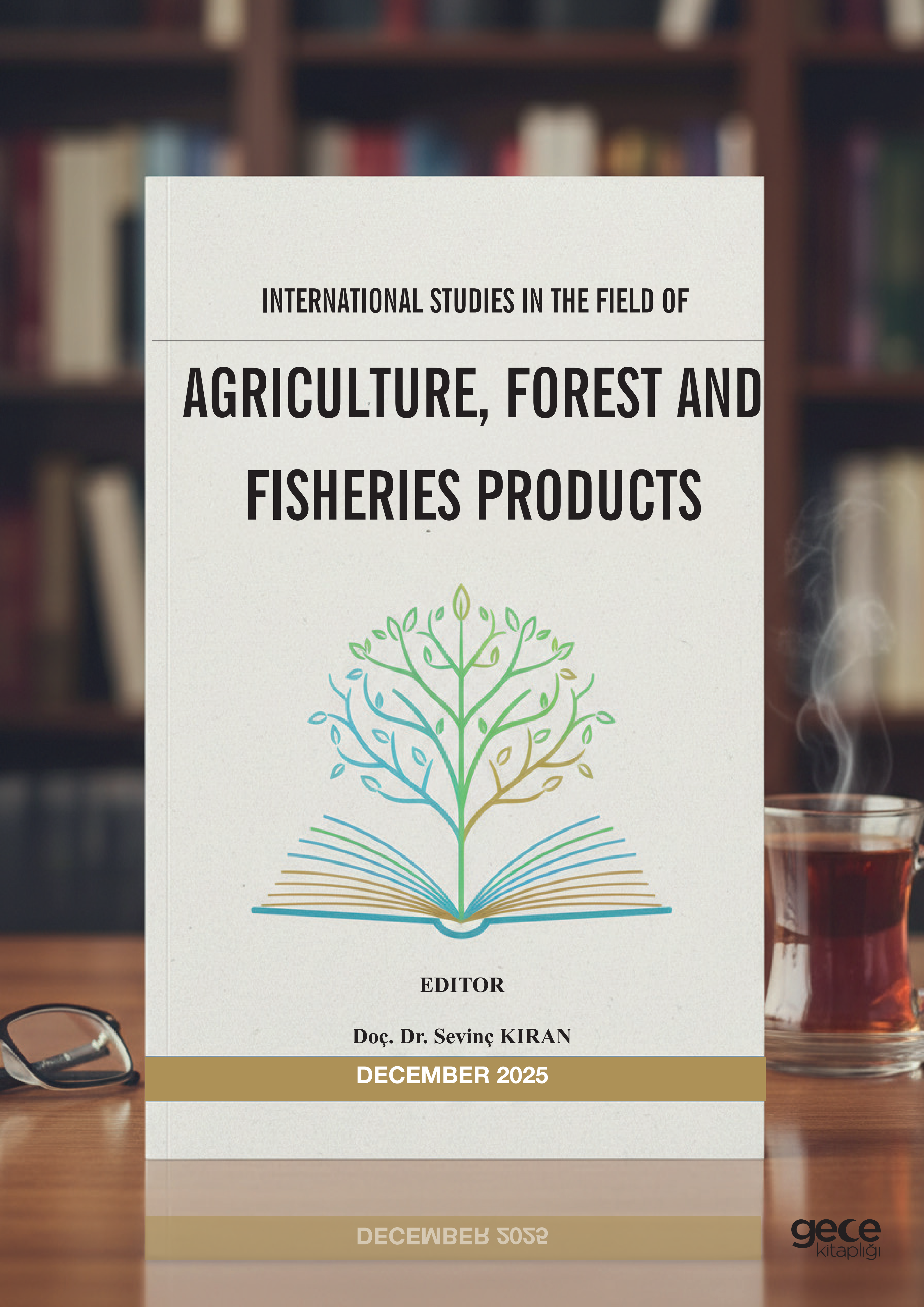

INTERNATIONAL STUDIES IN THE FIELD OF

AGRICULTURE, FOREST AND FISHERIES PRODUCTS

EDITOR

Doç. Dr. Sevinç KIRAN

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CHAPTER 1

PAPER INDUSTRY AND NATURAL DYES

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1.INTRODUCTION

The main purpose of this chapter, titled "The Paper Industry and Natural Dyes," is to present the transformation process that the paper industry is facing in the context of sustainability from a scientific perspective and to comprehensively evaluate the potential contributions that natural dyes can make to the sector. Today, environmental concerns, the toxic effects of chemical dyes, and the increasing environmental awareness of consumers necessitate the development of more environmentally friendly approaches in paper production. This section aims to provide information on the historical use of naturally derived dyes, important colors obtained from natural dyes, and their relevance to the paper industry, in order to meet the aforementioned requirement.

The need for people to express their feelings and thoughts gave rise to writing. Examining the shapes and symbols found in shelters and temples since the dawn of humanity reveals that while some have undergone changes, many remain in their original form in current alphabets. The transformation of shapes and symbols into writing over time has created different alphabets depending on the settlement. Writing, which emerged from people's desire to express themselves, has been used to keep the past alive and illuminate the future. Based on tangible evidence of emotions and expressions written on cave walls, columns, stones, wooden objects, metal plates, and animal bones and skins, as well as evidence obtained from anthropological studies, it is understood that the history of writing coincides with the existence of humankind.

The role of paper in the transmission of information to the present day is far more significant than other evidence. Its lightness, ease of processing, and portability led to its replacement of other types of inscriptions from the beginning of its invention. Because it was considered an important invention, the art and technical knowledge related to its production were kept secret. The spread of the art of paper production occurred without permission. Paper was first used in the 1st century AD. Paper is known to have been invented by Ts'aiLun in China in 105 AD. Paper production developed in Samarkand in 756 AD by Chinese prisoners of war captured during the Battle of Talas (Ersoy, 2001). Throughout history, sacred texts, international treaties, the majority of literary works, and maps have been transmitted on paper.

In recent times, the paper industry has ranked third among the five main production sectors that have driven the world economy: iron and steel, textiles, paper, organic chemicals, and petrochemicals (Bostancı, 1987). In the modern world, it has also become a crucial factor in education and training. Concerns arose that the invention of computers would lead to a decrease in paper consumption, but these were quickly dispelled. In fact, with the expansion of its uses, the demand for paper has increased. This increased paper production and demand has also brought about increased competition.

In the last century, chemical dyes began to be used to dye paper to enhance its appearance. With increasing environmental awareness and the resulting legal regulations, there is a strong possibility that restrictions will be placed on the use of chemical dyes in certain areas.

Studies highlight the disadvantages of chemical dyes for human and environmental health, and natural dyes are regaining appeal in the textile industry due to their non-toxicity, lack of allergenic effects on the human body, non-carcinogenicity, easy availability, and renewability (Adeel et al., 2009; Saha and Dutta, 2007). Efforts to develop harmless alternatives to all products that harm human and environmental health continue in every field. As awareness of human and environmental health comes to the forefront, governments are introducing new protective standards, and consequently, natural dyes are in demand by society as important alternative materials to synthetic and harmful dyes (Atılgan et al., 2013; Calogero and Marco, 2008; Kamel et al., 2005; Luciana et al., 1997).

In recent years, the use of natural resources has increased in all areas, replacing synthetic products. One of these areas is the production of natural dyes from plants. Natural dyes can be defined as high-grade coloring agents with numerous uses in textiles, paper, wood, varnish, leather, ink, food, cosmetics, pharmaceuticals, and toothpaste (Krishnamurty et al., 2002).

Despite the low cost of synthetic dyes, the abundance of natural dye sources allows them to compete in the global market (Dixit and Jahan, 2005; Öğütgen, 2008). Especially in the food and textile sectors, a "green wave" movement has begun with the increasing interest in environmentally friendly, non-toxic, antioxidant, anticarcinogenic, antibacterial, and antiallergic plant-derived natural dyes (Anon, 2010; Enez, 1987).

When giving a few examples of substances used in dyeing paper and the colors they produce, tea gives a creamy color, the outer shell of a walnut or pomegranate peel gives a brown color, and buckthorn seeds and onion peel give a reddish color (Anon, 2010; Öğütgen, 2008).

1.1 Purpose of the Study

Although historical documents exist regarding the addition of natural dyes to paper pulp, written studies on the raw materials and methods used have unfortunately not survived to the present day. The biggest, and perhaps the only, reason for this is that both paper production recipes and natural dye recipes have always been kept secret. Because in the past, until the second half of the 19th century, until the discovery of synthetic dyes, natural dyes were always used in writing books and coloring paper.

The purpose of this book chapter is to provide general information about natural dyes and to examine their usability in the paper industry. The past use of natural dyes, which were used until 1856 and subsequently became obsolete with the discovery of synthetic dyes, and their importance in the present and future are discussed. We believe this book chapter will be a valuable resource for researchers who want to conduct studies on natural dyes in the academic field, whether they are at the beginning of their research or are already working on it. The paper industry is the world's third largest industrial sector, and the dye industry is the world's fourth largest industry. For these reasons, the economic viability and usability of natural dye production have been examined.

1.2 Definition of the Paper Industry

The industry that produces pulp and paper, briefly called the "Paper Industry," is one of the oldest industries and currently ranks third among the world's top 5 industries, following iron and steel, textiles, paper, organic chemicals, and petrochemicals (Bostancı, 1987).

Paper is a material obtained by mechanically or chemically fiberizing plant cellulose or by re-fiberizing waste paper and rags (Eroğlu, 1989). It is a material obtained by converting all kinds of lignocellulosic raw materials, alone or in mixtures, into pulp and drying the sheet formed from this pulp using water. In addition, product groups obtained by easily recycling waste paper back into paper, and generally by recycling it back into paper as a mixture with virgin pulp, constitute inputs for the printing and packaging sectors.

1.2 Historical Development of Paper in Turkey and the World

Data on paper and paper derivatives, which are among the most consumed industrial products throughout a person's lifetime, constitute one of the leading universal measures of a country's level of development. Paper was invented by the Chinese in 105 AD. In Türkiye, factories established in Izmir and Beykoz in the 18th century during the Ottoman period closed shortly after their establishment because they could not compete with foreign companies due to capitulations and various privileges granted to foreigners. Paper, an indispensable product of the modern world, is mainly in sheets and consists of cellulosic fibers of wood pulp. Initially used as a writing medium, paper played an important role in the development of civilization and culture with this use. However, writing paper now constitutes only a small percentage of paper industry production (Anon, 2012).

Globally, two main raw materials are used in paper production: pulp obtained from trees and waste paper. Between 2015 and 2023, the share of waste paper in total raw materials increased. Pulp production rose from 165.1 million tons in 2015 to 174.9 million tons in 2023. During the same period, waste paper use increased from 228.25 million tons to 237.4 million tons, and its share in raw materials rose from 58% to 58.3%. Paper and cardboard production generally showed an upward trend during this period; production, which was 410 million tons in 2018, increased to 432 million tons in 2022, but decreased to 427.2 million tons in 2023. Consumption also increased similarly, rising from 405.9 million tons in 2018 to 423 million tons in 2023. The highest consumption in 2023 was in packaging products, reaching 275.6 million tons. While consumption of graphic, writing, and printing paper decreased, consumption of sanitary napkins steadily increased. As of 2023, global paper production capacity reached 490 million tons. A new capacity increase of 8 million tons is projected for the 2024-2026 period. It is anticipated that a large portion of these investments will take place in countries such as China, India, Brazil, Indonesia, and Poland; while some developed countries are expected to experience capacity reductions. From an export perspective, global paper industry exports increased from $172.15 billion in 2015 to $205.58 billion in 2023. Paper and cardboard products constituted the largest trade item at $93.94 billion, followed by sanitary and hygiene papers ($37.95 billion) and packaging products ($31.36 billion). China, Germany, and the USA are the largest exporters, while Sweden, Canada, Italy, and Poland are also significant exporting countries. The Netherlands and Belgium, on the other hand, mainly assume an intermediary function in trade. While countries such as Turkey, Indonesia, and the Czech Republic are increasing their production and exports; the share of developing countries such as India, Vietnam, and Brazil in foreign trade is also growing (ISO, 2025).

Between 2015 and 2023, the number of enterprises in Turkey's paper and paper products industry increased by 63% to 5,256, while employment rose by 43% to 97,517 people. Production value increased approximately 14-fold in Turkish Lira terms, reaching $16.8 billion from $11.26 billion in dollar terms. Value added reached $3.91 billion, with an average value-added ratio of 23-25% in the sector. The industry's share in manufacturing increased to 1.92% in employment and 1.14% in the number of enterprises. While production increased by 30.5%, labor productivity decreased by 8.8%. In 2023, paper and cardboard production capacity reached 7.015 million tons; production was 5.24 million tons, and consumption was 6.92 million tons. Exports peaked in 2022 with 1.63 million tons and $3.72 billion. In 2023, due to the global economic downturn, it fell to $3.51 billion. Exports account for 1.37% of the total. Turkey exports to all regions. Import volume showed a limited decrease between 2015-2023, falling to 2.69 million tons, peaking at $4.14 billion in 2022 before dropping to $3.17 billion in 2023. The country with the highest import volume is China, followed by Finland and Sweden (ISO, 2025).

1.3 Summary of the Turkish Paper Industry

The paper and paper products sector has shown a rapid growth trend in recent years. Considering that per capita paper consumption in Turkey is 75 kg, which is about half of the European average, it is understood that the sector has high growth potential. Some negative aspects of the paper sector in our country can be listed as follows:

- The sector has not yet reached a production capacity that can be a global player. One of the main reasons for this is that the prices of wood and chemicals required for cellulose production are high compared to abroad. The high electricity prices in Turkey, which constitute approximately 25% of total costs, also limit the sector's competitiveness in global markets.

- Waste paper is the main material for cardboard, corrugated cardboard, and paperboard production, and a secondary material for paper production. The recycling rate for waste paper, which is important for the sector, is at a low level of 40%. In addition, with the regulations made on waste paper imports, the unit price of imports has increased by approximately 13%. This development negatively affects the profit margin in the sector.

- In 2015, many raw materials used in the sector, primarily cellulose and pulp, were exempted from the Resource Utilization Support Fund (KKDF). This development limited the pressure on domestic producers in the current economic climate where production costs have increased in parallel with the exchange rate.

- On the other hand, the application of an additional tax of 10-20% on US-origin paper used in corrugated cardboard production is causing an increase in production costs.

- Another product protected against foreign markets in the sector is wallpaper. According to the new regulation in effect since August 2015, an additional cost of $5/kg has been imposed on imported wallpaper.

- Production capacity in the tissue paper sub-sector has increased significantly due to ongoing investments. Tissue paper exports have a significant share in the sector's total exports.

- Due to disruptions in transportation activities to Iraq and Iran, two of the sector's most important export markets, paper exports to these countries decreased by approximately 30% in 2015. In this context, market diversification is crucial for the sector.

- It is thought that the production of corrugated cardboard boxes, which account for 90% of agricultural product transportation, may slow down somewhat due to the embargoes imposed by Russia and problems in the Iraqi market (Çevik, 2016).

