alters precipitation patterns, and increased frequency of extreme weather events, poses significant challenges to ecosystems worldwide. Ecosystem resilience, or the ability of an ecosystem to withstand and recover from disturbances, is critical in the context of these changes. Understanding the relationship between climate change and ecosystem resilience is essential for developing strategies to protect and manage natural environments.

2.3.1 HOW CLIMATE CHANGE AFFECTS ECOSYSTEMS

Rising temperatures can affect species' physiological processes, distribution, and phenology. For example, coral reefs are highly sensitive to temperature changes, with increased sea temperatures leading to widespread coral bleaching and mortality (Hoegh-Guldberg, 1999). Changes in precipitation can influence water availability, affecting plant growth, soil moisture, and freshwater ecosystems. Drought conditions, for instance, can reduce the resilience of forest ecosystems by increasing tree mortality and altering species composition (Allen et al., 2010). The frequency and intensity of extreme weather events, such as hurricanes, floods, and wildfires, are increasing. These events can cause immediate, severe damage to ecosystems and disrupt long-term ecological processes. For example, hurricanes can devastate coastal ecosystems, altering habitat structure and function (Turner et al., 2003).

Understanding and enhancing ecosystem resilience in the face of climate change is crucial for maintaining biodiversity and the services ecosystems provide to humanity. Through informed conservation, restoration, and adaptive management practices, we can improve the ability of ecosystems to withstand and recover from the climate-related disturbances.

2.3.2 PREVIOUS STUDIES ON PLANT-POLLINATOR INTERACTIONS UNDER CLIMATE CHANGE

Plant-pollinator interactions are essential for ecosystem health, biodiversity, and agriculture. Climate change, characterized by rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events, has profound effects on these interactions. We summarize key findings from previous studies on how climate change influences plant-pollinator interactions.

1. **Phenological Shifts**

   Memmott et al. (2007) investigated the impact of climate change on plant-pollinator interactions by modelling phenological shifts in response to temperature changes. The study found that plants and their pollinators are advancing their phenological events, such as flowering and emergence, at different rates. This leads to potential mismatches in timing, where flowers bloom before their pollinators are active.
   Kudo & Ida (2013) examined the effects of climate change on the synchrony between flowering times of plants and the activity periods of pollinators in alpine ecosystems. They observed that early snowmelt induced by climate warming leads to earlier flowering, but pollinators such as bees did not always respond to the same environmental cues, resulting in temporal mismatches.

2. **Geographic Shifts**

   Miller-Struttmann et al. (2015) explored how the geographic ranges of bumblebees and their plant hosts are shifting due to climate change.

The study found that while some plants and pollinators are moving to higher altitudes or latitudes, not all species are able to relocate at the same rate, leading to potential disruptions in mutualistic relationships.

3. Impacts on Pollinator Behavior and Physiology

Scaven & Rafferty (2013) reviewed behavioral adaptations of pollinators to climate change. They reported changes in foraging behavior, flight activity, and nesting patterns in response to temperature changes. These behavioral shifts can influence pollination effectiveness and plant reproduction.

Rasmont et al. (2015) investigated the thermal tolerance of European bumblebees and the implications for their survival under climate change. Bumblebees exhibited varying levels of thermal tolerance, which could affect their ability to forage and pollinate effectively under rising temperatures. Species with lower thermal tolerance are at greater risk of decline.

4. Ecological and Evolutionary Consequences

Burkle et al. (2013) analyzed long-term changes in plant-pollinator networks by comparing historical data with current observations. The study found significant changes in network structure, with some pollinator species declining or disappearing. This has led to reduced network robustness and potential cascading effects on ecosystem stability. Bartomeus et al. (2011) explored the potential for evolutionary responses of pollinators to climate change. While some species may adapt to changing conditions through evolutionary changes in phenology and behavior, the rapid pace of climate change may outstrip the ability of many species to adapt, leading to declines and local extinctions.

Climate change poses significant challenges to plant-pollinator interactions, affecting phenology, geographic distribution, behavior, and physiology. These changes can lead to mismatches, reduced pollination efficiency, and disruptions in mutualistic networks, ultimately impacting biodiversity and ecosystem services. Continued research and monitoring are essential to understand these dynamics and develop strategies to mitigate the impacts of climate change on these critical interactions.

CHAPTER 3

METHODOLOGY

3.1 DATA COLLECTION

For this study, the primary data collected are phenological data of plant and pollinator species, specifically focusing on:

- **First appearance dates of Butterflies:** Data on the first appearance dates of various butterfly species, with a particular emphasis on Vanessa atalanta (red admiral).
- **Flowering times of Plants:** Data on the first bloom dates of key plant species, particularly Common lilac (Syringa vulgaris).

These data are essential for computing the arrival rates of pollinators and plants, which are critical inputs for the mathematical models used in this research.

To study the general pattern of phenological shifts in plants and pollinators due to climate change, we have collected data on the changes in first appearance dates for various pollinator species and first flowering dates for different plant species from regions around the world. This data is presented in Tables 3.1 and 3.2.

3.1.1 DATA SOURCES

The data were gathered from various research papers to ensure a comprehensive and reliable dataset:

- **Butterfly appearance data:** The first appearance dates for butterflies, including Vanessa Atalanta, were sourced from Roy & Sparks (2000).
- **Flowering time for different flower species:** The first flowering dates for various plant species were obtained from Fitter & Fitter (2002).
- **Flowering date for Syringa vulgaris:** The specific data on the flowering time of Syringa vulgaris were taken from the research article Wang et al. (2018).
- The data on changes in first appearance dates for various pollinators and first flowering dates for different plants, as

presented in Tables 2.2 and 2.3, was collected from various research papers and articles. The sources are listed below.

1. Freimuth et al. (2022)
2. Bartomeus et al. (2013)
3. Pollinators and Climate Change- Xerces Society
4. Wyver et al. (2023)
5. (Miller-Rushing et al., 2008)
6. Plants are Blossoming a month early in the U.K. because of climate change- Margaret Osborne (2022)
7. UK flowers are blooming a month earlier because of climate change. Here's why that's a problem- World Economic Forum
8. Amano et al. (2010)
9. Dorji et al. (2020)

3.1.2 DATA COLLECTION PROCEDURE

The procedures for collecting data from different research papers involved several steps to ensure the accuracy and consistency of the data:

- **Literature search:** Conducted a thorough search of scientific databases (e.g., PubMed, Web of Science, Google Scholar) using keywords related to butterfly phenology, plant flowering times, Vanessa atalanta, and Syringa vulgaris.

- **Selection criteria:** Selected studies based on criteria such as geographical relevance to the study area, the time period of data collection, and the methodological rigor of the research.

- **Butterfly appearance data:** Extracted the first appearance dates of Vanessa Atalanta from Roy & Sparks (2000) recorded over a time period of 1976-1988.

- **Flowering times of various plants:** Extracted data on the deviations of first flowering dates of different plant species from Fitter & Fitter (2002) over the time period 1991-2000.

- **Syringa vulgaris flowering time:** Extracted specific data on the first flowering time of Syringa vulgaris from Wang et al. (2018) over change in preseason temperature.

- **Cross-referencing:** Cross-referenced data from multiple studies to ensure accuracy and reliability. Where discrepancies were found, the original sources were revisited to clarify the correct data.

- **Proper citations:** Ensured all data extracted from research papers were properly cited, giving credit to the original authors and avoiding any issues of plagiarism.

3.1.3 CHALLENGES AND LIMITATIONS

- **Inconsistent reporting:** Variability in how different studies reported phenological data posed a challenge. Efforts were made to standardize the data, but some inconsistencies might still affect the analysis.
- **Geographical and temporal gaps:** Some studies covered different geographical areas or time periods, leading to gaps in the dataset. These were addressed by using data from a broad range of sources to ensure coverage.
- **Limited contextual information:** Not all studies provided detailed environmental context, which could limit the ability to fully understand the factors influencing phenological events.

The data collection process involved a systematic approach to gather, extract, and standardize phenological data from a variety of research papers. By combining data from multiple sources, this study ensures a comprehensive dataset that supports robust analysis of phenological shifts and their impacts on plant-pollinator interactions in the context of climate change. Proper ethical considerations and quality control measures were implemented to maintain the integrity and reliability of the data.