1.4 Natural Dyes

Natural dyes have been used since prehistoric times to dye natural fibers such as wool, cotton, linen, silk, fur, and leather. During the Roman Empire, they were also used in cosmetics, such as hair dyes and other cosmetic products. In addition, they were used in ink making, watercolors, and oil paintings, either alongside inorganic pigments or as natural organic pigments alone. In the mid-1960s and beyond, there was an international awareness regarding the control of environmental pollution. This led to an increase in interest in natural dyes. Recently, the dye industry has been increasingly struggling to reduce, prevent, and minimize the toxic residues of dyes and pigments that are potentially harmful to human health and the environment (Arraiza et al., 2017; Cristea et al., 2003). Examples of natural dye sources include plants, insects, sea snails, minerals, and microbial sources (Heer and Sharma, 2017; Vankar, 2017).

Natural dyes cause less environmental pollution and wastewater problems. Many synthetic dyes are toxic, carcinogenic, and cause environmental pollution. Therefore, natural dyes are considerably more environmentally friendly than synthetic dyes. They are also very important in terms of replacing synthetic dyes used for preservative purposes in all textile products and foods. They are believed to be safer because they do not have toxic and carcinogenic effects (El-Naagar et al., 2005; Verma and Gupta, 2017).

Despite the widespread development of the synthetic pigment, dye, and coloring industry today, natural dyes are still considered for achieving unique color tones. These natural dyes stimulate scientific interest in restoration and conservation as well as artistic works (Favaro et al., 2007).

1.4.1 Definition of Natural Dyes

Natural dyes can be defined as dyes found in the structure of plants, roots, stems, leaves, fruits, and fruit peels, and generally in the structure of animals such as crustaceans, snails, and scale insects (Bebekli, 1998).

Paint refers to substances used to protect the surfaces of objects from external factors or to make them look beautiful. It is applied to a surface with a drying binder using brushes or spray guns. They can be removed from the surface by scraping. Dyes, on the other hand, are substances used to color objects (fabrics, fibers, etc.) and cannot be removed by scraping (Önal, 2000).

1.4.2 History of Natural Dyes

The history of natural dyes dates back a very long time. Primitive people dyed the skins of animals they hunted and wore them in battles, and they applied these dyes to their bodies during religious ceremonies. Primitive people believed that colors were magical, and therefore protected them from evil spirits and brought victory in battles (Krishnamurty et al., 2002).

The history of natural dyeing is almost as old as the history of weaving. After 1947, a small amount of blue dye was found in the cracks of the floor stones in an archaeological excavation in the Indus Valley of the Moenjodaro region. The indigo dye found in this archaeological site, located within the borders of present-day Pakistan and dated to 3500 BC, is the oldest and most important data that has survived to this day (Karadağ, 2007).

Historically, until the mid-19th century, only plant- and animal-derived dyes were used to color woven fabrics. The dyeing method was primarily boiling, a natural dyeing technique that involved directly boiling the dye-containing material (plant or insect) and the woven fabric. Originating in China and Central Asia, natural dyes and dyeing techniques were further developed by the Egyptians. Indigo dyeing, in particular, was developed in India and its surrounding areas. Furthermore, around 2000 BC, the Chinese dyed silk fabrics with natural dyes known as indigo and Chinese green. This example provides a general overview of the history of natural dyeing in Asia. Natural dyes were also first used as printing dyes in India and in batik (the process of creating different patterns of color effects on woven fabrics) dyeing (Bebekli, 1998).

Anatolia's rich flora and dye plant history have served as a source of dyes for our hand weaving industry, from the Turkic tribes of Central Asia to the Ottoman Empire and up to the present day (Republic of Turkey). Until the synthesis of the first synthetic dye in the world (until 1856), it was known and recognized as the country that exported the highest quality and largest quantities of natural dyes (Korur, 1937; Bebekli, 1998).

1.4.3 Natural Dyes in Pre-Ottoman Turkish History

In pre-Islamic Turkish art, architectural works are rarely seen because the people did not transition to settled life. Settled life, which began with the Uyghurs, led to development in architectural structures. Book arts, influenced by different styles in different periods, produced magnificent works. The taste and appreciation of Turkish society, blended with a vast understanding of art, led to great progress. Excellent works were created, primarily in calligraphy, but also in illumination, miniature painting, bookbinding, marbling, and manuscript book arts. The works, whose writing, ornamentation, and binding were done separately by master artists, were not individual products but the result of collective work (Özkeçeci and Özkeçeci, 2007).

1.4.4 Natural Dyes in the Ottoman Empire

Since detailed studies have not yet been conducted on Ottoman-era dye houses, which we see existing in many Ottoman-era cities and even villages in Anatolia and which can be described as small industrial establishments, sufficient information on this subject is not available. It is seen that dyeing was also carried out in the regions under the dominion of the Ottoman Empire outside of Anatolian lands, and that many dye houses existed, and that these were referred to as "Masbağa," an Arabic term meaning a place where dyes were produced and dyeing was done, in archival documents (Canatar, 1998).

It is known that many of these dye houses specialized in certain colors. The expression "Tokat Blue Dye House" mentioned in Ottoman archives is one of them. It is seen that dye houses were located in places where weaving was done. The people who did the dyeing were called "Sabbağ," and the dye houses were called "Masbağa" (Genç and Okça Koyuncu, 2017).

In the mid-19th century, madder dye, which had gained great importance in İzmir's exports and its use in dye houses, rapidly lost its significance as a result of the entry of European-made synthetic dyes into Ottoman markets. Before this date, the British textile industry, which relied on imported agricultural raw materials for processing and dyeing, also imported red dye madder from the İzmir region. Madder dye, known as Turkish red and due to its ability to produce a stable red color, was the most preferred raw material for all branches of textiles. In the 1860s and early 1870s, natural dyes were replaced by synthetic dyes in less than twenty years. As a result, the share of red madder dye in Ottoman exports, which was 41.50% between 1840-1844, fell to 5.00% between 1870-1874 and largely lost its importance in subsequent years (Kasaba, 1993).

1.4.5 Advantages of Natural Dyes

The plant waste remaining after the natural dyeing process can either be burned to generate energy or buried in the soil to meet the soil's carbon and other needs. This process is an important practice for sustainability. Since natural dyes are obtained from plants and animals, they are constantly renewed in nature and therefore have sustainable properties without harming the environment.

Researching and using plants containing natural dyes as dyes will create job opportunities for people living in rural areas and encourage small-scale entrepreneurs, increasing inputs.

Sustainability is about reaching a consensus on meeting the needs of people today and in the future. Since natural dyes are constantly renewed in nature, they will be used in dyeing materials such as paper and textiles, providing benefits in terms of ecological sustainability. Synthetic dyes, on the other hand, are produced synthetically and do not biodegrade, causing significant damage to the environment; in short, synthetic dyes do not have sustainability features.

As is known, plants perform photosynthesis using carbon dioxide and water from the air in the presence of light, releasing oxygen into the atmosphere. Photosynthesis is extremely important from an environmental and ecological perspective, and this characteristic is renewable and sustainable as long as plants exist. Reducing carbon dioxide in the air through photosynthesis also helps reduce global warming.

Therefore, dye-producing plants are also cultivated for environmental greening purposes. For example, the sustainable production of plant-based indigo (SPINDIGO) project, implemented in Europe with the participation of 10 institutions from five countries, aims to meet approximately 5.00% of the total indigo consumption in Europe. Projects related to other dye-producing plants such as honeysuckle and madder root have also been implemented in the European Union. Such projects both green the environment and contribute to preventing global warming (Saxena et al., 2014).

1.4.6 Colors in Natural Dyes

Many natural colors, ranging from yellow to black, have been and continue to be obtained from natural dyes, generally derived from plants and some animals. Information on important colors obtained from mordanted and non-mordanted dyeing processes using natural dyes is given below and on other pages.

1.4.6.1 Purples, Lilacs

The dyes that produce these colors are both difficult to obtain and equally expensive. These colors were formerly extracted from several species of shellfish belonging to two genera, Murex and Purpura. It was estimated that 8000 creatures were needed to obtain 1 gram of dye. Excavations in the city of Tyre have unearthed large piles of shells as well as devices used to extract the shells from the animals (Eyüboğlu et al., 1983).

The color purple was used exclusively by kings for many years. In ancient Greece, the person who held sole political power was called a "tyrant." The name "tyrant's purple," representing political power, comes from this. For this reason, purple was used by Roman judges, priests, and emperors. Purple was only permitted on the edges of garments called "togas," worn by some young and unmarried individuals. Because its production was quite difficult, the use of purple dye, obtained from sea snails, was not allowed for the general public (Evecen and Ölmez, 2014).

Due to its rarity, it was very expensive. It was considered a symbol of high status and power by society. During the reign of King Nero, the penalty for wearing this color without deserving it was death. Julius Caesar, on the other hand, forbade anyone other than himself from wearing a purple helmet. The purple color was obtained 1600 years before Christ by leaving a yellowish-green secretion from the intestines of two shellfish called Gritte, Purpura and Murex in sunlight (Önal, 2000).

1.4.6.2 Reds

It has been known since ancient times that a bright red color is obtained from the female of a beetle called cochineal (*Coccus ilicis*). It grows on the cochineal oak (*Quercus coccifera*), an evergreen tree that grows in the Mediterranean region and Southeastern Europe. The cochineal beetle was one of the most important dyes in history. Cochineal constituted a portion of the tax paid to the invading Roman armies (Eyüboğlu et al., 1983).

Turkish red, formerly also used as a blush and diuretic, was obtained from the roots of the madder plant (Latin: *Rubia tinctorum*, German: Krapprot, English: Madder red). Towards the end of the 19th century, it was the third most important export product in the foreign trade of the Ottoman Empire after grain and silk. It was sold mainly to England, France, and other European countries. In Turkish red; The dyes found include alizarin, purpurin, pseudopurpurin, rubiadin, and munjistin. The most important is alizarin. This dye, which has a high fastness rating, was used to dye wool red in carpet and rug making (Önal, 2000).

Turkish Red

Madder has been known in Western Anatolia since ancient times. The fact that ancient Philadelphia was renamed Alaşehir in the 13th century stems from the development of dyeing in this region. Until the end of the 19th century, madder was the most important of the widely used plant-based dyes. Used in İzmir carpets, Anatolian and Syrian silk fabrics, and Thessaly and Macedonian cottons, this dye gained fame in Europe under the name "Edirne" or "Turkish Red". İzmir was the most important and only center of the madder trade, and its main buyer was England, which, despite having the most important textile industry of the time, did not grow madder in its soil. Attempts were made to develop madder cultivation in France and Italy with seeds taken from Anatolia. However, the superior quality of Anatolian madder could not be achieved (Eyüboğlu et al., 1983).

1.4.6.3 Blues, Dark Blues

It was known in ancient times that indigo (*Isatis tinctoria*) produced a dye that yielded various shades of blue after a long fermentation process. The richness of the resulting color depended on the quality of the plant and how many times the material being dyed was dipped into the dye bath. A fresh bath first gave dark blues, and when it was almost depleted, it gave blues. Indigo was one of the most important dyes used in Europe throughout the Middle Ages. After indigo (*Indigofera tinctoria)* began to be imported, the use of indigo also ended. In 1577, indigo growers in Europe opposed the importation of indigo, but they could not prevent it; within a few years, indigo replaced indigo in blue dyeing, causing it to gradually be forgotten. Indigo was also used in Anatolia before indigo. This plant grows naturally in many regions of Anatolia. This dye is known to have been used in carpets. The dyeing essence of both plants is the same. The most important substance in their composition is a glycoside called "indican," which is also found in the leaves of the plant (Eyüboğlu et al., 1983).

1.4.6.4 Yellow

Many plants produce the color yellow. Yellow daisies, saffron, buckthorn, and honeysuckle are some examples. The green and flower parts of honeysuckle contain the dye luteolin (Ünal, 2011).

1.4.6.5 Black-Brown

Black is a color that is difficult to obtain naturally (O'Neill, 1862). Any good black pigment needs to absorb light evenly across the entire visible light spectrum. This is chemically quite difficult. Finding or designing a molecular chromophore (light-absorbing component) with a broad and single absorption band is almost impossible. Therefore, many black coloring agents are produced from combinations of dyes. Almond oak (*Quercus infectoria Olivier*), acorn oak (*Quercus ithaburensis Decaisne*), and sumac (*Rhus coriaria L.*) plants have been used for black-brown color. Gall oak is a good source because it contains high amounts (70%) of tannin compounds and their derivatives. Gall oak is a plant used by the Sumerians in leather dyeing and ink production, in Seljuk carpets in the 13th century, and in Ottoman textile fabric dyeing in the 15th-20th centuries. Gall oak quickly produces black dye when used with iron sulfate mordant. Acorn oak is found in western Turkey; gall oak is distributed in the Eastern Mediterranean (Böhmer, 2002; Karabulut, 2014; Mantzouris et al., 2011; Yurdun et al., 2011; Wouters and Rosario-Chirinos 2011). A historical development related to the color black is the discovery of the logwood plant in Mexico by 16th-century Spaniards. The dye obtained from this plant... It can not only produce blue and gray colors, but also a true jet-black by combining it with a chrome mordant and a yellow dye like fuchsia (Zollinger, 2003).

1.4.7 Methods of Obtaining Natural Dyes

Dyes are applied to the material they will be dyed using dyeing methods such as impregnation, extraction, and mordanting. Natural dyes are examined in three main groups: animal-derived, plant-derived, and mineral-derived.

1.4.7.1 Animal-Derived Natural Dyes

Animal dyes, also known as insect dyes, are among the first natural dyes known and used since ancient times. Insects have been used especially in the production of colors such as red. This is because colors obtained from animal-derived dyes are brighter and more vibrant (Enez, 1987).

Examples of insects used in the production of animal dyes include cochineal, vordan vamir, and wagtail, from which red color is obtained (Bebekli, 1998).

1.4.7.2 Plant-Derived Natural Dyes

Plant-derived natural dyes are dyes obtained from parts such as bark, roots, seeds, fruits, leaves, and kernels of many plants that grow in the plant flora found in nature. The use of plant-derived dyes emerged at the beginning of the Bronze Age. In ancient times, it is reported that dyes extracted from colored flowers with water were transferred to fibers (Bebekli, 1998).

In the Ottoman Empire and subsequently in the Republic of Turkey, the most important and sole center for the trade of natural dyes was the port of Izmir. Natural dyes grown in Anatolia were brought to Izmir by land, blended there, and then exported. During the Ottoman Empire, 30% of natural dye exports were handled through the port of Izmir, securing its place in the world market. England, which had a significant textile industry, took the first place in the exports made by the Ottoman Empire (Bebekli, 1998).

Table 1.1 shows the price differences between madder dye grown in the Anatolian region of our country and madder dye grown in Syria, Cyprus, and Tripoli, as used as the basis for Ottoman-British customs tariffs from 1839, 1850, and 1867.

Table 1.1: Madder prices used as a basis for customs duties in the mid-19th century (Dölen, 1992).

	Average Price (cents/kilogram)	
Years	Anatolian Product	Cyprus, Damascus, Tripoli Product
1839	180	100,00
1850	208	103,50
1867	217	146,60

1.4.7.3 Mineral Dyes

Also known as earth dyes and mineral dyes. Since pigment dyes obtained from the mineral realm, such as chrome yellow, natural ginger, schweinfurt green (copper arsenite), ultramarine, etc., do not show affinity to the fiber, they can only be fixed to the fiber with the help of a binder (e.g., egg white) and by printing. For dyeing purposes, mineral dyes such as chrome yellow and Berlin blue are also formed on the fiber through a chemical reaction (Akgül, 2019).