3.2 MATHEMATICAL MODELLING

3.2.1 MODEL FRAMEWORK

In this study, we adopt the plant-pollinator interaction model developed by Fagan et al. (2014). This model is designed to capture the dynamics of both pollinator and plant populations by dividing each into two distinct categories:

- **Pollinators with pollen:** These are pollinators that have collected pollen from flowers.
- **Pollinators without pollen:** These are pollinators that have not yet collected pollen.
- **Unpollinated flowering plants:** These are plants with flowers that have not been pollinated.
- **Pollinated flowering plants:** Theses are plants with flowers that have been successfully pollinated.

To describe the interactions and dynamics of these populations, we use a set of differential equations for each of the four groups. These equations account for the rates of change in population sizes over time, incorporating key processes such as the arrival of pollinators and the opening of flowers.

Population dynamics:
The differential equations model the population dynamics by incorporating the following key components:

- **Pollinator arrival rate:** The rate at which pollinators arrive in the area, modeled using a gamma distribution.
- **Flower opening rate:** The rate at which flowers open, also modeled using a gamma distribution.

Adjusting visitation and pollination rate:
To further explore the dynamics of plant-pollinator interactions, we modify:

- **Visitation rate of pollinators to plants:** This rate influences how often pollinators visit plants, affecting the differential equations for pollinators.
- **Pollination rate:** This rate impacts the rate at which pollination occurs, affecting the differential equations for plants.

By adjusting these rates, we can visualize how changes in visitation and pollination rates influence the populations of both plants and pollinators. This allows us to simulate different scenarios and understand the sensitivity of the ecosystem to changes in these key interaction rates.

3.2.2 DIFFERENTIAL EQUATIONS

We will be using the following model by Fagan et al. (2014) for pollinator and plant populations.
The population dynamics of pollinators are described as:

$$\frac{dQ}{dt} = \overbrace{S_0 g_s(t, \theta_s)}^{\text{arrival/ emergence}} - \overbrace{\gamma(U + P)Q}^{\text{pollen collection}} - \overbrace{\alpha_s Q}^{\text{departure/ death}} + \overbrace{\beta R}^{\text{pollen removal}} \tag{3.1}$$

$$\frac{dR}{dt} = \overbrace{\gamma(U + P)Q}^{\text{pollen collection}} - \overbrace{\alpha_s Q}^{\text{departure/ death}} - \overbrace{\beta R}^{\text{pollen removal}} \tag{3.2}$$

The dynamics of flowers are described as:

$$\frac{dU}{dt} = \overbrace{U_0 g_p(t, \theta_p)}^{\text{flower opening}} - \overbrace{\mu_p U}^{\text{flower death}} - \overbrace{\alpha_p n U}^{\text{plant death}} + \overbrace{\Lambda U R}^{\text{pollination}} \tag{3.3}$$

$$\frac{dP}{dt} = \overbrace{\Lambda U R}^{\text{pollination}} - \overbrace{\alpha_p n P}^{\text{plant death}} - \overbrace{\mu_p P}^{\text{flower death}} \tag{3.4}$$

3.2.3 GAMMA DISTRIBUTION AND ITS PARAMETERS

The PDF governing plant and pollinator phenology are gamma distributions described by

$$g_x(t, \theta_x) = \begin{cases} 0 & t \leq \varepsilon_x \\ \frac{\lambda_x}{\Gamma(\zeta_x)} (\lambda_x (t - \varepsilon_x))^{\zeta_x - 1} e^{-\lambda_x (t - \varepsilon_x)} & t > \varepsilon_x \ , \ x = s, p \end{cases} \tag{3.5}$$

where $\theta_x = (\lambda_x, \zeta_x)$

3.3 ANALYSIS

The computed values of the pollinator arrival rate and the flower opening rate, derived from the gamma distribution, are used to parameterize the model. By solving the differential equations numerically, we can observe the population dynamics and rate of change for each group under different scenarios of visitation pollination rates. The results of the model simulations are visualized in plots, showing how the populations of pollinators and plants evolve over time. These plots illustrate the effects of varying visitation and pollination rates, providing insights into the resilience and adaptability of plant-pollinator interactions under changing environmental conditions.

This comprehensive model framework allows us to analyse the effects of climate change on plant-pollinator interactions, providing valuable insights into the resilience of ecosystems and the mutual dependencies between plants and pollinators. By examining the impact of varying visitation and pollination rates, we can better understand the potential consequences of environmental changes on these critical ecological interactions.

CHAPTER 4

RESULTS

4.1 PHENOLOGICAL SHIFTS IN POLLINATORS AND PLANTS

Phenology, the study of the timing of seasonal biological events, is crucial for understanding the interactions between plants and their pollinators. Climate change significantly impacts these timings, leading to potential mismatches in the life cycles of plants and their pollinators. Such mismatches can disrupt mutualistic relationships, impacting ecosystem health and resilience.
From the data we have gathered on phenological shifts in various plants and pollinators across different regions of the world, as shown in Tables 2.2 and 2.3, we can analyze how these species have been responding to climate change over the years.