1.4.12 Reasons for Dyeing Paper

Writing, which emerged from people's desire to express themselves, is a tool used to remember the past and transmit it to the future. Having gone through various stages in the past to reach the present day, writing has been done on many different surfaces, from stone to paper. When writing began on paper, the paper had to go through various stages to make it suitable for writing. Since raw paper has an absorbent and porous structure, it needs to be treated. To break up its raw white color, the paper is dyed. The dyeing process varies depending on the material to be used. Paper dyed with dyes obtained from natural substances is treated with sizing and stamping processes to make it ready for use. Especially throughout history, the methods of dyeing and finishing paper have preserved the permanence of written works and served as examples for new generations (Varol, 2017).

Until 1856, that is, until the discovery of synthetic dyes, natural dyes, especially plant-based dyes, were used in the dyeing process. Until 1856, natural dyes were also used to dye all types of paper. After the discovery of synthetic dyes, papers were also dyed with synthetic dyes. For about 20 years, there has been a forced return to natural products worldwide.

In this context, natural dyes have also begun to be used in paper dyeing. In underdeveloped and developing countries, efforts to return to natural dyes are progressing more slowly, but highly developed countries have already begun research into natural dyes and are purchasing their products. The use of natural dyes has been made mandatory, particularly in areas such as food and children's toys, and synthetic products have been banned. Developed countries also utilize waste materials, one of which is waste paper. To better protect trees and forests, production is carried out using waste paper. European countries, which produce a large amount of waste paper, dye the paper using dyes.

Some domestic tissue paper companies state that there is a high demand for dyed tissue paper, especially from abroad. This is because these countries use a large amount of waste paper. Consequently, the de-inking and re-bleaching processes of waste paper entail significant costs. After the de-inking stage, tissue papers are dyed and offered to the market without re-bleaching. One of the aims of this thesis is to guide the production of dyed tissue paper and develop a new method.

Besides tissue paper, synthetic dyes are used in all paper production, such as cardboard production, corrugated cardboard production, paper packaging production, coated paper, special purpose papers, etc. Producing naturally dyed paper should primarily enable our generation to use natural products, and also help make our country, and consequently the world, as livable a place as possible. Furthermore, the waste from natural dyes does not require any treatment; this waste is also preferred as natural fertilizer.

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CHAPTER 2

THE ROLE OF SILVICULTURE IN PREVENTING FOREST FIRES

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1. INTRODUCTION

When the relationship between forest fires and silviculture is considered, the focus is not on fire suppression or firefighting activities, but rather on silvicultural interventions aimed at managing the amount and structure of forest fuels that play a decisive role in fire occurrence. Engineering practices implemented in forests—whether naturally regenerated, artificially established, or planned for future establishment—are generally evaluated within the scope of silvicultural techniques. The primary objective of silviculture is to manage forests sustainably from the initiation of regeneration to the end of the rotation period through maintenance, rehabilitation, and regeneration practices. The main purpose of regeneration and tending operations is to establish ecologically based, close-to-nature forests that are resilient to biotic and abiotic factors and to ensure their long-term sustainability. Within this framework, forests managed in accordance with sound silvicultural principles exhibit lower incidence rates of biotic and abiotic damages, particularly forest fires, or such damages occur only at minimal levels. Since silvicultural interventions are fundamentally based on the principle of emulating natural processes, the silviculturist achieves sustainable forest management by thoroughly analyzing ecosystem characteristics and dynamics, determining appropriate intervention strategies, and implementing them accordingly. As is well known, ecosystem dynamics are shaped by the interaction of numerous internal and external factors. In forest ecosystems located within the Mediterranean climatic zone, forest fires constitute one of the most significant threats. From a silvicultural perspective, forest fires represent a dual phenomenon, being both a destructive event and, under certain conditions, a beneficial ecological process. Accordingly, a sound understanding of natural processes, the timely and technically appropriate implementation of preventive measures against potential disasters, and the application of silvicultural interventions—such as facilitating seed–soil contact through fire-related ecological processes (fire ecology) and reducing fuel loads through controlled and prescribed burning—are of critical importance. In particular, advances in mechanization techniques have provided substantial advantages in site preparation for both natural regeneration (seedbed preparation) and artificial regeneration practices. As conformity with natural processes constitutes one of the fundamental principles of silviculture, silvicultural interventions play a key role in maintaining ecological balance in a sustainable and functional manner.

Çepel (1995) states that when the ecological balance formed through the complex interactions among numerous life forms and between these organisms and environmental factors is disrupted, the restoration of this balance requires a considerably long period of time. Forests, which constitute one of the most important components of ecological balance and possess a self-renewing capacity, not only provide habitats for a wide range of living organisms but also contribute to the improvement and long-term stability of existing site conditions, particularly soil and climate (Barnes et al., 1997). The degradation of this balance due to various factors—most notably forest fires—leads to economic, ecological, and socio-cultural problems that threaten society as a whole, with particularly severe consequences for rural livelihoods.

In this study, silvicultural measures aimed at reducing fire hazard, as well as silvicultural practices that deliberately use fire as a management tool, are evaluated in a concise manner in response to the increasing frequency of forest fires in recent years. Silvicultural interventions related to forest fires are addressed within the framework of pre-fire and post-fire practices, and the silvicultural measures that should be implemented or further developed in this context are examined. In this way, forest fires that cause loss of life and property can be transformed from unavoidable disasters into manageable phenomena. This is particularly important because, under adverse weather conditions and in areas with high fuel loads, fire suppression efforts often prove to be largely ineffective.

In summary, rather than focusing on fire suppression, this study emphasizes silvicultural technical interventions aimed at preventing the occurrence of forest fires, as well as the practices required for the restoration of burned areas.

2. FOREST FIRES

Forest fires are characterized as freely spreading fires due to their exposure to open environments, consuming forest fuels such as grasses, leaves, branches, logs, shrubs, dead or dry materials, and living trees (Çanakçıoğlu, 1993). Forest fuels are also classified according to their vertical position as: (1) below-ground fuels, (2) surface fuels, and (3) aerial or elevated fuels (Çanakçıoğlu, 1985). In terms of size and structure, fuels are commonly grouped as fine fuels and coarse fuels. Organic materials such as leaves, bark, needles, small twigs (<5 cm), and cones are categorized as fine fuels, whereas tree stems and large branches are considered coarse fuels. Fuel characteristics are of critical importance not only for fuel load management but also for determining fire risk and influencing fire behavior and suppression strategies (Küçük, 2000). In general, conditions characterized by very high temperatures and relative humidity falling below 10% are regarded as having an extremely high potential fire danger. Low fuel moisture content facilitates the ignition of needles and fine fuels in the forest floor and significantly accelerates fire spread (Bilgili et al., 2021).

Forest fires constitute one of the major threats to the sustainability and multifunctionality of forests worldwide, including in Türkiye. In Türkiye, which lies predominantly within the Mediterranean climatic zone, numerous forest fires occur each year as a result of climate change and intensified human–forest interactions, leading to the loss of thousands of hectares of forest land. It is widely expected that, unless effective preventive measures are implemented, this threat will continue to increase in the future.

Forest fires not only endanger forest areas but also pose a serious global threat to biodiversity, thereby disrupting the provision of essential ecosystem services. Throughout this process, forests are known to suffer substantial economic, social, and cultural losses. In brief, forest fires represent one of the most significant disasters threatening ecosystems. Their impacts include the combustion and loss of organic matter, the destruction or degradation of flora and fauna, and alterations in soil structure and properties.

Considering the high forest fire risk in Türkiye, particularly within the Mediterranean climatic zone, it is imperative that the requirements of forest engineering practice be fully and rigorously implemented in order to control these risks. Among these measures, reducing forest fuel loads—one of the primary factors contributing to fire ignition—is of critical importance. Accordingly, with appropriate management strategies and technically sound interventions, the negative impacts of forest fires can be substantially minimized.

Individuals working in the field—particularly forest engineers—who thoroughly analyze site conditions and ecosystem dynamics and conduct the necessary scientific assessments play a key role in mitigating disasters and hazards such as forest fires. It is well recognized that many catastrophic events arise largely from human activities that are not aligned with natural processes. Forest ecosystem dynamics develop under the influence of numerous internal and external factors, ranging from simple organismal levels to complex ecosystem scales. Within this system, silviculture plays a fundamental role in the management of factors such as species composition, pure or mixed stand structure, stand density, vertical stratification, and canopy closure. Consequently, there remains a wide range of responsibilities in managing nature–human interactions, both in the context of forest fires and other forestry practices. It should also be emphasized that all personnel involved in forestry services—including engineers, forest rangers, and workers—must be evaluated not only from a technical perspective but also within broader socio-economic, political, and cultural dimensions, and that solutions should be developed accordingly.

3. THE CONCEPT OF SILVICULTURE

When considered in terms of its scope of application and the activities with which it interacts, the concept of silviculture occupies a central position within the profession of Forest Engineering and represents an applied scientific discipline that involves active interventions in forest ecosystems. In numerous scientific sources (Saatçioğlu, 1971; Atay, 1975; Turna, 2013a), silviculture is commonly defined as an applied science concerned with the planned establishment of new forests, the tending and cultivation of these forests together with existing natural stands, the systematic harvesting of stands that have reached the cutting age, and the regeneration of harvested areas through the establishment of new forest generations, thereby ensuring the optimal continuity of forest resources. The primary objective of silviculture is to obtain, at the lowest possible cost, forest products of the highest achievable quality and quantity under existing site conditions, suitable for multiple uses, and to establish productive forests that are resilient to external disturbances and capable of continuously meeting the demands of the national economy for forest products, including both timber and non-wood forest products. It should be emphasized that silviculture is not an end in itself, but rather a means by which broader management objectives are achieved.

4. THE RELATIONSHIP BETWEEN FIRE AND SILVICULTURE

In combating forest fires, the foremost priority is to clearly identify the primary factors that may cause fires and to take preventive measures against them. A forest fire is initiated by the convergence of combustible material (fuel), oxygen, and a heat source (Çanakçıoğlu, 1993). This triad is commonly referred to as the “fire triangle.” However, these elements primarily describe the conditions required for combustion or ignition to occur; therefore, the terms “combustion triangle” or “ignition triangle” may be considered more appropriate. In order to refer to an event as a fire, ignition must be activated in some manner and, supported by prevailing atmospheric conditions, must spread to surrounding fuels and exhibit a distinct behavior. Following ignition, all tendencies, movements, and responses exhibited by a fire—depending on climatic and meteorological conditions, fuel load, and topography—are collectively defined as “fire behavior” (Kavgacı et al., 2023). Combustible materials such as dry grasses, leaves, and branches are ignited by heat sources including high temperatures, solar radiation, or sparks. In forested areas dominated by open-environment conditions, it is not possible to exert control over oxygen availability. Temperature, as a critical climatic variable, is likewise difficult to modify or control under such conditions. In particular, within the context of climate change, excessive increases in temperature, accompanied by declining relative humidity and reductions in both the amount and distribution of precipitation, highlight the growing importance and uncontrollability of atmospheric factors. In addition, wind speed and direction, together with physiographic factors, play a decisive role in determining the extent and spread of fires. A fire that initially begins as a small flame can rapidly expand under the influence of wind. The rate of fire spread varies depending on vegetation type, fuel moisture content, wind intensity, and topographic conditions.

Another key factor influencing fire occurrence is the presence, distribution, moisture content, type, and quantity of combustible materials (such as dry grasses and fine branches, shrubs, dry leaves, needles, bark, and logs). Through the proper, timely, and scientifically grounded implementation of engineering practices, this factor can be effectively managed, thereby preventing the activation of the fire triangle and reducing the likelihood of fire occurrence.

In addition to the presence of heat, oxygen, and combustible materials, the occurrence of a forest fire also requires an ignition action. This ignition may result from natural causes—such as lightning strikes, prolonged drought, low relative humidity combined with high temperatures, and, in rare cases, volcanic activity—as well as from human-induced factors. Human-related causes include negligence and carelessness, such as unattended picnic fires and discarded cigarette butts; uncontrolled stubble burning for agricultural land clearing; sparks originating from power transmission lines, transportation vehicles, or industrial activities; and deliberately ignited fires (arson or sabotage). Based on forest fire statistics, Bilgili (1997) reported that forest fires originate from four main causes: negligence and carelessness, intentional ignition, natural causes (lightning), and fires of unknown origin, noting that a substantial proportion of fires classified as having unknown causes are, in fact, human-induced.

Education, public awareness, the regulation and supervision of activities within and adjacent to forest areas, and the strengthening of early warning systems are of vital importance for the prevention of forest fires. The highest priority should be given to public relations, educational programs, and awareness-raising activities. These efforts should be supported by legal frameworks, while enforcement measures and sanctions should be considered only as a last resort. Beyond these preventive measures, it should not be overlooked that, as part of their professional responsibilities, forest engineers are required to implement a range of engineering practices in forested areas—particularly in fire-prone zones.

Because forests and forestry activities are carried out under open-environment conditions and across extensive landscapes, there is a need for scientifically grounded efforts aimed at minimizing the impacts of both biotic and abiotic factors or preventing damage caused by them. Given that the focus of this study is forest fires, particular emphasis is placed on silvicultural practices, which constitute one of the foremost forestry interventions for managing and reducing forest fuel loads as a primary means of fire prevention.

Under natural conditions, the degree of fire impact within a forest stand depends on a wide range of factors. These include stand size, tree species, stand composition (pure or mixed and their proportions), stand density, vertical stratification, and stand age. In addition, several vegetation- and species-related characteristics play a decisive role, such as the physiological condition of the vegetation, light requirements and the resulting natural pruning and bole differentiation, bark thickness and texture, branching pattern and growth form, root system characteristics, the condition and degree of decomposition of the forest floor, and the flammability of needles or leaves. Analyzing stand structure and managing forest ecosystems through appropriate silvicultural interventions based on such analyses constitute the primary responsibility of the silviculturist. Through silvicultural practices, abiotic disturbances—including forest fire risk—can be prevented or effectively controlled at minimal levels. For example, in order to reduce damage from storms and strong winds, silvicultural measures such as avoiding the use of shallow-rooted species in the direction of prevailing winds, preventing the opening of stand edges through inappropriate tending cuts, conserving existing natural windbreaks, establishing artificial windbreaks where necessary, and promoting the establishment and continuity of mixed stands that are resilient to abiotic disturbances can be successfully implemented. Forest fuels involved in wildfires are highly diverse. When forest fires occur under open-environment conditions, their rate of spread varies not only according to climatic factors but also in relation to the type and characteristics of fuels, including shrubs, dry and fine branches, dry grasses, dry logs, and dead materials such as leaves and needles.

With regard to forest tending measures, Agee and Skinner (2000) reported that modifications in fuel loads are closely related to fire behavior and can significantly alter it, noting that reduced crown closure can decrease the likelihood of transition to crown fires. Similarly, Van Wagtendonk (1996) emphasized that tending practices are effective in slowing and interrupting fire spread and in reducing flame length.