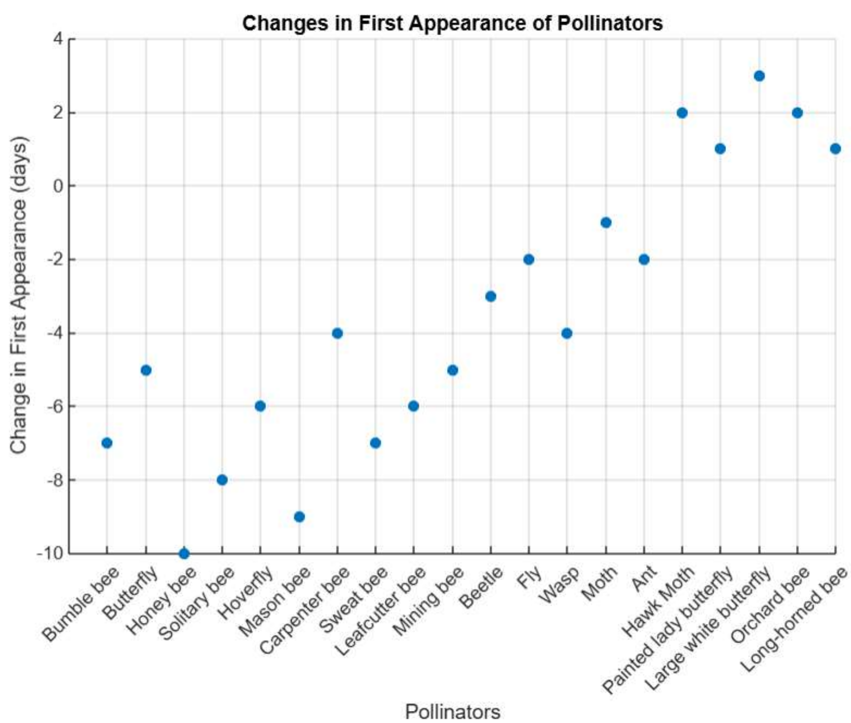


Fig. 4.1: Change in first appearance of pollinators

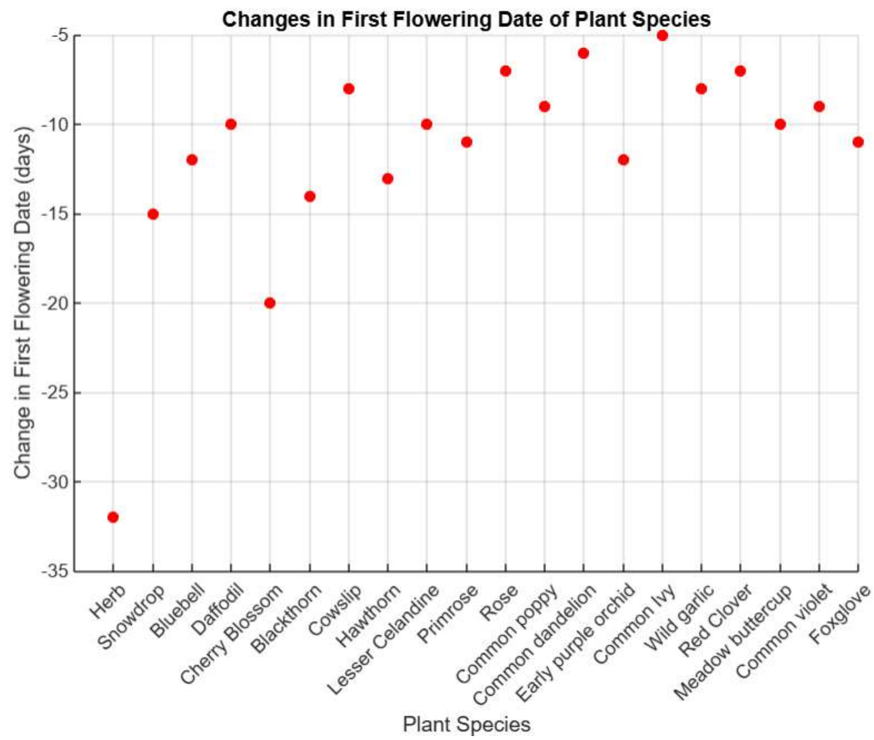


Fig. 4.2: Change in first flowering date of plant species

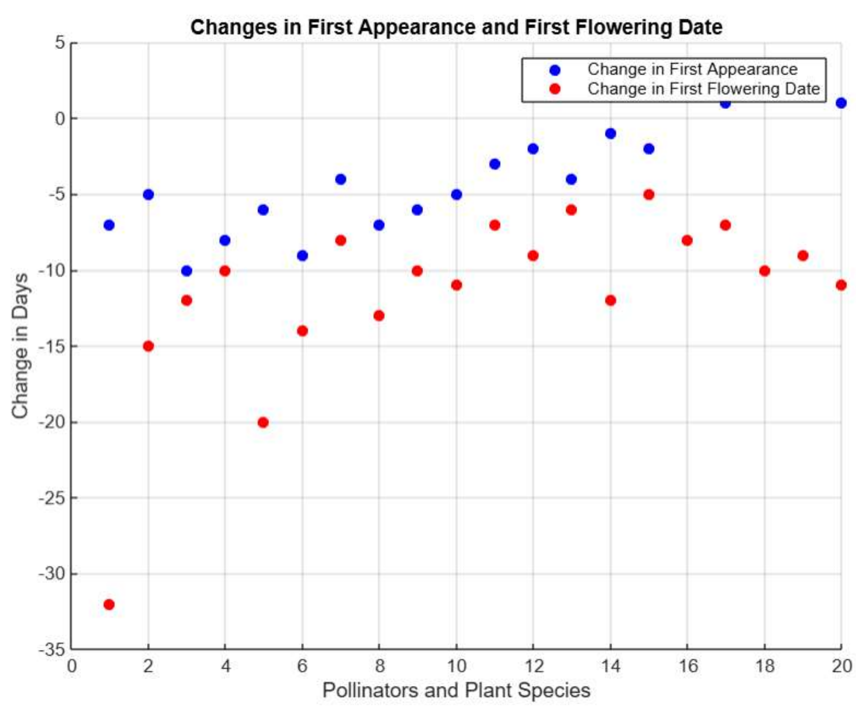


Fig. 4.3: Change in first appearance and first flowering dates of pollinators and plant species

4.1.1 ANALYSIS OF THE DATA FOR BUTTERFLY AND PLANT SPECIES

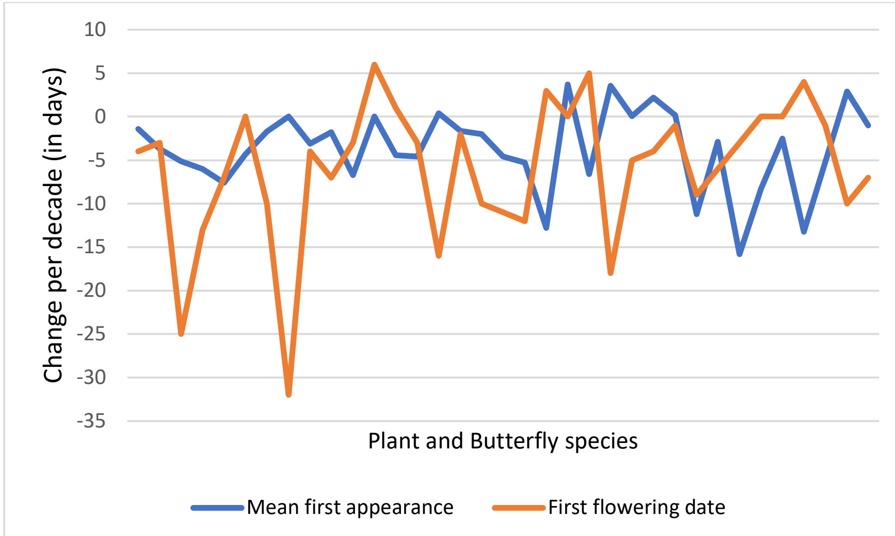


Fig. 4.4: Change in mean first appearance and first flowering date of different plants and butterfly species.

The graph in figure 4.4 presents the change per decade in mean first appearance of various butterfly species (blue line) and the first flowering date of different plant species (orange line). This data, sourced from Roy & Sparks (2000) and Fitter & Fitter (2002), illustrates how these timings have shifted over time, likely in response to climate change.

1. **Trends and Patterns:**

   The blue line (butterflies) shows a general trend of advancing first appearances over the decades, with fluctuations indicating periods of both advancement and delay. The orange line (plants) similarly shows a trend towards earlier flowering dates, though the fluctuations appear more pronounced compared to the butterflies.
   Both lines exhibit changes, with some species showing shifts of up to 30 days. This indicates a high sensitivity of both plants and pollinators to climatic changes.

2. **Comparison and Synchronization:**

   While both plants and butterflies show advancing trends, the rates and patterns of change are not identical. This asynchrony suggests potential temporal mismatches where butterflies might emerge before or after the peak flowering periods, leading to inefficient pollination.

3. **Implications for ecosystem resilience**

Mismatched phenologies can disrupt the mutualistic relationships, leading to reduced reproductive success for plants and food shortages for pollinators. Such disruptions can cascade through the ecosystem, affecting biodiversity and ecosystem stability.

The graph effectively highlights the significant and variable phenological shifts in both butterflies and plants over the decades. These shifts underline the importance of continuous monitoring and adaptive conservation strategies to mitigate the potential adverse impacts of climate change on plant-pollinator interactions and overall ecosystem resilience.

4.1.2 ANALYSIS OF GAMMA DISTRIBUTION

We collected data on the arrival times of the butterfly species Vanessa atalanta from 1976 to 1998, as reported by Roy & Sparks (2000). Additionally, we obtained data on the first bloom dates of the plant species Syringa vulgaris for various preseason temperatures from 1963 to 2018, as documented by Wang et al. (2018). Using this data, we calculated the probability density for the arrival rate and flowering rate of the butterfly and plant species, respectively, employing the gamma distribution defined by equation (3.5).

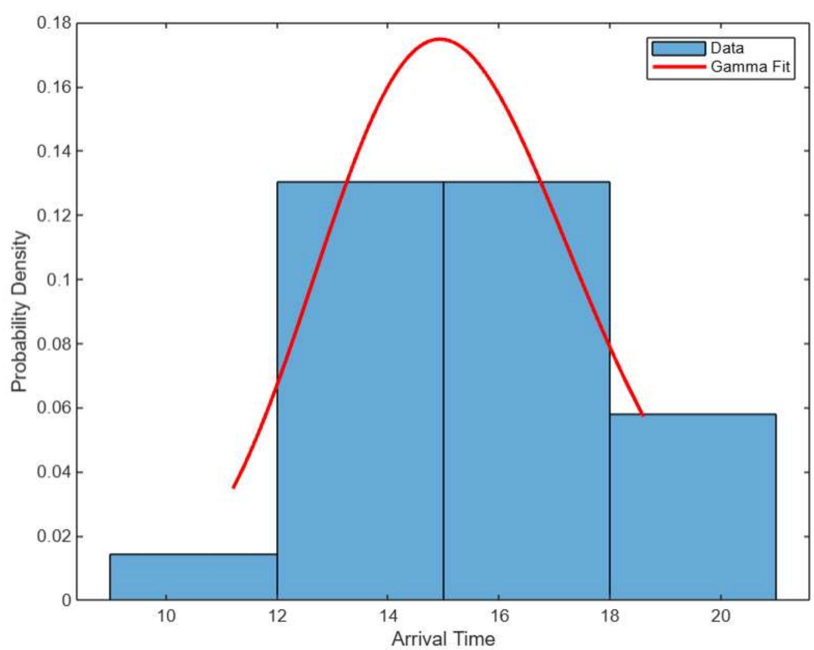


Fig. 4.5: Probability density for first appearance of Vanessa atalanta.

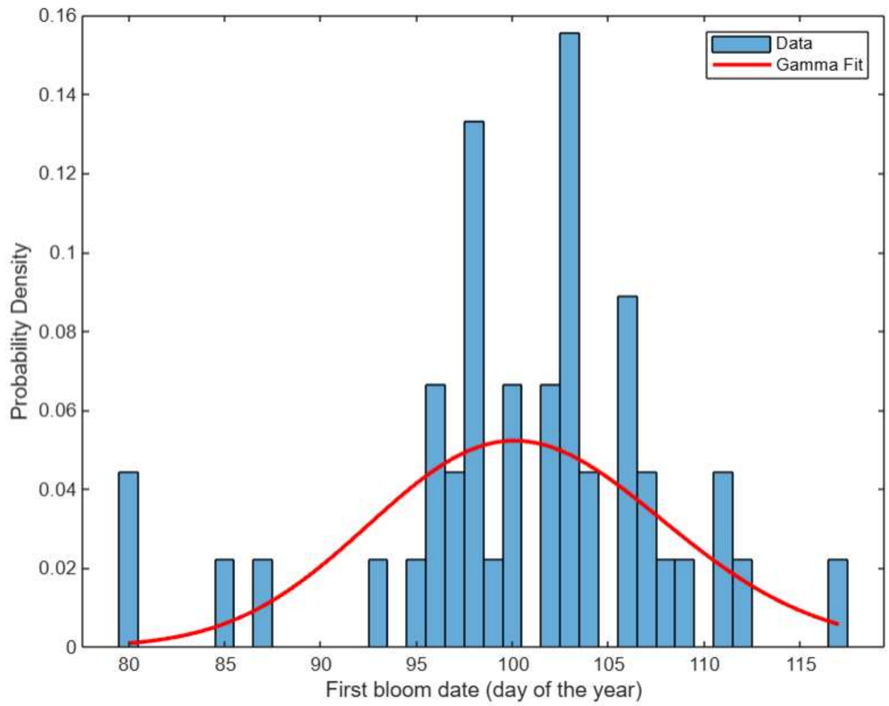


Fig. 4.6: Probability density for first bloom date of Syringa vulgaris.

The gamma fit curve shows a smooth, continuous distribution that approximates the observed arrival times and first bloom dates.
The peak of the gamma fit curve suggests the most common arrival time and first bloom date, around which most data points are clustered.
The spread of the curve indicates the variability in arrival times and first bloom dates.
The MATLAB code for Fig. 4.5 and 4.6 is given in Appendix I.

4.2 MODEL SIMULATIONS

4.2.1 RESULTS FROM THE MODEL SIMULATIONS SHOWING POPULATION DYNAMICS

We incorporated the calculated arrival rate for Vanessa atalanta into the differential equation models (3.1) and (3.2) to analyse the population dynamics of pollinators. By varying the visitation rates, we were able to study how population dynamics respond to the occurrence of phenological mismatches. The MATLAB code for simulating population dynamics and pollinator rate of change is provided in Appendix II.1.

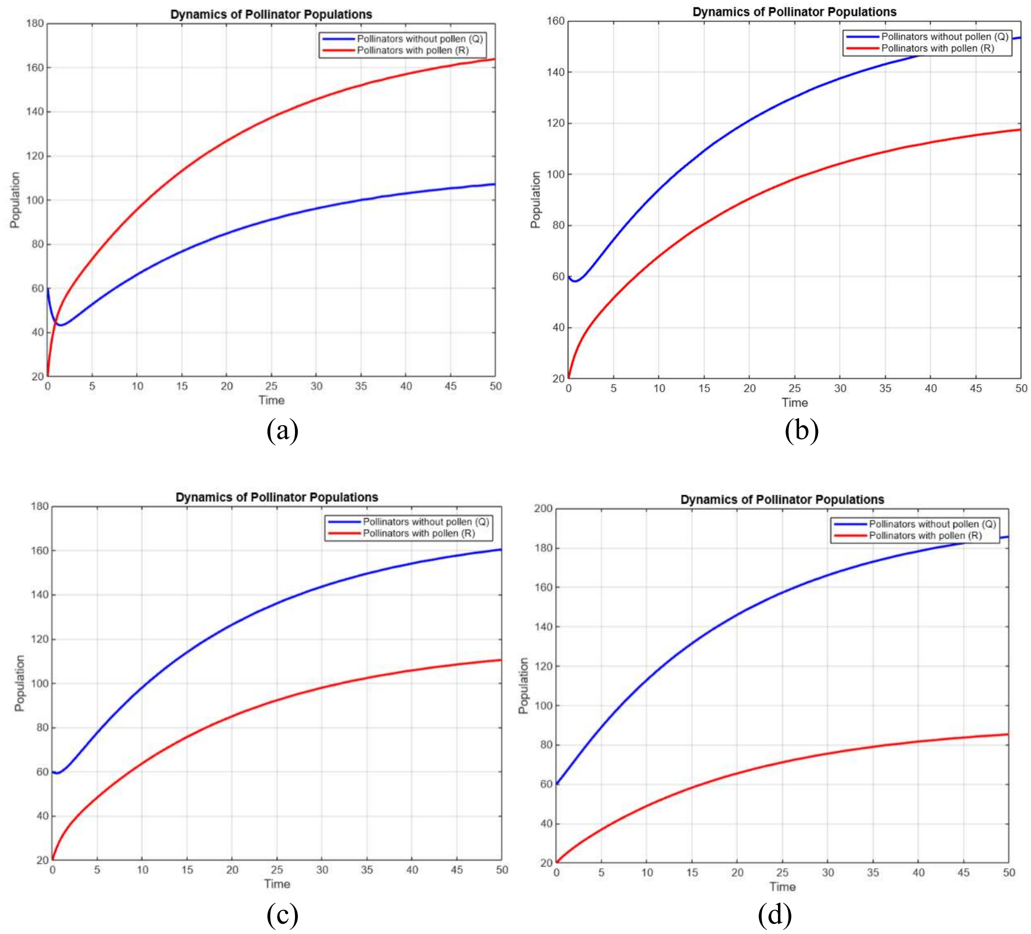
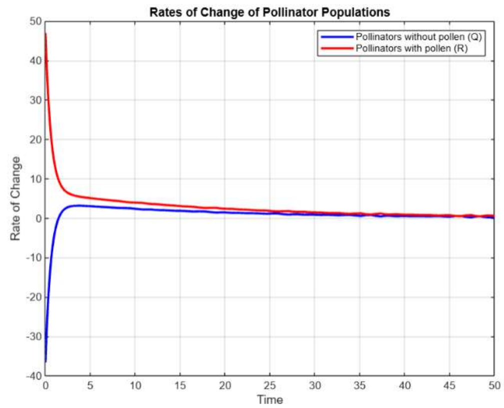


Fig. 4.7: Population dynamics of pollinators with (R) and without (Q) pollen over time with decreasing visitation rate.

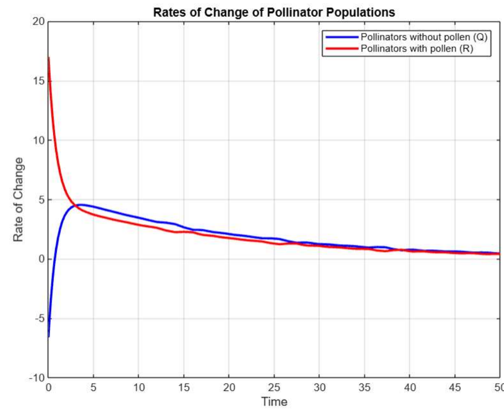
The graphs in figure 4.7 illustrates the dynamics of pollinator populations over time for pollinators with pollen (R) and without pollen (Q) under different scenarios of decreasing visitation rates. Initially the population R is relatively high, indicating frequent and successful pollination events. It fluctuates around a stable, high value. The population Q is lower compared to R, suggesting that most pollinators are efficiently collecting pollen. It remains relatively stable at a lower level.

As visitation rate decreases, there is a noticeable decline in the population of R and the population Q begins to increase slightly as fewer pollinators successfully collect pollen. In the scenario of very low visitation rate, the population of R drops to a low level, reflecting a critical reduction in pollination success. The population may approach zero or show high variability, indicating possible collapse. The population Q peaks at its highest, showing significant instability. This trend suggests that most pollinators are unable to collect pollen, leading to potential disruptions in the ecosystem.