When the moisture content of fine dead fuels falls below 7% and wind speed exceeds 25 km h^{-1}, the rate of fire spread, fire intensity, and the overall extent of damage increase substantially. Under such conditions, direct fire suppression is often not feasible, particularly when fuel characteristics, terrain conditions, and—most critically—weather conditions are unfavorable. During periods characterized by extreme weather conditions, the only viable strategy for large fires is often to avoid direct engagement and instead focus on protective measures aimed at safeguarding priority areas and critical resources (Bilgili et al., 2021). However, when similar weather conditions prevail prior to fire occurrence (i.e., relative humidity below 7% and wind speed above 25 km h^{-1}), the likelihood of fire ignition should be critically questioned in the absence of available fuels. Moreover, considering that a large proportion of forest fires in Türkiye are human-induced, preventing fire ignition by eliminating or reducing fuel loads—particularly in fire-prone areas—should be regarded as more important than post-ignition fire suppression efforts. Indeed, according to records of the General Directorate of Forestry (OGM, 2021), 89% of forest fires occurring between 1988 and 2020 were human-caused, while Bilgili et al. (2021) reported an even higher proportion of 97%, clearly demonstrating the dominant role of human activities in forest fire occurrence.

It is evident that the first and second components of the fire triangle—heat (temperature) and oxygen, which are closely linked to climatic factors—are almost impossible to control through human intervention. In contrast, the third component, namely combustible vegetation forming the fuel complex, can be effectively managed through silvicultural practices, which constitute a primary responsibility of forest engineers. Within this context, engineering services related to tending, regeneration, protection, and production–marketing activities become particularly prominent.

In this study, emphasis is placed on the role of silviculture in preventing forest fires, and the relationship between fire occurrence and silvicultural interventions implemented at different stand development stages is examined. Post-fire silvicultural practices—such as restoration, rehabilitation, and reforestation—are beyond the scope of this study and are therefore not addressed.

4.1. The Relationship Between Forest Tending Practices and Fire

In stands established through natural or artificial regeneration or afforestation, the purposeful silvicultural practices carried out over a long period, beginning with the introduction of regeneration or planted stock into the site and continuing until the regeneration of stands that have completed their rotation, and aimed at guiding stand development in accordance with management objectives, are referred to as “forest tending practices,” “forest tending,” or “stand tending” (Saatçioğlu, 1971; Atay, 1986; Genç, 2011). The susceptibility of stands subject to forest tending to forest fires varies according to their developmental stages. These differences in susceptibility require differentiated approaches not only with respect to the adverse impacts of fires but also in terms of the preventive measures to be taken against fire risk.

Among stand development stages, the regeneration stage is the most severely affected by forest fires. This effect is particularly pronounced in fire sensitive coniferous forests, especially pine stands. The thicket stage, characterized by increasing canopy closure and intensive natural pruning and stem differentiation, is a critical stage that requires careful consideration in terms of both fire ignition potential and the degree of fire impact, as the potential fuel load within the stand is very high during this period. In the subsequent development stages, namely pole, small timber, and mature tree stages, the risk of fire gradually begins to decrease due to higher crown bases resulting from natural pruning and the elevated position of the tree crowns. According to a study conducted in Prussian forests reported by Baş (1965), the fire hazard was 33% in pine stands aged between 1 and 40 years, whereas it declined to 8.7% in pine stands older than 40 years. Therefore, silvicultural interventions aimed at reducing fire occurrence must differ according to stand development stages. For this reason, forest tending measures against forest fires should be addressed and implemented with consideration of stand development stages.

4.1.1 Regeneration and Plantation Tending Practices: In stands established through natural or artificial means, silvicultural interventions carried out during the developmental stage extending from the introduction of regeneration or planted stock into the site until the formation of canopy closure and the onset of natural pruning are referred to as regeneration and plantation tending practices. During this stage, regeneration is characterized by short height growth, a limited number of lateral branches, and relatively short branch lengths. In general, this stage focuses on evaluating the effects of regeneration and plantation tending measures on the occurrence of forest fires.

Protection of regeneration from damaging agents: This refers to safeguarding newly established regeneration against all types of biotic and abiotic factors. During this stage, protective measures such as fencing the site and implementing both stationary and mobile supervision during the fire season in fire prone areas are required, including the presence of guards and forest protection officers. Just as regeneration must be carefully protected from grazing animals, particularly goats, it must also be protected from fire. Measures such as the maintenance of firebreak roads and strips, as well as the establishment and protection of broadleaved species, are also considered within the scope of protection activities.

Thinning of dense natural regeneration: This constitutes one of the most important tending measures to be implemented against forest fires. In stands with very dense regeneration, the amount of combustible material is particularly high. In order to both accelerate regeneration development and reduce fuel loads, thinning interventions should be completed before the onset of the fire season. At this stage, it is essential that harvesting residues located along stand edges, such as roadsides, settlement areas, and agricultural lands, are removed from the site, not left within the stand, and disposed of through controlled burning. Where possible, incorporating these residues into the soil using shrub shredders or similar equipment represents an ideal practice. Indeed, a study conducted by Stephens and Moghaddas (2005) demonstrated that conifer plantations younger than 12 years exhibited higher fire intensity compared to other forest stands.

Regulation of species mixture: In pure stands or conifer dominated mixtures, particularly in pine stands, establishing mixtures with fire resistant species along stand edges represents an important opportunity. In mixed stands, supplementary planting to maintain the continuity of species composition is also of considerable importance. Especially along the margins of settlements, agricultural areas, and roads, buffer zones should be established using fire resistant plant materials such as trees, shrubs, and even medicinal and aromatic herbaceous species, as recommended within the framework of the YARDOP project. These practices contribute both to the regulation of species composition and to the establishment of forests that are more resistant to fire.

Weeding and soil cultivation: This is an important regeneration tending measure for preventing the ignition of forest fires. Rather than being applied across the entire area, weeding and soil cultivation should be carried out within buffer zones of approximately 10 to 15 m, particularly along roadsides and near agricultural and settlement areas, prior to the fire season. Through soil cultivation, combustible materials are incorporated into the soil, which both eliminates surface fuels and contributes to the enrichment of soil organic matter.

4.1.2. Precommercial Thinning: The developmental stage extending from the formation of canopy closure until the onset of intensive natural pruning and stem differentiation in forest stands is referred to as the thicket stage. The tending operations carried out during this stage are known as precommercial thinning. Precommercial thinning involve the removal of undesirable and poor quality individuals through negative selection in order to provide favorable growing conditions for individuals exhibiting superior characteristics.

During the thicket stage, stand density leads to the dieback of lower branches that are unable to receive sufficient light. This situation also disrupts stand stability, rendering unmanaged and structurally unstable stands more susceptible to biotic agents such as fungal and insect damage as well as abiotic disturbances including fire, windthrow, and snow breakage. In terms of forest fires, such stands are extremely vulnerable, both with respect to fire suppression efforts and post fire reforestation or revegetation activities. This is because, in unmanaged stands at this stage, surface fires and crown fires tend to occur simultaneously, making fires difficult to control. The absence of an adequate number and proper layout of tending access paths within the stand further increases this risk.

In thicket stage stands, post fire conditions for natural regeneration are generally unfavorable. The primary reason for this is that young individuals have not yet produced a sufficient number of cones, resulting in the loss of natural regeneration potential following fire. In such areas, artificial regeneration represents both a high economic cost and a more intensive intervention into natural processes. Therefore, timely implementation of precommercial thinning operations, together with the establishment of tending access paths, is a critical management measure in thicket stage stands. In addition, harvesting residues located near roads, settlements, and agricultural field edges must not be left within the stand and should be removed from the site as an essential fire prevention measure.

Following precommercial thinning, pruning of dry and partially live lower branches of trees located along stand edges adjacent to roads, settlements, and agricultural lands up to a height of approximately 1.5 to 2.0 m contributes to reducing fire hazard within the stand and facilitates access for subsequent tending operations such as thinning. These interventions should be applied in a moderate and gradual manner. The appropriate intensity of precommercial thinning can be defined as a level at which tree crowns neither press excessively against one another nor create large gaps between crowns. Examples of precommercial thinning and pruning practices carried out in Calabrian pine stands at the thicket stage in the Gazipaşa Forest Management Directorate are illustrated in Figure 1.

Figure 1. Pruning practices for fire prevention in Calabrian pine (*Pinus brutia* Ten.) stands at the thicket stage

In a precommercial thinning study conducted in the forests of the Kütahya Regional Directorate of Forestry, which are located in fire prone areas, the number of individuals and the proportion of dry branches in the control plot, as well as the general appearance of the stands after tending interventions, are presented in Figure 2 (Bayar and Deligöz, 2019).

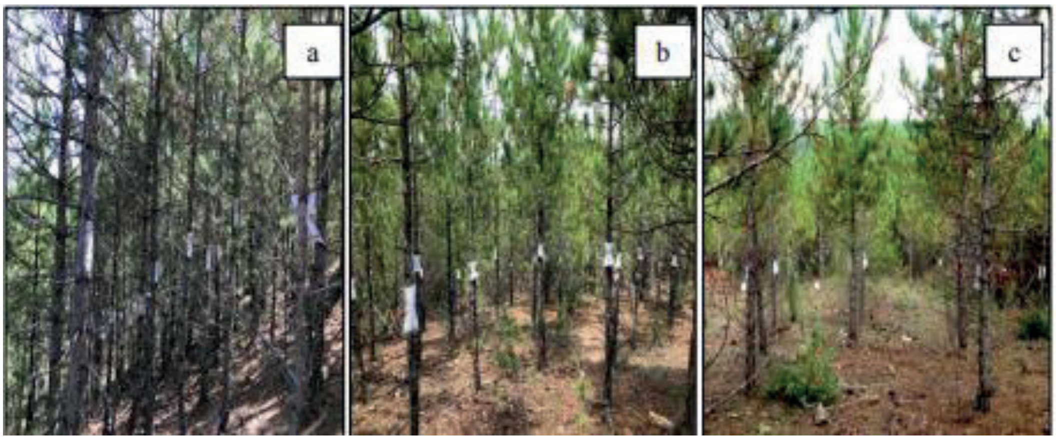

Figure 2. Precommercial thinning interventions in Anatolian black pine (Pinus nigra Arnold. subsp. pallasiana) stands at the thicket stage (a = control, b = 2–2.5 × 2–2.5 m, c = 3–3.5 × 3–3.5 m)

As can be seen in Figure 2, the control plot is heavily covered with combustible materials, whereas the amount of combustible material in the tended stands is negligible. This difference is of particular importance with regard to forest fire risk. The amount of combustible material present in an unmanaged stand is illustrated in Figure 3.

Figure 3. An unmanaged stand without precommercial thinning (left) and a stand subjected to precommercial thinning (right)

4.1.3. Thinning: The stand development stage that begins with the occurrence of natural pruning and pronounced stem differentiation and continues until diameter increment, together with height increment, declines to a minimum is defined as the pole, small timber, and mature stand stages. The continuous and planned tending interventions that actively regulate the competition among stand individuals during these stages are referred to as thinning operations. Stand structure at these stages is typically characterized by an upper layer composed of dominant individuals, an intermediate layer consisting of less developed trees, and a lower layer formed by suppressed and weak individuals. The primary objectives of thinning are to enhance stand resistance to biotic and abiotic hazards, to prepare the stand for natural regeneration, to improve the aesthetic appearance of the forest, and to obtain intermediate yields from the stand. Thinning represents the art of silviculture in which the silviculturist analyzes the stand from ecological, economic, and socio cultural perspectives and manages it in a sustainable manner that is compatible with natural processes.

Through thinning interventions, maximum protection of the stand against a wide range of biotic and abiotic threats can be achieved. One of these objectives is to eliminate forest fire risk or to reduce it to minimal levels.

Figure 4. Tending practices in stands at the pole and small timber stages

In stands at the thinning stage where silvicultural interventions are implemented in accordance with technical principles, potential forest fires generally occur in the form of surface fires, depending on prevailing weather conditions such as temperature and humidity. Such fires are relatively easier to control and the subsequent reforestation processes are more manageable. However, in unmanaged stands, when surface fires transition into crown fires, fire control becomes considerably more difficult. In particular, in unmanaged young stands at the pole and small timber stages, approximately 80% of fires tend to shift from surface fires to crown fires, rendering them largely uncontrollable. In these stands, cone production is generally insufficient, which necessitates artificial regeneration during reforestation efforts.

In fire prone regions, even when the intermediate yield obtained from thinning interventions in stands at the thinning stage cannot be economically utilized, it remains essential that these tending operations are not neglected. In order to reduce fire risk, felled material and harvesting residues must not be left within the forest. These measures should be applied not necessarily across the entire stand, but particularly in sensitive areas such as near settlements, agricultural lands, and firebreak strips.

When implementing silvicultural treatments in shelterbelts and protective stand edges, fire hazard considerations must be taken into account. Especially in arid and semi arid climatic regions, maintaining stand shelterbelts through appropriate tending practices is important for conserving upper soil moisture and providing habitat for wildlife. However, when shelterbelts consist of fire sensitive tree species, their branches may remain live down to ground level and appear less flammable, yet surface fires fueled by surrounding grasses and shrubs can easily transition into crown fires. Therefore, pruning of dry branches that contribute to fuel accumulation should be carried out, and the establishment of shelterbelts using broadleaved species should be preferred. In fire prone regions dominated by Mediterranean climate conditions, existing fire resistant maquis elements should be conserved where present, and where absent, reinforcement with species such as eucalyptus, carob, and cypress is recommended. Additionally, preventive measures can be enhanced by establishing bare and well maintained strips in front of windbreaks to prevent fire from advancing into forested areas.

4.1.4. Pruning Practices: Pruning refers to the removal of dry and, in some cases, partially live branches from plant stems in accordance with specific technical principles. Pruning operations are carried out using different techniques depending on their intended objectives. In pruning practices aimed at forest fire prevention, the primary objective is to remove branches that have dried as a result of light deficiency associated with canopy closure. In areas where there is a high likelihood of fires approaching forest stands, particularly along stand edges, dry pruning should be complemented by green pruning, which involves the selective removal of live branches according to defined criteria, and the pruned material should be removed from the site. Pruning operations implemented within buffer zones along agricultural fields and roadsides, as well as in the vicinity of settlements, when combined with the incorporation of the surface litter layer into the soil, can effectively prevent the ignition of forest fires and limit the expansion of their impact area.

In forest areas located in fire sensitive regions, sections of approximately 25 to 50 m along forest roads, firebreak roads and strips, and stand edges bordering settlements and agricultural lands require the pruning of dry branches together with a portion of live branches in a strip like arrangement. This practice constitutes a particularly important tending measure in fire prone regions. It is well known that a substantial proportion of forest areas burned in Türkiye are affected by crown fires.

From the perspective of fire behavior, the height at which pruning is carried out is of critical importance. The primary objective is to interrupt the vertical continuity of fuels and to reduce flame length. This is closely related to fire intensity and the density of available combustible material. Güngöroğlu et al. (2014) reported that reducing the density of grasses and shrubs within fire stopping zones and thinning the live vegetation in adjacent stands from the edge of the fire stopping zone inward to a distance equivalent to one and a half times tree height is important for reducing fire intensity and rate of spread and for breaking the horizontal continuity of heat sources. In the same study, it was suggested that if tending of live ground vegetation cannot be implemented, the crown base height of stands adjacent to fire stopping zones should be raised to a level corresponding to one and a half times both the height of the live ground vegetation within the stand and the height of grasses and shrubs within the fire stopping zone. This approach is considered more suitable for stand types classified as b, bc, and in some cases c. In addition, it is recommended that in stands adjacent to fire stopping zones, the spacing between tree crowns be adjusted so that the distance between two crowns is approximately equal to the average crown diameter, and that this treatment be applied along a belt of 20 to 50 m.