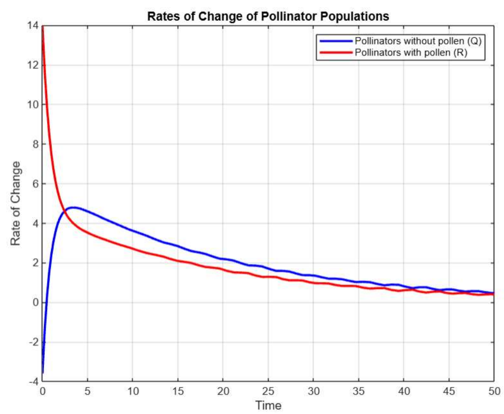
We will now look at the rate of change of pollinator population.



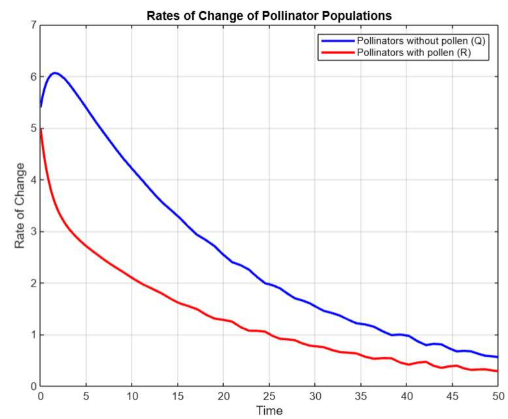
(a)



(b)



(c)



(d)

Fig. 4.8: Rate of change of pollinator population over time for pollinators with (R) and without (Q) pollen with decreasing visitation rate.

In the figure 4.8, the rate of change of Q starts negative, indicating that initially, the population of pollinators without pollen is decreasing. Over time, this rate of change increases, approaching zero, suggesting that the decline in the population of pollinators without pollen slows down and eventually stabilizes. The rate of change of R starts positive, indicating that initially, the population of pollinators with pollen is increasing. Over time, this rate of change decreases, also approaching zero, indicating that the increase in the population of pollinators with pollen slows down and stabilizes. The stabilization of populations becomes progressively slower as the visitation rate decreases. The rates of increase for pollinators with pollen and decrease for pollinators without pollen both diminish, indicating reduced pollination efficiency.

We used calculated flowering rate of Syringa vulgaris in the differential equation models (3.3) and (3.4) to observe population dynamics of plants. The MATLAB code for simulating population dynamics and plant rate of change is provided in Appendix II.2.

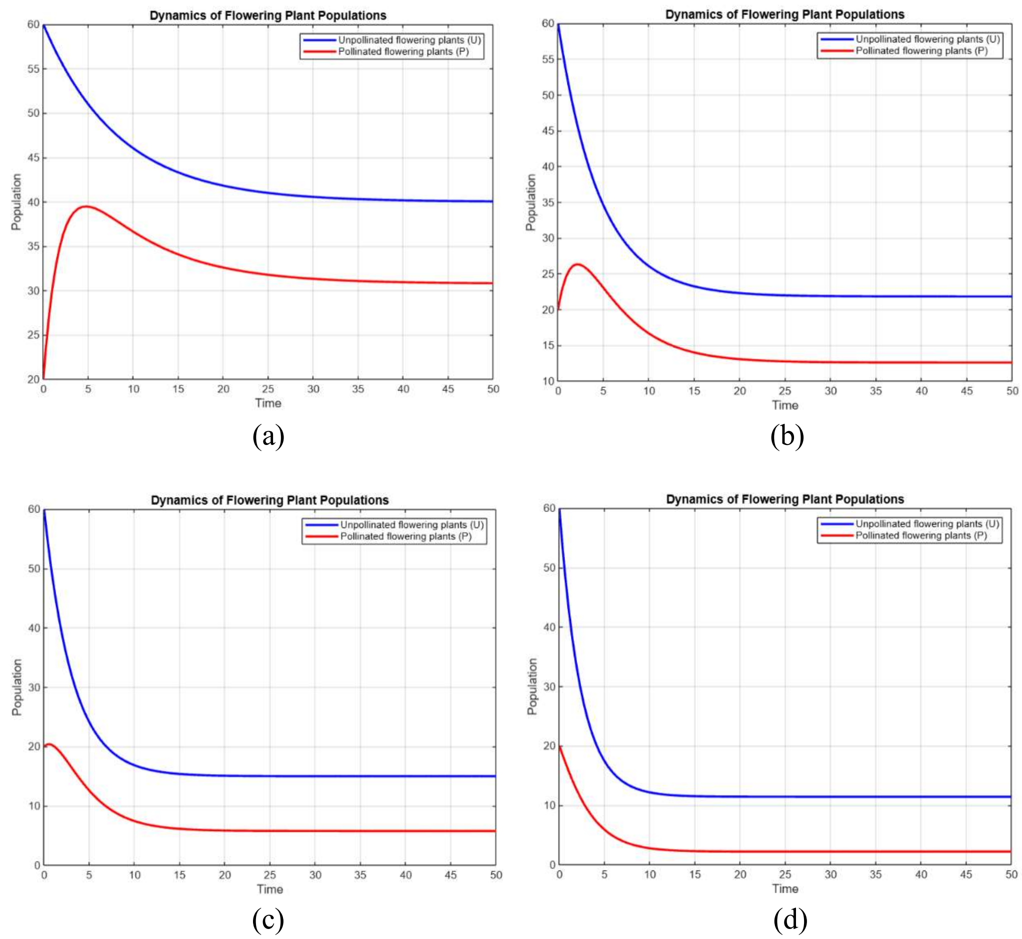


Fig. 4.9: Population dynamics of unpollinated (U) and pollinated (P) flowering plants over time with decreasing pollination rate.

The graphs in figure 4.9 illustrate the dynamics of flowering plant populations over time, showing the populations of unpollinated flowering plants (U) and pollinated flowering plants (P) with varying pollination rates. Initially, the population of unpollinated plants is high. Over time, the population decreases, reflecting the process of pollination and the conversion of unpollinated plants to pollinated plants. Initially, the population of pollinated plants is low. Over time, the population increases as more plants get pollinated, peaking before gradually stabilizing, indicating a high rate of successful pollination. As the pollination rate decreases, the decrease in unpollinated plants and the increase in pollinated plants both slow down significantly. It indicates a less efficient pollination process, which can affect plant reproduction and overall ecosystem health.

We will now look at the rate of change of plant population.

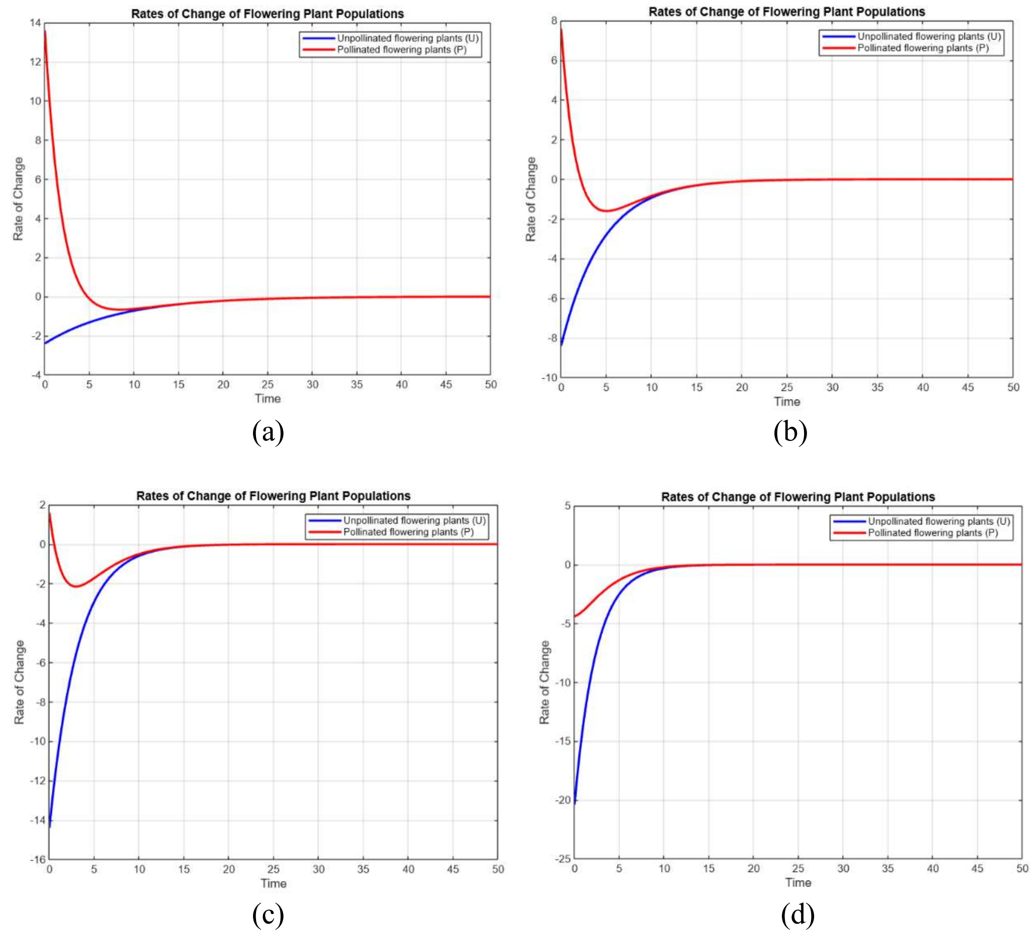


Fig. 4.10: Rate of change of plant population over time for unpollinated (U) and pollinated (P) flowering plants with decreasing pollination rate.

In the figure 4.10, the rate of change for U initially starts negative, indicating a decrease in the unpollinated plant population. The rate of change for P initially starts positive, indicating an increase in the pollinated plant population. The rate of change eventually approaches zero, indicating a stabilization of the unpollinated and pollinated plant population. It reflects a healthy and efficient pollination process, with rapid conversion of unpollinated plants to pollinated plants. It indicates a robust ecosystem where pollination is highly effective. As the pollination rate decreases progressively, the rate of decrease in unpollinated plants and the rate of increase in pollinated plants both slow down significantly. It indicates less effective pollination process, which can negatively impact reproduction and overall ecosystem health.

4.3 IMPACT OF PHENOLOGICAL MISMATCHES

Reduced visitation rates may be a result of mismatches where pollinators are not present when plants are in bloom. This misalignment leads to decreased pollen transfer efficiency, adversely impacting both pollinator and plant reproductive success. Over time, persistent mismatches could result in lower pollinator populations as their food resources (flowering plants) diminish. Lower pollination rates due to phenological mismatches result in fewer plants being pollinated. This leads to reduced reproductive success for plants, impacting their population dynamics and potentially leading to a decline in plant species over time. The stability of plant populations is compromised, potentially leading to reduced biodiversity and altered ecosystem functioning.

Phenological mismatches undermine the mutualistic relationships between plants and pollinators, essential for ecosystem resilience. Persistent mismatches can lead to population declines in both pollinators and plants, reducing the overall stability and health of the ecosystem. Reduced reproductive success in plants can lead to decreased plant diversity. Lower plant diversity impacts the availability of resources for pollinators, further exacerbating the decline in pollinator populations. If phenological mismatches continue, we may observe long-term declines in both plant and pollinator populations. These declines could lead to significant shifts in community structure, with potential cascading effects on other species and ecosystem services.

The model simulations highlight the critical importance of synchronized phenologies for the stability of plant-pollinator interactions. Phenological mismatches, driven by factors such as climate change, can have profound negative impacts on both plant and pollinator populations. Understanding and addressing these mismatches is essential for preserving ecosystem resilience and biodiversity.

CHAPTER 5

DISCUSSION

5.1 INTERPRETATION OF RESULTS

Numerous studies have highlighted the negative impacts of phenological mismatches on plant-pollinator interaction. For example, Visser & Both (2005) discuss how shifts in the timing of biological events, driven by climate change, can disrupt established ecological relationships. Burkle et al. (2013) provided empirical evidence showing that temporal mismatches between flowering plants and pollinators can lead to reduced pollination services, negatively affecting both plant reproduction and pollinator populations. The simulation results align with findings, showing that decreased pollinator visitation rates lead to reduced populations of pollinators with pollen (R) and lower pollination success rates for plants. The graphs demonstrate that as the visitation and pollination rate decrease, both pollinator and plant populations stabilize at lower levels, indicating a clear disruption in their mutualistic relationship.

Studies such as Potts et al. (2010) have documented declines in pollinator populations due to various factors, including habitat loss, pesticides, and climate change. These declines are often exacerbated by phenological mismatches, which reduce the availability of floral resources. Memmott et al. (2007) emphasized the potential for climate change to cause mismatches in mutualistic interactions, predicting significant declines in pollinator populations as a result. The negative initial rate of change for pollinators without pollen (Q) and the positive initial rate for pollinators with pollen (R) indicate a crucial dependency on the availability of flowers and successful pollination events. The trend observed, where reduced visitation rates lead to lower stabilized populations, supports the idea that pollinator declines are closely tied to the availability of floral resources and the timing of flowering events.

The reproductive success of flowering plants is highly dependent on effective pollination. Studies like those by Gallai et al. (2009) have shown that reduced pollination services can lead to decreased seed set and fruit production. J. Forrest & Miller-Rushing (2010) highlighted how changes in flowering times can lead to mismatches with pollinator activity, affecting plant reproduction and leading to potential declines in plant populations. The results showing decreased pollination rates leading to lower populations of pollinated plants (P) align with these studies. The reduced rate of change for pollinated plants as pollination rates decrease highlights the critical role of pollinators in plant reproductive success. The initial peak in the population of pollinated plants (P) followed by a decline and stabilization at lower levels further underscores the dependency of plants on timely and effective pollination.

5.2 IMPLICATIONS OF ECOSYSTEM RESILIENCE

Ecosystem resilience refers to the ability of an ecosystem to absorb disturbances and still retain its basic structure, functions, and feedbacks. In the context of plant-pollinator interactions, ecosystem resilience is crucial for maintaining biodiversity and the services provided by these interactions, such as pollination.

1. Understanding Ecosystem Resilience

Holling (1973) introduced the concept of ecological resilience, describing it as the capacity of an ecosystem to withstand shocks and stresses without shifting to an alternative stable state. Walker et al. (2004) expanded on this concept, emphasizing the importance of adaptive capacity and the ability of ecosystems to reorganize in response to disturbances. The simulations indicate that as visitation and pollination rate decrease, both pollinator and plant populations stabilize at lower levels, suggesting a reduced capacity to maintain population size under stress. The results highlight the potential vulnerability of ecosystems to phenological mismatches, where the timing of biological events such as flowering and pollinator activity becomes desynchronized.

2. Impact of Phenological Mismatches on Resilience

Parmesan (2006) documented how climate change can lead to mismatches between species, disrupting interactions and potentially leading to population declines and reduced resilience. Burkle et al. (2013) showed that mismatches in timing between plants and pollinators can lead to decreased pollination success and reproductive output, further stressing the resilience of ecosystems. The observed declines in pollinator and plant populations due to reduced visitation and pollination rates suggest that phenological mismatches can weaken the resilience of ecosystems. Reduced resilience means that ecosystems are less able to recover from disturbances and maintain their functional integrity.

3. Ecosystem Services and Resilience

Ecosystem services, such as pollination, are critical for food production and biodiversity. Studies like those by Klein et al. (2007) have highlighted the economic and ecological importance of maintaining healthy pollinator populations. Writing et al. (2005) emphasized that resilient ecosystems are better able to provide essential services and adapt to changes and disturbances. The results indicate that decreased pollinator and plant populations could lead to a decline in ecosystem services such as pollination. This decline can have cascading effects on food production and biodiversity. Ensuring ecosystem resilience requires maintaining synchronized phenologies and addressing factors contributing to phenological mismatches, such as climate change and habitat loss.

4. Conservation and Management implications

Strategies to enhance ecosystem resilience often include habitat restoration, conservation of keystone species, and the creation of climate-resilient landscapes (Folke et al., 2004). Tylianakis et al. (2008) emphasized the need for adaptive management practices that can respond to changing conditions and mitigate the impacts of disturbances. The study underscores the importance of conservation efforts aimed at preserving the synchronization between plant and pollinator phenologies. This includes protecting habitats, promoting biodiversity, and implementing adaptive management strategies. Enhancing ecosystem resilience requires a holistic approach that considers the interconnectedness of species and the potential impacts of climate change on ecological interactions.