Within the framework of forest fire prevention, tending practices are essentially aimed at reducing fire risk. In particular, all silvicultural tending activities carried out along forest edges bordering roads, agricultural lands, and settlements in fire prone regions, including regeneration tending, precommercial thinning, thinning, and pruning, as well as prescribed burning and the mechanical removal or incorporation of combustible materials into the soil, are evaluated within the scope of fire ecology or fire oriented silviculture.

4.2. The Relationship Between Agroforestry and Fire

Agroforestry is defined as land use based production systems aimed at obtaining more than one product from the same land unit simultaneously or sequentially over time (Turna, 2023; Nair, 2012). These systems include agrosilvicultural systems, in which agricultural and forestry activities are jointly implemented, silvopastoral systems, which are based on the integration of forestry and grazing, and agrosilvopastoral systems, where agricultural, forestry, and grazing activities are applied together. The selection of the appropriate system depends on site characteristics and management objectives.

With regard to forest fires, regardless of which of these three systems is applied, agroforestry practices contribute significantly to rural development and sustainable land use. Since production activities are carried out jointly with local communities within buffer zones established along forest edges, particularly in agricultural lands and rural settlement areas, the likelihood of forest fire ignition can be reduced. Although the width of buffer zones varies depending on site conditions, it generally ranges between a minimum of 30 m and 50 m. Within these zones, fire resistant species, particularly locally adapted medicinal and aromatic plants and fruit trees, are introduced together into the same area. In such systems, a multilayered structure is formed, and soil cultivation is carried out, while irrigation systems are established when necessary and made available for controlled use by local communities. Agroforestry systems have a high potential for application within settlement area forest separation zones and agricultural area forest separation zones implemented under the YARDOP project (Rehabilitation of Burned Forest Areas and Establishment of Fire Resistant Forests) (OGM, 2010). These practices should be implemented in various forms, primarily by taking site conditions, especially climatic factors, into account. However, it should be emphasized that all such activities must be planned and implemented within a well defined project framework.

Evaluating agroforestry practices in terms of fire behavior and ensuring the participation of local communities in these practices are essential. In the Bergama region of İzmir, stone pine plantations established with wide spacing intervals of 8 × 8 m to 10 × 10 m allow the cultivation of a wide variety of horticultural crops during the early years within an agrosilvicultural system, while in later stages they support livestock oriented forage production and grazing activities within a silvopastoral system (Turna, 2013b, 2017, 2023). During the initial establishment phase, stone pines can be cultivated together with various herbaceous, predominantly vegetable crops such as tomato, cabbage, bean, lettuce, and eggplant. In these areas, woody medicinal and aromatic species such as thyme, mint, rosemary, and basil can also be cultivated. Indeed, a study conducted by Turna et al. (2019) emphasized that both the Aegean subregion and the Inner Western Anatolia region possess a geography rich in medicinal and aromatic plants, that all three main agroforestry systems have significant application potential in these regions, and that these practices need to be transferred to practitioners in a conscious and well structured manner. The fact that these regions are dominated by fire prone Mediterranean climatic conditions further increases their importance with respect to forest fire risk.

A striking example of the role of agroforestry in fire behavior was observed during a forest fire that started on 26 July 2025 in the Gürsu district of Bursa and lasted for two days. Within an approximately 100 ha forest area that was completely burned, an orchard located inside the forest remained entirely green. The 2.5 ha nectarine orchard suffered no damage from the fire. The main reasons for this outcome were the use of a drip irrigation system and the continuous removal of dry grasses both within the orchard and along its boundaries (Figure 5) (URL.1).

Figure 5. A nectarine orchard remaining intact after the Bursa Gürsu forest fire (URL.1)

Grazing in forested areas is defined as the feeding of domestic animals under human control and wild animals through natural processes within forests and forest openings. While controlled grazing provides both direct and indirect benefits, uncontrolled grazing leads to significant direct and indirect damages. For instance, uncontrolled grazing results in the depletion of soil humus content, soil compaction, and increased erosion. In particular, regeneration areas are highly vulnerable to uncontrolled grazing until young plants achieve biological independence. Under such conditions, regeneration either fails completely or occurs at a very low success rate.

When the positive effects of grazing on forest fires are considered, controlled grazing plays a significant role in eliminating or reducing the accumulation of combustible materials. Conversely, the complete prohibition of grazing may lead to the excessive growth of grasses, particularly in coniferous stands, which can reach hazardous levels during dry periods. Among coniferous species, Calabrian pine, Scots pine, and Anatolian black pine are considered the most fire sensitive forest tree species, and they are characterized by high light requirements. Pure or mixed stands composed of such light demanding species tend to form open canopies at advanced ages. In the absence of appropriate silvicultural interventions, these stands accumulate substantial amounts of combustible material in the intermediate and lower layers, including surface litter, standing dead fuels, and materials resulting from natural pruning. Even when silvicultural treatments are applied, ground vegetation consisting of grasses and other live cover elements develops in the understory depending on site conditions.

In such stands, during periods characterized by high temperatures, relative humidity below 10%, and strong winds, live ground vegetation poses a serious fire hazard due to its flammability. When combined with additional fuels such as dry branches, needles, bark, and cones produced through natural pruning, only a single ignition source is sufficient to initiate a fire. Therefore, reducing the amount of combustible grasses and other live ground vegetation through controlled grazing in both forested areas and forest openings represents an important management practice. This approach is applicable not only in natural stands but also particularly in afforestation and plantation areas (Figure 6).

Figure 6. Dry grasses as combustible materials and grazing in forested areas (natural and artificial stands)

To achieve the desired effectiveness in controlled grazing, decisions should be made by considering factors such as livestock density, grazing timing, the size of the grazing area, grazing duration, and the availability and quantity of forage. This issue becomes particularly critical along stand edges adjacent to settlements, roadsides, and agricultural lands. Therefore, starting with public engagement, it is essential to prepare grazing management plans and to provide training aimed at promoting greater sensitivity, especially during fire seasons.

While emphasizing the importance of grazing in forest fire prevention, it must be ensured that grazing is implemented only in fire prone regions, under controlled and supervised conditions, and with great caution. Grazing should strictly not be allowed in stands at the regeneration stage, and it should preferably be carried out using small ruminants, particularly sheep. As the term implies, controlled grazing reduces fuel loads by consuming dry grasses, shrubs, and other wild vegetation, while simultaneously contributing to rural development through livestock production. Moreover, it enables forest villagers and shepherds to be regarded as active stakeholders in forest fire prevention and suppression efforts. As practiced in developed countries, scientific studies focusing on the role of grazing in forest fire prevention should be conducted. However, the detrimental effects of excessive and uncontrolled grazing on forest degradation, particularly its negative impacts on regeneration, must also be carefully taken into account.

Grazing in forested areas is also regulated under Article 19 of the Forest Law. According to the law, matters related to the designation of areas where grazing is permitted, the types of animals allowed, as well as the determination and announcement of grazing periods and durations, are regulated by specific bylaws. Grazing is strictly prohibited in burned forest areas, as well as in areas allocated for regeneration or afforestation (Anonim, 1956).

In a study evaluating the implementation of fire resistant forest projects, silvicultural measures aimed at facilitating fire suppression by influencing fire behavior were examined. These measures include the reduction of surface fuels, the removal of ladder fuels, and the decrease of crown density through practices such as prescribed burning, grazing, and mechanical removal of live ground vegetation. The study concluded that while YARDOP projects offer several benefits, one of the major challenges encountered in relation to fire resistant species is the lack of adequate tending measures to effectively manage grazing pressure and shrub encroachment (Güngöroğlu et al., 2014). In addition, Turna et al. (2024) highlighted fire prevention as one of the key benefits of windbreaks established around agricultural lands.

4.3. The Relationship Between Regeneration Practices and Fire

A large proportion of forest tree species that have reached the regeneration stage, particularly pines among coniferous species, whether in pure stands or mixed within the same species group, exhibit optimal seed germination on mineral soil. This characteristic provides the silviculturist with an opportunity to apply the technique known as fire culture in pine stands at the regeneration stage, under suitable conditions, in order to ensure seed contact with mineral soil. Atay (1975) defines fire culture as the elimination of undesirable live and dead ground vegetation in regeneration areas by means of a surface fire, applied during mast years before seed fall in natural regeneration, or prior to sowing or planting in artificial regeneration. Ata (1995) describes fire culture as the burning of live ground vegetation such as shrubs and grasses, as well as harvesting residues and forest floor litter present on the soil surface of stands designated for regeneration, which would otherwise hinder the establishment of regeneration. Through the partial or complete removal of existing live and dead ground cover and the exposure of mineral soil, fire culture facilitates the establishment of natural regeneration and, in the case of artificial regeneration, simplifies sowing and planting operations while increasing success rates (Saatçioğlu, 1971). In brief, fire culture represents a practicable method in regeneration areas, as it provides the benefits of site preparation and soil treatment more rapidly and economically. However, successful implementation of this method requires a thorough analysis of site conditions and the silvicultural characteristics of the stand to be regenerated. Fire culture is a fire event applied under the direct control of the silviculturist within the regeneration stand. In contrast, the use of prescribed or intentional burning aimed at preventing forest fires, including in young stands, may lead to uncontrollable outcomes, particularly under the conditions of silvicultural practice in Türkiye. The primary objective and application of fire culture must therefore strictly adhere to silvicultural principles. Fire culture has been known and applied in silviculture since ancient times.

The removal of live and dead ground cover from regeneration areas through burning is a method more commonly applied in the forestry practices of northern countries. For example, in Scotland, a raw humus layer lying on mineral soil is frequently observed, typically reaching a thickness of 40 to 50 cm and, in some locations, exceeding 100 cm (Atay, 1966). Due to excessive precipitation combined with insufficient light availability, microbial activity remains limited, leading to the accumulation of this layer. The removal of such raw humus by means of a surface fire and the subsequent exposure of mineral soil bring the practice of fire culture into consideration.

At first glance, fire culture is often perceived as deliberately setting forests on fire and is therefore criticized by a large segment of society. However, when the objective and application technique of fire culture are examined from the perspective of forest engineering, it becomes clear that it represents a highly important silvicultural intervention in forestry. Prescribed burning is a technical operation primarily aimed at facilitating regeneration and ensuring the successful establishment of young stands, and secondarily at reducing or eliminating potential forest fire risk.

From a silvicultural perspective, forest fires are classified into four categories according to their mode of occurrence and the components they affect, namely soil fires, surface fires, crown fires, and stem fires. A soil fire is a type of fire that occurs through the burning of peatlands or thick layers of raw humus. A surface fire involves the combustion of live and dead ground cover, particularly grasses, needles, leaves, humus, mosses, cones, dry branches, heather, small seedlings, and harvesting residues. A crown fire develops when a surface fire spreads upward and ignites dry branches, resin, mosses, and foliage in tree crowns. Crown fires pose a particularly serious threat to stands at the thicket stage. A stem fire, on the other hand, refers to the burning of an individual dead or hollow stem, often initiated by lightning strikes (Atay, 1975). These definitions clearly indicate that the primary material underlying forest fire occurrence is the availability and quantity of combustible fuels. Regardless of weather conditions, the probability of forest fire occurrence is very low in the absence of human influence. For instance, the majority of fires occurring in the Eastern Black Sea region take place during winter or early spring and are typically soil or surface fires. All of these fires are human induced and are mainly associated with land clearing activities.

The application of fire culture for regeneration purposes can be carried out both in open areas created by clearcutting and under shelterwood systems. Depending on stand structure and site conditions, the practice is implemented in three different ways (Ata, 1995):

- *Fire culture applied over the entire area:* All shrubs present in the regeneration area are cut and evenly distributed across the site together with other harvesting residues found within the stand. To prevent the fire from spreading beyond the treatment area, the perimeter of the site is thoroughly cleared over a width of 3 to 5 m. Areas beneath the shelter of remaining trees are also cleaned in a similar manner. After all combustible materials have been evenly distributed, they are left to dry for one to two weeks, depending on weather conditions, to facilitate ignition. On a day with light wind, ignition is carried out in the direction of the wind so that the fire progresses slowly as a surface fire. The number of ignition points is increased according to the size of the area. It is essential that this practice is never applied under strong wind conditions and that it is conducted in a fully controlled manner.

- *Fire culture applied to partial areas:* When live or dead ground cover is concentrated in certain parts of the regeneration area rather than being uniformly distributed, fire culture is applied only in those specific sections. The primary objective in this case is to remove problematic live ground vegetation and harvesting residues from localized areas where they occur.

- *Spot burning:* In situations where burning combustible materials across the entire area or even in partial areas is considered risky or undesirable, combustible materials are collected at designated points within the stand or removed outside the stand and burned in piles. As with other methods, strict control and careful consideration of weather conditions are required during this operation.

When fire culture is applied across the entire regeneration area, not only the existing live ground vegetation and harvesting residues are burned, but the forest floor litter layer is also consumed. This practice is therefore defined as controlled and purposeful burning. In this context, it is important to recall both the advantages and disadvantages of fire culture, as this method, although controlled and intentional, also involves a number of inherent risks.

The most important advantage of fire culture is that it enables rapid site preparation in regeneration areas by eliminating live and dead ground cover elements that hinder seed–soil contact and the establishment of regeneration. The ash produced after burning acts as an organic amendment for the soil. Another advantage is that the removal of combustible materials reduces the potential risk of uncontrolled forest fires that could otherwise arise if these materials were left on site. Ash resulting from burning increases soil pH, which can neutralize acidic soils and enhance the activity of soil bacteria involved in nitrification and nitrogen fixation processes (Atay, 1987). However, elevated soil pH levels may also increase the risk of damping off in seedlings. In areas affected by fire, only 40% of one year old Douglas fir (Pseudotsuga sp.) seedlings were found to be mycorrhizal one year after burning, whereas in unburned areas 65% of one year old seedlings carried mycorrhizae (Atay, 1987).

Among the disadvantages of fire culture is the combustion of all organic residues present on the site, with part of these materials, particularly nitrogen, being lost to the atmosphere in gaseous form. A wide range of soil organisms, including both belowground and aboveground biota such as microorganisms, are adversely affected by fire. In addition, depending on soil type, fire may lead to desiccation in light textured soils and hardening in heavy textured soils, thereby exerting negative effects on soil structure and texture. On sloping sites, fire culture may also increase the risk of soil erosion (Atay, 1987; Ata, 1995).

As briefly summarized above, fire culture is a silvicultural intervention method that entails both advantages and disadvantages. Therefore, its application requires not only technical knowledge but also experienced and careful implementation. Decisions regarding the use of fire culture should be based on comprehensive and multidimensional analyses that take into account site conditions, particularly temperature and wind, tree species and associated vegetation, as well as socio economic conditions.

It has been emphasized that fire culture can be used to improve regeneration conditions, especially in pine species and cedar stands, provided that fuels are not excessively dry at the time of burning and that weather conditions are carefully considered. Under controlled burning, favorable conditions for seedling establishment and growth can be achieved. In particular, studies conducted in Calabrian pine stands have demonstrated that prescribed burning yields positive results in terms of both regeneration success and soil conditions (Neyişçi, 1989). While organic matter loss occurs in the upper few centimeters of soil during burning, no significant loss has been observed in deeper soil layers, and soil pH increased by approximately 3% by the end of the first year after fire, returning to pre burning levels by the end of the third year. In the same study, the survival rate of planted Calabrian pine seedlings after five years was 59% on burned sites, compared to 31% on unburned sites. Mean seedling height was also greater on burned areas, measuring 59.8 cm compared to 42.2 cm on unburned areas. Similarly, Kantarcı et al. (1986) reported that in cedar stands, the average height of one year old seedlings was 11.5 cm on burned sites, whereas it was only 7.6 cm on unburned sites.

Controlled burning conducted in both Calabrian pine and cedar stands indicates that this practice can be used in regions within the Mediterranean climatic zone where natural regeneration has proven unsuccessful (Odabaşı et al., 2007).

Prescribed burning or controlled burning is defined as the removal of the existing fuel load within a specific area, at a specific time, and under suitable environmental conditions through a fire that is intentionally and carefully conducted by trained specialists. Although this method is widely used within the framework of establishing fire resistant forests, it can also be applied in other silvicultural practices such as natural regeneration and afforestation. In Türkiye, applications within this scope are also referred to as fire culture (Neyişçi, 1987; Kantarcı et al., 1986; Boydak et al., 1996).

The application of fire culture outside regeneration or afforestation areas, whether in the form of controlled or purposeful burning, is an issue that requires extensive research under the conditions of Turkish forestry and implementation based on scientifically derived results. In particular, when applied at stand development stages other than the regeneration stage of stands that have reached the end of their rotation, namely the thicket, pole, small timber, and young to middle aged mature stages, the advantages and disadvantages of fire must be carefully analyzed. This is because the degree of damage caused by fire varies considerably among tree species and from stand to stand. In general, coniferous forests are known to be more severely affected by fire than broadleaved forests. Shallow rooted tree species are more vulnerable than deep rooted species, and young trees with thin bark are more susceptible than older trees with thick bark. Taking these characteristics into account, it is necessary to assess in which stand types and development stages prescribed or controlled burning can be applied.

Among coniferous species in Türkiye, Calabrian pine is considered one of the most fire resistant pine species, followed by Anatolian black pine and Scots pine. Fire related damage in these species generally manifests as injuries to tree stems. The severity of damage varies depending on fire intensity, the transition from surface fire to crown fire, and the duration and rate of fire spread. When fires escape control and develop into crown fires, cone structure and seed characteristics of tree species also become decisive factors. For example, the cone and seed traits of Calabrian pine and Scots pine exhibit different responses in the context of fire culture, and these differences must be taken into consideration. Forest fires also have adverse effects on seeds present in the soil. When the organic matter layer on the soil surface is burned, seeds contained within this layer are also destroyed, with Calabrian pine being a notable exception. While this situation may appear favorable for suppressing undesirable species, it is generally undesirable for the regeneration of target forest tree species.

It should not be overlooked that all tree species are affected by uncontrolled and high intensity fires. In pine stands, trees are highly sensitive and lack resistance to fire before reaching the small timber stage, that is, during the thicket and pole stages. For this reason, the use of fire should in no way be considered in stands at these developmental stages.

In unmanaged stands composed of coniferous species, the accumulation of forest floor litter may reach a thickness of 20 to 30 cm. In such cases, a fast moving fire that merely passes over the litter layer may not significantly affect the mineral soil. In contrast, a slow moving fire that gradually consumes the litter layer and exposes the mineral soil can substantially alter the physical, chemical, and biological properties of the soil. If such a fire occurs on shallow soils with limited mineral soil depth, the resulting damage may be far more severe. In forest soils where organic matter has accumulated to a depth of 25 to 30 cm, this layer can easily and completely burn during dry seasons. When this occurs on shallow mineral soils, the damage becomes critical, leaving behind a surface composed of a thin soil layer interspersed with rock fragments. The restoration and reestablishment of forest cover on such sites are extremely difficult and may require many years (Atay, 1987).

In summary, in fire prone areas, establishing a multilayered stand structure and ensuring its continuity through appropriate tending practices constitute an effective preventive measure. In particular, carrying out tending operations to reduce fuel loads in stands at the thicket and early thinning stages, together with pruning the lower branches of trees along stand edges, plays a significant role in reducing fire risk.

In regeneration and afforestation areas, fire culture should not be applied merely because it appears easier and more economical than mechanical or chemical methods for controlling live and dead ground cover that hinders seed germination. Implementing this method without a thorough site specific analysis is not appropriate. The destructive impacts of uncontrolled forest fires should not be underestimated (Atay, 1987). Moreover, advances in mechanical site preparation technologies have demonstrated that effective control of live ground vegetation can be achieved without excessively high costs. Therefore, the applicability of fire culture should be tested through comprehensive research before being adopted as a widespread practice in regeneration areas. Considering the structural characteristics of forests in Türkiye, including tree species composition and stand structure, site conditions, the level of technical expertise regarding fire culture, the availability of preventive measures, and above all the potential disadvantages of fire, it becomes evident that fire culture should not be regarded as a primary method in Turkish forestry.

Among silvicultural practices aimed at preventing forest fires, the establishment of firebreak roads and strips, together with the regular maintenance of existing structures, occupies a central role. Firebreak roads and strips are protective areas created by utilizing natural or artificial barriers to limit the spread of an ongoing fire, where the surface is kept bare or planted with fire resistant species. In addition to physically restricting fire spread, these roads and strips are effectively used as defensive lines in firefighting operations, for backfiring applications, and for facilitating access during fire suppression activities.

Numerous scientific and practical studies, particularly within the framework of YARDOP initiatives, have addressed the establishment and maintenance of firebreak roads and strips (OGM, 2010, 2014; Neyişçi, 1987, 1996, 2011; Neyişçi et al., 1996; Kılıç and Cebeci, 2009; Kavgacı and Tavşanoğlu, 2010). Turkish forestry practice and forest engineers possess extensive experience and expertise in structural and vegetation based measures aimed at fire prevention. As stated by Yılmaz et al. (2013), the General Directorate of Forestry continues to achieve significant success through its extensive experience, qualified human resources, and broad access to modern technical equipment. In this context, YARDOP principles and projects represent major and valuable contributions. However, rather than implementing numerous YARDOP projects across all fire prone regions, developing region specific projects based on the outcomes of pilot applications established in selected areas would enable more informed and effective decision making in the fight against forest fires.

5. CONCLUSIONS

When scientific approaches are applied to potential climate change–driven natural events and appropriate preventive measures are taken, the frequency of disasters will not increase in the Mediterranean climatic zone, including Türkiye, as in many other parts of the world. On the contrary, as long as actions that disrupt ecosystem balance continue, so-called natural disasters will be encountered with increasing frequency. Under such circumstances, both the number and the extent of damage caused by forest fires, including large or mega fires, are expected to rise. In this context, the primary cause will often be attributed to climate change rather than to human activities.

For this reason, far greater emphasis should be placed on pre-fire forest planning and silvicultural interventions, namely preventive measures, than on fire suppression efforts alone. Within this framework, forest areas should be classified according to their degree of fire sensitivity, and potential fire risk and hazard maps should be developed and presented through dynamic modeling approaches. In addition to education and awareness-raising activities, silvicultural measures aimed at reducing fire risk and hazard, such as fuel management, the establishment and maintenance of firebreak roads and strips, should be implemented. Particular attention should be given to high-risk areas where fuel accumulation has reached critical levels. When silvicultural interventions are carried out in a timely manner and with effective organization, it becomes possible to restore burned areas rapidly in a way that re-establishes both ecological and economic balance.

Projects implemented under the General Directorate of Forestry and developed within the scope of YARDOP should be revised according to fire-prone ecosystem conditions and applied accordingly. Beyond species selection and establishment techniques, it is essential that tending operations are conducted on time and without interruption. Especially in YOAT and ZOAT areas, maintenance interventions such as grazing, soil cultivation, pruning, and irrigation aimed at reducing fuel loads are of particular importance.

Human activities that disrupt ecosystem balance, including those leading to forest fires, require a fundamental shift toward respect for nature. Necessary measures against potential adverse effects such as climate change must be taken in a timely manner, and natural resources should be utilized at optimal levels. Achieving this requires forestry practices that are nature-based and guided by scientific principles.

As frequently discussed in social media and in many scientific studies, wildfire management often focuses on so-called fire combat or suppression organizations, mechanization techniques, equipment support, and firefighting methods. However, the essential issue lies in eliminating the causes of fire ignition. This requires a correct understanding and careful interpretation of nature, followed by the timely implementation of appropriate engineering and management practices. Sustainable management cannot be achieved through exploitative approaches to nature or by tolerating forest destruction through fire.

Finally, education and awareness-raising, the regulation of activities within and around forest areas, and the strengthening of early warning systems are of vital importance in preventing forest fires. Priority should be given to public relations, educational programs, and awareness campaigns. Legal measures and sanctions should be considered supportive tools and applied only as a last resort.

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CHAPTER 3

NEXT-GENERATION SEQUENCING (NGS) APPLICATIONS IN AGRICULTURAL ENTOMOLOGY AND INTEGRATED PEST MANAGEMENT

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1. Introduction

Plant protection in modern agriculture faces a complex set of challenges driven by environmental, technological, and socio-economic factors. Climate change is a major concern, as it destabilizes farming practices, alters pest and disease dynamics, and increases the frequency and severity of invasive species outbreaks. These shifts make it harder to predict and manage threats, requiring more adaptive and resilient protection strategies (Mesías-Ruiz et al., 2023; Bouri et al., 2023).

Traditional chemical control methods, while effective in boosting yields, have led to significant problems such as the development of pest resistance, environmental degradation, and health risks to humans and non-target organisms. The over-reliance on pesticides has also resulted in regulatory restrictions and increased costs for developing and registering new products, making it difficult for farmers to access effective solutions (Kubiak et al., 2022). Meanwhile, biological and cultural control methods, though more sustainable, often face challenges related to scalability, variable effectiveness, and dependence on specific environmental conditions (Huded et al., 2023).

Technological innovations, such as artificial intelligence, machine learning, drones, and precision agriculture, offer promising avenues for more targeted and efficient plant protection. However, these technologies come with high setup costs, require specialized expertise, and are not always accessible to all farmers, particularly in developing regions. Data quality, integration with existing practices, and the need for robust digital infrastructure further complicate widespread adoption (Huded et al., 2023; Mesías-Ruiz et al., 2023; Aziz et al., 2025).

Integrated Pest Management (IPM) and the use of low-risk plant protection products are increasingly promoted as sustainable solutions. Yet, IPM faces its own hurdles, including inconsistent definitions, gaps between theory and practice, insufficient farmer engagement, and limited policy support. The transition to low-risk products is hampered by technical, regulatory, and economic barriers, as well as a lack of comprehensive research on their long-term effectiveness and integration into existing systems (Zhou et al., 2024).

The challenges of plant protection in modern agriculture are multifaceted, involving the need to balance productivity, sustainability, and safety. Addressing these issues requires multidisciplinary research, policy innovation, capacity building, and the integration of advanced technologies with traditional knowledge (Mesías-Ruiz et al., 2023; Huded et al., 2023).

The identification of insects is critically important in agriculture because it underpins effective pest management, crop protection, and sustainable farming practices. Accurate identification allows farmers and agronomists to distinguish between harmful pests and beneficial insects, such as pollinators or natural predators. Misidentification can lead to inappropriate control measures, unnecessary pesticide use, and the disruption of ecological balances, potentially harming beneficial species and reducing the effectiveness of pest management strategies (Teixeira et al., 2023; Yang et al., 2025).

Early and precise detection of insect pests enables timely interventions, reducing crop losses and minimizing the need for broad-spectrum chemical applications. This targeted approach not only improves crop yield and quality but also supports environmental sustainability by decreasing pesticide overuse and its associated risks to human health and ecosystems (Teixeira et al., 2023). For example, knowing the specific pest species and their population dynamics allows for the implementation of integrated pest management (IPM) strategies, which combine biological, cultural, and chemical controls for more efficient and eco-friendly outcomes (Yang et al., 2025).

Traditional insect identification methods, which rely on expert taxonomists and manual inspection, are often time-consuming, labour-intensive, and prone to human error. Advances in digital imaging, artificial intelligence, and machine learning have revolutionized this process, enabling rapid, automated, and highly accurate identification of insect species in real time. These technologies empower farmers with timely information, supporting data-driven decisions and more precise pest control measures (Tannous et al., 2023).

Furthermore, systematic insect identification and monitoring contribute to long-term agricultural planning and research. They provide valuable data for forecasting pest outbreaks, understanding the spread of invasive species, and developing predictive models that help mitigate the impact of climate change and evolving pest populations on crop production. In summary, the ability to accurately identify insects is foundational to modern agriculture, supporting productivity, sustainability, and resilience in the face of ongoing environmental and economic challenges (Teixeira et al., 2023; Yang et al., 2025).

Next-Generation Sequencing (NGS) is a powerful, high-throughput technology that enables the rapid sequencing of millions of DNA or RNA fragments simultaneously. Unlike traditional Sanger sequencing, which processes one DNA fragment at a time, NGS can analyse entire genomes or large sets of genes in a single run, dramatically increasing speed and reducing costs (Satam et al., 2023; Hu et al., 2021). This parallel sequencing approach has revolutionized genomics by making it possible to generate vast amounts of genetic data quickly and efficiently.

NGS works by fragmenting DNA or RNA samples into smaller pieces, which are then sequenced in parallel. The resulting short sequences, or "reads," are assembled using advanced bioinformatics tools to reconstruct the original genetic material. This process allows for comprehensive analysis of genome structure, genetic variations, gene expression, and even epigenetic modifications (Satam et al., 2023). NGS platforms can be used for whole-genome sequencing, targeted gene panels, exome sequencing, and transcriptome (RNA) sequencing, among other applications.

The impact of NGS extends across many fields, including clinical diagnostics, cancer research, infectious disease surveillance, and personalized medicine. For example, NGS enables the identification of disease-causing mutations, the discovery of novel pathogens, and the development of targeted therapies (Satam et al., 2023; Yadav et al., 2023). In clinical settings, NGS is increasingly used for diagnosing genetic disorders, guiding treatment decisions, and monitoring disease progression.

Recent advancements in NGS technology have focused on improving sequencing accuracy, reducing costs, and enhancing data analysis capabilities. These improvements have made NGS more accessible and practical for both research and clinical applications, paving the way for new discoveries and innovations in genomics and beyond (Satam et al., 2023; Hu et al., 2021).

1.1. The Evolution of Molecular Approaches in Agricultural Entomology

Molecular approaches in agricultural entomology have evolved rapidly, transforming pest monitoring, species identification, and pest management strategies. The field has shifted from early DNA marker systems to advanced genomics and gene-editing technologies, enabling more precise, efficient, and sustainable solutions for agricultural pest challenges. Initial molecular methods focused on DNA markers such as mitochondrial DNA, microsatellites, RAPD, AFLP, and ESTs. These tools enabled researchers to explore genetic diversity, map important genes, and understand population structures of pest insects. They also facilitated the identification and tracking of pest species, which was previously limited by morphological similarities and labour-intensive taxonomy (Ibrahim et al., 1997; Handler & Beeman, 2003; Behura, 2006).

The advent of next-generation sequencing (NGS) and DNA metabarcoding has revolutionized biomonitoring. These technologies allow for the rapid, high-resolution identification of insect communities from environmental samples, increasing throughput and enabling the construction of ecological networks. Metabarcoding, in particular, has enhanced the detection of pests and beneficial insects, supporting more effective integrated pest management (IPM) and biodiversity conservation (Paula, 2021; Suresh et al., 2024).