The existing literature highlight the critical need to address phenological mismatches and other disturbances that can disrupt plant-pollinator interactions. Maintaining synchronized phenologies and implementing adaptive management practices are essential for preserving ecosystem resilience, ensuring the continued provision of ecosystem services, and supporting biodiversity. Future research and conservation efforts should focus on understanding and mitigating the factors that threaten the resilience of ecosystems, thereby enhancing their capacity to adapt to and recover from disturbances.

5.3 LIMITATIONS OF THE STUDY

1. Simplified Model Assumptions:

The model focuses on specific plant and pollinator species, such as Vanessa Atalanta and Syringa vulgaris, which may not capture the complexity and diversity of real-world ecosystems where multiple species interact.

2. Data Limitations:

The study relies on historical data from Roy & Sparks (2000), Fitter & Fitter (2002), and Wang et al. (2018), which may not account for recent changes or trends in phenological patterns. The data may have limitations in temporal resolution, potentially missing fine-scale variations in phenological events that could influence the results.

3. **Model Parameters and Calibration:**

The accuracy of model predictions depends on the precise estimation of parameters such as visitation rates, pollination rates, and gamma distribution parameters. Inaccuracies in these estimates can affect the model outcomes. The model may not have fully calibrated against empirical data from multiple sources or field observations, which could affect the reliability of the results.

4. **Phenological Mismatches:**

The model primarily addresses phenological mismatches due to climate change but may not consider other factors such as habitat loss, pesticide use, and invasive species, which can also impact plant-pollinator interactions. The model may not fully capture the dynamic and adaptive nature of plant-pollinator interactions, where species can exhibit plasticity and evolve in response to changing conditions.

5. **Ecosystem Complexity:**

The model simplifies the ecosystem by considering only direct interactions between plants and pollinators, potentially overlooking indirect interactions, such as competition, predation, and mutualistic relationships with other species. Real-world ecosystems are multifunctional, and focusing solely on plant-pollinator interactions may not capture other essential ecosystem functions and services.

6. **Future Climatic Scenarios**

The study may use specific climate projections to simulate phenological changes, but there is inherent uncertainty in future climate scenarios, which can affect the predictions and generalizability of the results. The model may not incorporate socio-economic factors such as land use changes, agricultural practices, and conservation policies, which can significantly impact plant-pollinator interactions.

CHAPTER 6

CONCLUSION, FUTURE SCOPE AND SOCIAL IMPACT

6.1 SUMMARY OF FINDINGS

This study investigates the impact of phenological mismatches between plants and pollinators on ecosystem stability and resilience, using a mathematical model framework adapted from Fagan et al. (2014). The primary focus is on how variations in pollinator arrival rates and flowering times influence population dynamics under different environmental scenarios.

1. Impact of Visitation Rate on Pollinator Populations:

The model simulations revealed that decreasing visitation rates lead to significant declines in both pollinators with pollen (R) and pollinators without pollen (Q). Pollinators without pollen (Q) exhibited a rapid initial negative growth rate, stabilizing at lower population levels compared to those with pollen (R). This indicates that pollinators without pollen are more sensitive to decrease in visitation rates.

2. Impact of Pollination Rate on Plant Populations:

Unpollinated flowering plants (U) showed a sharp initial decline in population, eventually stabilizing at lower levels as pollination rates decreased. In contrast, pollinated plants (P) also experience a decline but stabilized at relatively higher levels than unpollinated plants. These trends suggest that reduced pollination rates significantly affect plant populations, with unpollinated plants being more vulnerable to such changes.

3. Population Dynamics under Phenological Mismatches:

The simulations demonstrated that phenological mismatches, represented by changes in the timing of pollinator arrival and flowering events, can lead to disrupted plant-pollinator interactions. These disruptions result in lower overall population levels for both pollinators and plants, highlighting the critical importance of temporal synchrony for maintaining ecosystem functions.

4. Ecosystem Resilience

The study underscores the vulnerability of ecosystems to climate-induced phenological mismatches. The results suggest that maintaining temporal alignment between pollinators and flowering plants is essential for sustaining pollinator services and plant reproduction. Adaptive conservation strategies are needed to mitigate the adverse effects of climate change on plant-pollinator mutualisms, ensuring long-term ecosystem resilience.

These findings provide valuable insights into the mechanisms driving ecosystem resilience and emphasize the need for integrated conservation efforts that address the complex interplay between biological, environmental, and socio-economic factors. Future research should explore multi-species interactions and spatial variability to develop more comprehensive strategies for protecting plant-pollinator interactions in the face of climate change.

6.2 FUTURE RESEARCH DIRECTIONS

Building on the findings of this study, several avenues for future research can be identified to further understand and mitigate the impacts of phenological mismatches on plant-pollinator interactions and ecosystem resilience:

1. Multi-Species Interactions:
Expand the current model to include multiple plant and pollinator species to capture the complexity and diversity of real-world ecosystems. Investigating how different species interact and compete can provide a more comprehensive understanding of ecosystem dynamics.

2. Spatial and Temporal Variability:
Incorporate spatial variability into the models to account for different environmental conditions across landscapes. Studying the effects of spatial heterogeneity, such as microclimates and habitat fragmentation, can offer insights into how local conditions influence plant-pollinator interactions. Enhance temporal resolution in phenological data to capture fine-scale variations and short-term fluctuations in life cycle events, which may significantly affect population dynamics.

3. Adaptive Behaviors and Evolutionary Responses:
Investigate the potential for adaptive behaviors and evolutionary responses among plant and pollinator species to changing environmental conditions. Understanding how species might adjust their phenology in response to climate change can inform conservation strategies.

4. Field Experiments and Long-Term Monitoring:
Conduct field experiments and long-term observational studies to validate and calibrate model parameters with empirical data. Such studies can provide robust datasets to refine model predictions and improve their accuracy. Monitor plant and pollinator populations over extended period to observe real-time responses to environmental changes and identify emerging trends.

5. Socio-Economic and Land Use Factors:
Integrate socio-economic factors and land use changes into the models to examine how human activities, such as agriculture, urbanization, and conservation policies, impact plant-pollinator interactions. Assessing the role of socio-economic drivers can help in designing holistic and practical conservation strategies. Explore the implications of different land management practices and their potential to enhance or mitigate the effects of phenological mismatches.

6. Climate Change Scenarios:
Utilize a range of climate change scenarios to assess the robustness of plant-pollinator interactions under different future conditions. Analyzing the impacts of varying degrees of climate change can help in identifying thresholds and tipping points for ecosystem resilience. Investigate the role of extreme weather events, such as heatwaves and droughts, on phenological mismatches and their subsequent effects on plant and pollinator populations.

7. Ecosystem Services and Functional Diversity:
Study the broader implications of phenological mismatches on ecosystem services beyond pollination, such as nutrient cycling, pest control, and habitat provision. Understanding the interconnectedness of ecosystem functions can highlight the cascading effects of disrupted plant-pollinator interactions. Assess the role of functional diversity within pollinator and plant communities in enhancing ecosystem resilience to phenological mismatches.

8. Policy and Conservation Strategies:
Develop and evaluate policy frameworks and conservation strategies aimed at mitigating the effects of phenological mismatches. This includes creating adaptive management plans, establishing protected areas, and promoting practices that support biodiversity and ecosystem health. Investigate the effectiveness of different conservation interventions, such as habitat restoration, creation of ecological corridors, and species translocations, in maintaining or enhancing plant-pollinator interactions.

6.3 SIGNIFICANCE AND SOCIAL IMPACT OF THE STUDY

Significance

1. Understanding Ecosystem Dynamics:
This study provides critical insights into the complex dynamics of plant-pollinator interactions, particularly under the influence of climate change. By elucidating how phenological mismatches affect these interactions, it contributes to a deeper understanding of ecosystem functioning and resilience.

2. Conservation Biology:
The research highlights the importance of temporal synchrony in plant-pollinator relationships, emphasizing the need for conservation strategies that account for phenological changes. This can inform the development of more targeted and effective conservation plans to protect vulnerable species and ecosystems.

3. Theoretical Contributions:
The study advances theoretical models of plant-pollinator interactions by integrating real-world phenological data and examining the effects of varying environmental parameters. This enhances the predictive power of ecological models and provides a robust framework for future research.

4. Climate Change Adaptation:
By demonstrating the potential impacts of climate-induced phenological shifts, the study underscores the urgency of addressing climate change and its ecological consequences. It provides valuable data for policymakers and conservationists to develop strategies that enhance ecosystem resilience to climate change.

Social Impact

1. Agricultural Productivity:
Plant-pollinator interactions are crucial for the pollination of many crops, which directly impacts food production and security. Understanding how climate change affects these interactions can help in developing agricultural practices that mitigate negative effects, ensuring stable and productive food systems.

2. Biodiversity and Ecosystem Services:
Pollinators play a vital role in maintaining biodiversity and supporting ecosystem services such as food production, nutrient cycling, and cultural values. Protecting pollinators and their interactions with plants can sustain these services, which are essential for human well-being.

3. **Public Awareness and Education:**
The study raises awareness about the interconnectedness of climate change, biodiversity, and human well-being. By communicating the findings to the public, it can foster greater appreciation for pollinators and the need for conservation efforts, potentially leading to increased community involvement and support for environmental initiatives.

4. **Informed Policy Making:**
The insights from this study can inform policymakers about the critical need to address climate change impacts on natural systems. It provides scientific evidence that can be used to advocate for stronger environmental policies, funding for conservation programs, and international cooperation on climate action.

5. **Sustainable Development:**

Ensuring the health of plant-pollinator interactions aligns with broader goals of sustainable development, particularly in maintaining ecosystem services that support livelihoods, health, and economic stability. The study’s findings can contribute to achieving sustainable development goals related to life on land (SDG 13), and zero hunger (SDG 2).

In summary, this study not only advances scientific understanding of plant-pollinator dynamics in the context of climate change but also has far-reaching implications for agriculture, biodiversity conservation, public awareness, and policy making. By addressing these critical issues, it contributes to the broader effort of building resilient ecosystems and sustainable communities.

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APPENDICES

Appendix-I

I.1 The probability density graph in Fig. 4.5 uses the following MATLAB code

```
% Example arrival times data (in weeks)
arrival_times = [14.2, 18.3, 17.9, 18.1, 17.5, 18.3, 13.1, 15.3, 17.6, 16,
15.8, 15.8, 17, 15, 13.1, 18.6, 12, 12, 14.6, 13.3, 13.2, 13.5, 11.2];

% Estimate parameters using the mean and variance method
mu = mean(arrival_times);
sigma2 = var(arrival_times);
alpha = mu^2 / sigma2;
beta = sigma2 / mu;

% Fit gamma distribution using MLE
pd = fitdist(arrival_times', 'Gamma');

% Display the estimated parameters
disp(['Estimated alpha: ', num2str(pd.a)]);
disp(['Estimated beta: ', num2str(1/pd.b)]);

% Plot the fitted gamma distribution
x = linspace(min(arrival_times), max(arrival_times), 100);
y = pdf(pd, x);

figure;
histogram(arrival_times, 'Normalization', 'pdf');
hold on;
plot(x, y, 'r-', 'LineWidth', 2);
xlabel('Arrival Time');
ylabel('Probability Density');
legend('Data', 'Gamma Fit');
```

I.2 The probability density graph in Fig. 4.6 uses the following MATLAB code

```
% Example arrival times data (in weeks)
arrival_times = [111, 80, 104, 117, 109, 108, 112, 107, 106, 106, 103, 107,
111, 85, 103, 103, 106, 103, 103, 106, 103, 102, 98, 97, 100, 98, 102, 96,
103, 100, 102, 80, 104, 100, 96, 98, 98, 96, 97, 95, 99, 98, 93, 98, 87];

% Estimate parameters using the mean and variance method
mu = mean(arrival_times);
sigma2 = var(arrival_times);
alpha = mu^2 / sigma2;
beta = sigma2 / mu;

% Fit gamma distribution using MLE
pd = fitdist(arrival_times', 'Gamma');

% Display the estimated parameters
disp(['Estimated alpha: ', num2str(pd.a)]);
disp(['Estimated beta: ', num2str(1/pd.b)]);

% Plot the fitted gamma distribution
x = linspace(min(arrival_times), max(arrival_times), 100);
y = pdf(pd, x);

figure;
histogram(arrival_times, 'Normalization', 'pdf');
hold on;
plot(x, y, 'r-', 'LineWidth', 2);
xlabel('First bloom date (day of the year)');
ylabel('Probability Density');
legend('Data', 'Gamma Fit');
```

Appendix-II

II.1 The population dynamics and rate of change of pollinators shown in Fig. 4.7 and Fig. 4.8 uses the following MATLAB code

```
% Define the parameters
S0 = 80; % Total pollinator population size
g = 0.18; % Rate at which pollinators arrive
alpha = 0.05; % Constant death rate
gamma = 0.006; % Visitation rate of pollinators to flowering plants
beta = 0.6; % Rate at which pollen is removed from a pollinator
U = 40; % Abundance of unpollinated flowering plants
P = 10; % Abundance of pollinated flowering plants

% Define the system of differential equations
differential_equations = @(t, y) [
    S0 * g - gamma * (U + P) * y(1) - alpha * y(1) + beta * y(2);
    gamma * (U + P) * y(1) - alpha * y(2) - beta * y(2);
];

% Initial conditions for Q and R
initial_conditions = [60, 20]; % Assuming equal distribution at t=0

% Time span for the simulation
tspan = [0 50];

% Solve the differential equations using ode45
[t, y] = ode45(differential_equations, tspan, initial_conditions);

% Extract the solutions
Q = y(:, 1);
R = y(:, 2);

% Plot the results
figure;
plot(t, Q, 'b-', 'LineWidth', 2);
hold on;
plot(t, R, 'r-', 'LineWidth', 2);
xlabel('Time');
ylabel('Population');
legend('Pollinators without pollen (Q)', 'Pollinators with pollen (R)');
title('Dynamics of Pollinator Populations');
grid on;
hold off;
```

```
% Calculate the rates of change
Qdot = zeros(size(t));
Rdot = zeros(size(t));
for i = 1:length(t)
    dydt = differential_equations(t(i), y(i, :));
    Qdot(i) = dydt(1);
    Rdot(i) = dydt(2);
end

% Plot the rates of change
figure;
plot(t, Qdot, 'b-', 'LineWidth', 2);
hold on;
plot(t, Rdot, 'r-', 'LineWidth', 2);
xlabel('Time');
ylabel('Rate of Change');
legend('Pollinators without pollen (Q)', 'Pollinators with pollen (R)');
title('Rates of Change of Pollinator Populations');
grid on;
hold off;
```

II.2 The population dynamics and rate of change of plants shown in Fig. 4.9 and Fig. 4.10 uses the following MATLAB code

```
% Define the parameters
U0 = 80; % Total number of flowers
g = 0.06; % Rate of opening of flowers
mu = 0.02; % Death rate for flowers
alpha = 0.05; % Death rate for plants
b = 0.01; % Rate of pollination of flowers
n = 10; % Number of flowers per plant
R = 10;
% Define the system of differential equations
differential_equations = @(t, y) [
    U0 * g - mu * y(1) - alpha * n * y(1) + b * y(1) * R;
    b * y(1) * R - alpha * n * y(2) - mu * y(2);
];

% Initial conditions for U and P
initial_conditions = [60, 20]; % Assuming equal distribution at t=0

% Time span for the simulation
tspan = [0 50];

% Solve the differential equations using ode45
[t, y] = ode45(differential_equations, tspan, initial_conditions);
```

```
% Extract the solutions
U = y(:, 1);
P = y(:, 2);

% Calculate the rates of change
Udot = zeros(size(t));
Pdot = zeros(size(t));
for i = 1:length(t)
    dydt = differential_equations(t(i), y(i, :));
    Udot(i) = dydt(1);
    Pdot(i) = dydt(2);
end

% Plot the population dynamics
figure;
plot(t, U, 'b-', 'LineWidth', 2);
hold on;
plot(t, P, 'r-', 'LineWidth', 2);
xlabel('Time');
ylabel('Population');
legend('Unpollinated flowering plants (U)', 'Pollinated flowering plants
(P)'); % Position the legend inside the graph
title('Dynamics of Flowering Plant Populations');
grid on;
hold off;

% Plot the rates of change
figure;
plot(t, Udot, 'b-', 'LineWidth', 2);
hold on;
plot(t, Pdot, 'r-', 'LineWidth', 2);
xlabel('Time');
ylabel('Rate of Change');
legend('Unpollinated flowering plants (U)', 'Pollinated flowering plants
(P)'); % Position the legend inside the graph
title('Rates of Change of Flowering Plant Populations');
grid on;
hold off;
```

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