Recent advances include the use of whole-genome sequencing, transcriptomics (RNA-seq), and gene-editing tools like CRISPR/Cas9. These approaches have uncovered the molecular mechanisms underlying insecticide resistance and pest adaptation, and have enabled the development of genetically engineered pest control strategies, such as sterile insect techniques and gene drives (Alphey & Bonsall, 2017; Niu et al., 2024).

Modern molecular approaches are increasingly integrated with traditional monitoring and computational tools, such as AI-based image analysis, to create robust, scalable, and automated biomonitoring systems. This integration supports real-time pest detection and ecosystem management (Cuff & Watt, 2024; Suresh et al., 2024).

1.2. Fundamentals of Next-Generation Sequencing (NGS) Technologies

Next-Generation Sequencing (NGS) refers to a suite of high-throughput technologies that enable the rapid sequencing of millions to billions of DNA or RNA fragments in parallel. This represents a significant advancement over traditional Sanger sequencing, which processes one DNA fragment at a time. The core advantage of NGS is its ability to generate massive amounts of sequence data quickly and cost-effectively, making genome-scale studies accessible to a wide range of researchers and clinicians (Satam et al., 2023; Cheng et al., 2023).

The NGS workflow typically begins with the extraction of nucleic acids (DNA or RNA) from a sample, followed by library preparation. During library preparation, the nucleic acids are fragmented and specific adapters or barcodes are attached to each fragment. These adapters allow the fragments to be amplified and later identified during sequencing. Depending on the platform, template preparation may involve clonal amplification (as in second-generation technologies) or single-molecule sequencing (as in third-generation technologies) (Besser et al., 2017; Hu et al., 2021).

Sequencing itself is performed in a massively parallel fashion, with platforms such as Illumina, Ion Torrent, Pacific Biosciences, and Oxford Nanopore each employing distinct chemistries and detection methods. Short-read (second-generation) technologies are known for their high accuracy but are limited in the length of DNA they can read in a single run. Long-read (third-generation) technologies can sequence much longer fragments, which is valuable for resolving complex genomic regions, though they have historically faced challenges with accuracy. Recent advancements are bridging the gap between read length and accuracy, further expanding the utility of NGS (Hu et al., 2021; Satam et al., 2023; Kumar et al., 2019).

After sequencing, the resulting data undergoes several stages of bioinformatic analysis. This includes converting raw signals into nucleotide sequences, aligning these sequences to reference genomes, assembling genomes de novo, and interpreting genetic variants. The sheer volume of data generated by NGS requires robust computational infrastructure and sophisticated algorithms for data management, analysis, and storage (Cheng et al., 2023).

NGS technologies have revolutionized genomics by enabling comprehensive studies of genome structure, genetic variation, gene expression, and epigenetic modifications. Their applications span basic research, clinical diagnostics, cancer genomics, infectious disease surveillance, and personalized medicine. As NGS platforms continue to evolve, ongoing improvements in speed, accuracy, and cost-effectiveness are expected to further expand their impact across diverse fields (Satam et al., 2023).

1.3. NGS and Integrated Pest Management: A Transformative Intersection

The integration of Next-Generation Sequencing (NGS) technologies with Integrated Pest Management (IPM) is revolutionizing how pests and pathogens are identified, monitored, and controlled in agriculture. NGS enables rapid, accurate, and comprehensive identification of pest species, including those that are invasive or difficult to detect with traditional methods. This is particularly valuable for early detection and timely intervention, which are critical for effective IPM strategies. Beyond species identification, NGS can uncover genes associated with pesticide resistance, allowing for more informed decisions on pesticide use and helping to prevent the spread of resistance within pest populations. Additionally, NGS facilitates the detection of pest-associated viruses, endosymbiotic bacteria, and even provides insights into pest diets and invasion pathways, offering a holistic view of pest ecology. These capabilities support the development of more targeted, sustainable, and environmentally friendly pest management programs by integrating molecular diagnostics with traditional IPM approaches, ultimately enhancing the precision and effectiveness of pest control efforts (Frey et al., 2022; Délye et al., 2019; M. et al., 2024).

2. NGS Applications in Insect Pest Diagnostics

Next-Generation Sequencing (NGS) technologies have transformed insect pest diagnostics by enabling rapid, accurate, and high-throughput identification of pest species, detection of pesticide resistance genes, and discovery of associated pathogens. One notable application is the use of Oxford Nanopore MinION sequencing for the identification of 66 insect specimens across 29 species and 13 genera. This approach not only allowed for precise species identification without prior taxonomic knowledge but also enabled the detection of pesticide resistance genes and the presence of arthropod-infecting viruses and endosymbiotic bacteria within the same workflow. For example, in Diptera species such as *Bactrocera dorsalis*, *Drosophila suzukii*, and *Liriomyza sativae*, NGS was used to confirm the presence of genes involved in pesticide resistance, providing valuable information for pest management strategies (Frey et al., 2022).

Another significant application is DNA metabarcoding, which allows for the simultaneous identification of multiple insect species from bulk trap samples. This high-throughput method is particularly useful for surveillance programs targeting invasive pests, as it can process hundreds of samples and detect both known and unexpected species, thereby improving early detection and response efforts (Piper et al., 2019). Additionally, NGS has been instrumental in the discovery of novel insect viruses, which can impact pest management and experimental outcomes. For instance, transcriptome and small RNA sequencing have been used to identify covert viral infections in insect populations, revealing the complexity of insect-pathogen interactions and informing the development of more effective control measures (Liu et al., 2011).

2.1. Rapid Species Identification Through DNA Barcoding and Metabarcoding

NGS-based DNA barcoding and metabarcoding have transformed pest diagnostics by enabling rapid and accurate identification of multiple species in a single sequencing run. This is especially valuable for monitoring insect communities in traps, soil, or plant material where traditional morphological identification is slow or impossible due to damaged specimens. A notable case study comes from fruit fly surveillance programs, where metabarcoding was used to identify *Bactrocera*, *Ceratitis*, and *Anastrepha* species from mixed trap samples. The NGS results allowed quarantine authorities to detect invasive fruit fly incursions earlier than with conventional methods, improving response times and reducing crop losses (Armstrong & Ball, 2005; Yu et al., 2012).

2.2. Resolving Cryptic Species Complexes.

Many agricultural pests consist of cryptic species that are morphologically similar but genetically distinct, leading to misdiagnosis and ineffective control strategies. NGS helps clarify these complexes by providing genome-level resolution of species boundaries. A well-documented example involves the *Bemisia tabaci* whitefly complex, where whole-genome sequencing and high-throughput genotyping distinguished multiple cryptic species with different host ranges and insecticide resistance profiles. (De Barro et al., 2011). This genomic clarification reshaped whitefly management programs globally, allowing region-specific control tactics and more accurate risk assessments.

2.3. Diagnostics for Vector-Borne Plant Pathogens

NGS is also used to detect plant pathogens carried by insect vectors, improving diagnostic accuracy when symptoms are unclear or pathogens are difficult to culture. For instance, metagenomic NGS was applied to phloem-feeding psyllids to identify *Candidatus Liberibacter asiaticus*, the bacterium responsible for citrus greening (HLB). Sequencing of psyllid samples allowed early pathogen detection before visible symptoms appeared in trees. This approach has strengthened surveillance programs by enabling simultaneous detection of both vector species and the pathogens they transmit (Li et al., 2006).

2.4. Identification of Larval and Immature Stages

Immature insects often lack diagnostic morphological traits, making species identification challenging. NGS technologies provide a solution by enabling diagnostic sequencing from larval tissue, frass, or even environmental residues. A key example is the identification of stored-product pests in grain facilities. When larvae of *Tribolium*, *Sitophilus*, or *Rhyzopertha* species contaminating grain cannot be determined morphologically, amplicon-based NGS allows facility managers to detect the exact pest species present (Short et al., 2021). This enables targeted treatment decisions that are more cost-effective and reduce unnecessary fumigation.

2.5. High-Throughput Screening of Field Samples

NGS allows simultaneous processing of hundreds of field-collected insects, supporting large-scale pest diagnostics. In one case study, NGS metabarcoding was used to screen armyworm populations (*Spodoptera frugiperda*) across Africa to monitor the spread of the invasive strain. The technique allowed researchers to detect population admixture, distinguish native and invasive haplotypes, and track migration patterns with unprecedented detail (Goergen et al., 2016; Zhang et al., 2020). This high-throughput approach enhanced early-warning systems and informed rapid responses to new outbreaks.

These case studies illustrate how NGS technologies are advancing insect pest diagnostics by providing comprehensive, scalable, and sensitive tools for species identification, resistance monitoring, and pathogen discovery, ultimately supporting more effective and sustainable pest management practices (Frey et al., 2022; Liu et al., 2011; Piper et al., 2019).

3. Population Genomics and Pest Dispersal Dynamics: Case Studies and Insights

3.1. Gene Flow, Population Structure, and Local Adaptation

NGS technologies have revolutionized the study of gene flow, population structure, and local adaptation in agricultural insects by enabling genome-wide analyses at high resolution. These tools allow researchers to identify genetic markers, assess genetic diversity, and detect signatures of selection across populations, even in non-model species (Pita et al., 2025).

NGS-based approaches, such as whole-genome resequencing and genotyping-by-sequencing, have been used to reveal population structure and gene flow in pests like the colorado potato beetle (*Leptinotarsa decemlineata*), cotton bollworm *Helicoverpa armigera*, and the black soldier fly (*Hermetia illucens*). These studies show how gene flow can either facilitate or hinder local adaptation, and how population connectivity impacts the spread of traits like insecticide resistance (Pélissié et al., 2021).

In the turnip moth (*Agrotis segetum*), population genomics identified distinct genetic clusters and candidate genes linked to local adaptation, such as cold tolerance and pesticide resistance, across different environments (Wang et al., 2024). Similarly, studies on the soybean looper and Queensland fruit fly used NGS to associate genetic differentiation with host plant use and climatic variables, revealing adaptive responses to agricultural landscapes and environmental gradients (Parvizi et al., 2023).

NGS has uncovered repeated, rapid adaptation in pests, often involving selection on standing genetic variation rather than new mutations, highlighting the dynamic evolutionary potential of agricultural insects (Pélissié et al., 2021; Parvizi et al., 2022).

3.2. Tracing Origins and Invasion Routes of Invasive Insects

Understanding the origins and invasion routes of invasive insects is crucial for effective management and prevention strategies. Advances in molecular genetics and genomics, particularly the use of whole-genome resequencing and population genomics, have enabled researchers to reconstruct detailed invasion histories and dispersal pathways with unprecedented precision. By comparing genetic markers across native and invaded populations, scientists can identify source populations, the number and timing of introduction events, and the routes taken during global spread (Funari et al., 2025; Sun et al., 2023).

For example, whole-genome resequencing of the Japanese beetle (*Popillia japonica*) revealed six distinct genetic clusters corresponding to different colonization areas. The data showed that the initial invasion to the USA originated from North/Central Japan, followed by independent "bridgehead" events from the USA to the Azores and Italy. This approach also highlighted the role of human activities, such as international trade and direct flights, in facilitating these invasions and subsequent genetic isolation in some populations (Funari et al., 2025; Nardi et al., 2024). Similarly, genomic studies of the Asian longhorned beetle (*Anoplophora glabripennis*) demonstrated that most North American infestations resulted from multiple independent introductions from the native range, with subsequent genetic bottlenecks and expansions. These findings help distinguish between unique invasions and secondary spread, informing targeted management and eradication efforts (Cui et al., 2024).

Genomic tools have also been applied to other invasive insects, such as the brown marmorated stink bug (*Halyomorpha halys*), the grape phylloxera (*Daktulosphaira vitifoliae*), and the cotton mealybug (*Phenacoccus solenopsis*), revealing complex patterns of multiple introductions, admixture, and rapid demographic expansions. These studies often uncover that invasive populations may serve as "bridgeheads," acting as sources for further invasions into new regions, and that genetic diversity can be maintained or even increased through repeated introductions and admixture (Sun et al., 2023).

Overall, integrating genomic data with historical, ecological, and observational records provides a comprehensive framework for tracing the origins and invasion routes of invasive insects. This knowledge is essential for predicting future invasions, improving biosecurity protocols, and developing more effective control strategies (Cristescu, 2015; Sun et al., 2023).

3.3. Genomic Markers for Pest Surveillance Systems

Genomic markers have become essential tools in modern pest surveillance systems, enabling rapid, accurate, and large-scale monitoring of agricultural pests. By targeting specific DNA sequences unique to pest species or resistance alleles, these markers allow for the identification and tracking of pests even at early invasion stages or low population densities. Techniques such as DNA barcoding, multi-locus sequence analysis, and high-throughput sequencing (HTS) can distinguish between closely related species, detect cryptic invasions, and monitor the spread of resistance genes, all of which are critical for timely and effective pest management interventions (Hiszczyńska-Sawicka et al., 2022; Frey et al., 2022).

The integration of genomic markers into surveillance programs offers several advantages over traditional morphological or phenotypic methods. For instance, DNA metabarcoding and shotgun sequencing of environmental DNA (eDNA) from air or bulk trap samples enable simultaneous detection of multiple pest species, including unexpected or non-target organisms, without the need for labor-intensive specimen sorting. This high-throughput approach dramatically increases the scale and sensitivity of surveillance, making it possible to monitor pest communities across large geographic areas and over time (Mikko et al., 2025). The accuracy of these methods, however, depends on the quality and completeness of reference genomic databases, which are continually expanding as more pest genomes are sequenced (Mikko et al., 2025; Frey et al., 2022).

Genomic markers are also invaluable for resistance monitoring. Molecular diagnostics can detect resistance-associated mutations in pest populations before resistance becomes widespread or leads to control failures. For example, targeted assays such as qPCR, ddPCR, and CRISPR-based diagnostics can identify specific resistance alleles, enabling rapid, on-site decision-making for pesticide use and resistance management (Mavridis et al., 2025). Genomic surveillance can also reveal the origins and invasion routes of pests, track the influx of resistant individuals during biological invasions, and inform biosecurity responses by characterizing population structure and gene flow (Hiszczyńska-Sawicka et al., 2022; Frey et al., 2022).

Overall, the use of genomic markers in pest surveillance systems enhances the ability to detect, monitor, and manage agricultural pests and their resistance traits, supporting more sustainable and evidence-based pest control strategies (Mikko et al., 2025; Frey et al., 2022).

4. Insecticide Resistance Studies Using NGS

Next-generation sequencing (NGS) has revolutionized the study of insecticide resistance by enabling high-throughput, genome-wide analysis of genetic changes associated with resistance in pest populations. NGS allows researchers to identify single nucleotide polymorphisms (SNPs), copy number variations (CNVs), and gene expression changes that underlie resistance mechanisms. For example, targeted NGS has been used to detect hundreds of SNPs linked to resistance against specific insecticides such as malathion and permethrin in mosquito populations, with many of these mutations occurring in genes encoding detoxification enzymes like cytochrome P450s, esterases, and glutathione S-transferases (Bharadwaj et al., 2025; Kothera et al., 2019). These approaches also reveal increased gene copy numbers and well-known resistance mutations, such as the kdr mutation in the voltage-gated sodium channel gene and mutations in acetylcholinesterase, which confer resistance to organophosphates (Bharadwaj et al., 2025; Kothera et al., 2019; Acford-Palmer et al., 2023; Collins et al., 2022).

NGS-based transcriptomic studies (RNA-seq) further enhance understanding by comparing gene expression profiles between resistant and susceptible strains. Such studies have identified hundreds to thousands of differentially expressed genes, particularly those involved in detoxification pathways, transport, and regulation, across various insecticide classes and pest species (Bezerra, 2018; Faucon et al., 2017; Ullah et al., 2023; Silva et al., 2012). In the fall armyworm, for instance, NGS-based multi-amplicon panels have enabled rapid, high-throughput detection of known resistance mutations, supporting timely resistance monitoring and management (Chen et al., 2023). Similarly, amplicon sequencing in mosquitoes and other pests has facilitated the identification of both known and novel resistance mutations, providing a cost-effective and scalable tool for resistance surveillance (Acford-Palmer et al., 2023; Collins et al., 2022; Acford-Palmer et al., 2023; Yamanaka et al., 2022; Collins et al., 2025).

NGS also supports the discovery of resistance mechanisms in non-model pests and across diverse geographic regions, revealing the complexity and diversity of resistance evolution. Studies in aphids and lepidopteran pests have shown that resistance can involve both metabolic and target-site mechanisms, with NGS uncovering new candidate genes and regulatory elements involved in these processes (Niu et al., 2024; Bass & Nauen, 2023; Silva et al., 2012). The integration of NGS data with traditional bioassays and biochemical analyses provides a comprehensive framework for understanding, monitoring, and managing insecticide resistance in agricultural and public health contexts (Bharadwaj et al., 2025; Bezerra, 2018; Kothera et al., 2019; Chen et al., 2023; Délye et al., 2019).

5. Insect–Microbiota Interactions via NGS

Next-generation sequencing (NGS) has transformed the study of insect–microbiota interactions by enabling comprehensive, high-resolution profiling of microbial communities associated with insects. NGS technologies, particularly 16S rRNA gene sequencing and metagenomics, allow researchers to identify and quantify both culturable and unculturable microbes within insect guts and other tissues, revealing the diversity, structure, and functional potential of these communities (Fukatsu, 2012; Shi et al., 2010; Mereghetti et al., 2017). This approach has uncovered that insect microbiomes are often composed of a few dominant bacterial taxa alongside a variety of minor associates, with the major symbionts often occupying specific gut regions and playing key roles in nutrition, immunity, and development (Fukatsu, 2012; Schmidt & Engel, 2021; Chen et al., 2016).

NGS has also enabled the exploration of how environmental factors, such as diet, habitat, and geographic location, shape the assembly and dynamics of insect microbiota. For example, studies have shown that while some insects acquire their gut microbes primarily from the environment (e.g., soil or host plants), others rely more on vertical transmission from parent to offspring (Shan et al., 2024; Majumder et al., 2019). NGS-based analyses have revealed that the composition of the gut microbiome can be relatively stable despite changes in diet or environment, suggesting strong host selection and homeostatic control over key symbionts (Fukatsu, 2012; Shan et al., 2024). Additionally, NGS has been instrumental in identifying specific microbial taxa associated with particular insect functions, such as anti-inflammatory effects in medicinal insects or enhanced reproductive success in plant-sucking bugs (Geng et al., 2022; Shan et al., 2024).

Beyond taxonomic profiling, NGS facilitates functional studies through metagenomics, metatranscriptomics, and metaproteomics, providing insights into the metabolic and immunological roles of microbiota in insect hosts (Shi et al., 2010; Chen et al., 2016; Meiqi et al., 2021). These approaches have revealed that gut microbes contribute to nutrient acquisition, detoxification, pathogen defense, and even influence host behavior and ecological interactions (Wang et al., 2024; Zhang et al., 2023; Chen et al., 2016). NGS has also highlighted the importance of considering confounding factors, such as the presence of dominant endosymbionts like *Wolbachia,* which can skew microbiome analyses if not properly accounted for (Wilches et al., 2021; Nowak et al., 2025).

Overall, NGS has opened new avenues for understanding the complexity and ecological significance of insect–microbiota interactions, offering potential applications in pest management, biotechnology, and the study of host–microbe coevolution (Mereghetti et al., 2017; Shi et al., 2010; Zhang et al., 2023).

6. NGS Insights into Plant–Insect–Microbe Interactions

Next-generation sequencing (NGS) has dramatically advanced the understanding of the complex interactions among plants, insects, and microbes by enabling high-throughput, detailed profiling of all three partners in these tripartite systems. NGS-based metagenomics and metabarcoding approaches allow researchers to simultaneously characterize the diversity and functional potential of microbial communities associated with both plants (in the rhizosphere and phyllosphere) and insects, as well as to track the exchange of microbes and genetic material between them (Das et al., 2023; Mayoral-Peña et al., 2022; Sugio et al., 2015). This has revealed that many microbial taxa are shared between plants and their herbivorous insects, but their abundance and functional roles can differ significantly, influencing plant health, insect adaptation, and the outcome of their interactions (Mayoral-Peña et al., 2022; Das et al., 2023).

NGS has also enabled the detection of plant DNA within insect vectors and vice versa, providing new ways to map feeding relationships and host plant use, even in cryptic or polyphagous species. For example, anchored hybrid enrichment and long-multiplex metabarcoding have been used to recover plant genes from insect samples, revealing broad diet breadths and unexpected host associations, which are critical for understanding the spread of plant pathogens and the ecology of vector-borne diseases (Gabrys et al., 2025; Zhang et al., 2019; Cao & Dietrich, 2021). These molecular tools have also uncovered how plant-associated microbiomes, such as beneficial rhizosphere and phyllosphere microbes, can modulate plant resistance to insect pests and pathogens, and how insect-associated microbes can detoxify plant defenses or alter plant signaling pathways to benefit their insect hosts (Das et al., 2023; Sugio et al., 2015; M. et al., 2024; Coolen et al., 2022).

Furthermore, NGS has facilitated functional inference studies, showing that microbial communities contribute to key processes such as nutrient cycling, secondary metabolite biosynthesis, and xenobiotic degradation, which can affect both plant and insect fitness (Mayoral-Peña et al., 2022; M. et al., 2024). The integration of NGS data from all three partners is revealing the dynamic and reciprocal nature of these interactions, highlighting the importance of microbial mediation in plant–insect coevolution and ecosystem functioning. These insights are opening new avenues for sustainable pest management and crop improvement by targeting or harnessing specific microbial functions within these multitrophic networks (Das et al., 2023; M. et al., 2024; Coolen et al., 2022).

7. NGS Applications in Biological Control Agent Development: Transforming Biocontrol Strategies

Next-generation sequencing (NGS) has become a pivotal tool in the development and optimization of biological control agents (BCAs), offering unprecedented insights into their genetics, interactions, and efficacy. NGS enables comprehensive characterization of BCA genomes, transcriptomes, and associated microbiomes, facilitating the identification of traits linked to effective pest suppression and environmental adaptation (Ferguson, 2020; Massart et al., 2015).

NGS allows researchers to sequence and assemble the genomes of candidate BCAs, revealing genetic diversity, heritability of desirable traits (such as parasitism rate or stress tolerance), and potential for selective breeding or genetic improvement (Leung et al., 2020; Ferguson, 2020). This approach supports marker-assisted and genomic selection, enabling the targeted enhancement of BCA performance while minimizing unintended side effects. NGS also aids in monitoring genetic variation during mass rearing and after field release, ensuring long-term efficacy and stability (Ferguson, 2020).

By profiling the microbiomes of BCAs and their environments, NGS uncovers how microbial communities influence BCA establishment, persistence, and biocontrol efficacy (Massart et al., 2015; Wei et al., 2016). It can identify “helper” microbes that synergize with BCAs or reveal shifts in microbial communities that affect disease suppression (Massart et al., 2015). This holistic view enables the design of more robust biocontrol strategies, such as combining BCAs with beneficial microbiota or optimizing application timing and formulation (Massart et al., 2015; Wei et al., 2016).

NGS-based transcriptomics and proteomics elucidate the molecular mechanisms underlying BCA modes of action, such as the production of antimicrobial compounds, stress responses, and interactions with both pests and host plants. These insights inform the development of improved strains and novel biocontrol products with enhanced efficacy and environmental safety (Leung et al., 2020).

8. NGS in Pest Surveillance and Early Warning Systems

Next-generation sequencing (NGS) technologies have transformed pest surveillance and early warning systems by enabling the rapid, sensitive, and simultaneous detection of a wide range of pests and pathogens. Unlike traditional monitoring methods, which are often organism-specific and labor-intensive, NGS allows for high-throughput sequencing of environmental DNA (eDNA) from sources such as air, water, soil, or bulk trap samples. This approach can detect DNA from multiple organisms—including insects, fungi, bacteria, and viruses—down to the species level, even when present at low abundance or in early stages of invasion (Mikko et al., 2025; Piper et al., 2019; Pochon et al., 2013; Nafea et al., 2024; Prasanna et al., 2024).

NGS-based surveillance offers several key advantages. It enables early detection of invasive or emerging pests before they cause significant damage, supports the identification of new or unexpected species, and allows for the monitoring of resistance genes and pathogen evolution (Mikko et al., 2025; Frey et al., 2022; Pochon et al., 2013; Nafea et al., 2024; Prasanna et al., 2024). For example, shotgun sequencing of airborne eDNA has been shown to correlate with observed crop damage, demonstrating its potential for real-time, large-scale monitoring of crop health and pest pressure (Mikko et al., 2025). DNA metabarcoding and metagenomics approaches can process hundreds of trap or environmental samples simultaneously, dramatically increasing the scale and efficiency of surveillance programs (Piper et al., 2019; Pochon et al., 2013; Prasanna et al., 2024).

Additionally, NGS can be applied to routine monitoring in agriculture, aquaculture, and public health, providing actionable data for early warning and targeted interventions. It is already being used for active surveillance in poultry farms, detection of marine invasive species, and tracking of plant and animal pathogens (Pochon et al., 2013; Afonso & Afonso, 2023; Prasanna et al., 2024). However, challenges remain, including the need for high-quality reference databases, specialized bioinformatics expertise, and cost considerations, but ongoing technological advances are making NGS increasingly accessible for routine surveillance (Mikko et al., 2025; Nafea et al., 2024; Prasanna et al., 2024).

9. Results and Discussion

The evolution of molecular approaches in agricultural entomology has moved from basic DNA markers to sophisticated genomics and gene-editing, greatly enhancing pest identification, monitoring, and management. These advances promise more sustainable, precise, and environmentally friendly agricultural practices. NGS applications provide powerful, detailed insights into gene flow, population structure, and local adaptation in agricultural insect pests.

Next-Generation Sequencing (NGS) technologies represent a major leap forward in genomics, enabling the rapid and simultaneous sequencing of millions of DNA or RNA fragments. Unlike traditional Sanger sequencing, which is slower and more limited in throughput, NGS platforms can generate vast amounts of data in a single run, providing detailed insights into genome structure, genetic variation, gene expression, and epigenetic modifications. NGS technologies are broadly categorized into short-read (second-generation) and long-read (third-generation) platforms. Short-read technologies, such as Illumina and Ion Torrent, are known for their high accuracy but are limited by the length of DNA they can sequence at once. In contrast, long-read technologies like Pacific Biosciences and Oxford Nanopore can sequence much longer DNA fragments, which helps resolve complex genomic regions, though historically with somewhat lower accuracy (Satam et al., 2023; Hu et al., 2021). These advances support more effective pest management and a deeper understanding of evolutionary processes in agroecosystems.

The versatility of NGS has expanded its applications across many fields, including clinical genomics, cancer research, infectious disease surveillance, and microbiome studies. NGS is used for whole-genome sequencing, targeted sequencing, transcriptome analysis (RNA-seq), and single-cell sequencing, among other applications. These technologies have enabled the development of precision medicine approaches, improved diagnostics, and a deeper understanding of biological processes. However, the massive data output from NGS also presents challenges in data storage, analysis, and interpretation, necessitating advanced bioinformatics tools and infrastructure. Ongoing advancements in NGS are focused on increasing speed, accuracy, and cost-effectiveness, as well as developing new algorithms for data analysis and expanding the range of applications in both research and clinical settings (Zhang et al., 2011; Slatko et al., 2018).

Next-generation sequencing (NGS) has revolutionized agricultural entomology and integrated pest management (IPM) by enabling high-resolution analysis of insect genomes, transcriptomes, and associated microbiomes. NGS has facilitated the identification of genes linked to insecticide resistance, pest adaptation, and host interactions, supporting the development of targeted and sustainable pest control strategies. The integration of genomic data with advanced gene-editing tools, such as CRISPR/Cas9 and RNA interference (RNAi), has opened new avenues for species-specific pest management, reducing reliance on chemical pesticides and minimizing non-target effects. These advances have also improved the understanding of ecological interactions and evolutionary dynamics within agroecosystems, contributing to more effective and resilient IPM programs. It has fundamentally reshaped agricultural entomology by providing unprecedented resolution for understanding insect diversity, population dynamics, microbial associations, and resistance evolution. Its capacity to generate large, highly informative genomic datasets enables more accurate species identification, deeper insight into cryptic diversity, and robust monitoring of invasive or outbreak-prone pests. In the context of Integrated Pest Management (IPM), NGS accelerates the discovery of molecular markers linked to insecticide resistance, host adaptation, and environmental stress responses, thereby informing more responsive and evidence-based management interventions. Furthermore, metagenomics and microbiome sequencing have expanded scientific understanding of insect–microbe–plant interactions, yielding novel targets for biological control and opportunities to manipulate microbial assemblages to suppress pests. Through these contributions, NGS has become a core technology supporting precision agriculture and more sustainable pest suppression strategies.

Despite these achievements, several challenges and opportunities for future research remain. The rapid accumulation of genomic and transcriptomic data has created a bottleneck in data analysis, highlighting the need for improved bioinformatics tools and standardized protocols. Expanding and curating reference databases will enhance the accuracy of species identification and functional annotation, which is especially important for non-model and newly emerging pest species. There is also a need to better integrate NGS data with ecological and evolutionary frameworks to predict pest dynamics and resistance development more effectively.

Future research should focus on developing more efficient and portable sequencing platforms, improving sample preservation and DNA extraction methods for field-collected specimens, and advancing gene-editing technologies such as CRISPR/Cas9 and RNA interference for species-specific pest control. Additionally, interdisciplinary collaboration and data sharing will be essential to maximize the impact of NGS in IPM. As sequencing technologies become more affordable and accessible, their integration into routine pest surveillance, early warning systems, and the development of novel biocontrol agents is expected to further enhance the sustainability and effectiveness of agricultural pest management (Li et al., 2019; Frey et al., 2022; Paula, 2021; Poelchau et al., 2016; Satam et al., 2023; Wachi et al., 2018).

Expanding the use of microbiome engineering also represents an emerging field. Manipulating symbiotic microbes—through targeted inoculation, paratransgenesis, or disruption of key microbial pathways—may offer species-specific, environmentally benign pest management tools. Continued work is also needed to leverage eDNA and environmental metagenomics for landscape-scale surveillance of pest communities, natural enemies, and pollinators. Additionally, research should focus on developing standardized reference genomes and curated databases for agriculturally relevant taxa, ensuring reproducibility, interoperability, and broader adoption of sequence-based diagnostics.

Finally, interdisciplinary collaboration between genomics, bioinformatics, ecology, and extension science will be critical. Knowledge transfer to farmers, regulators, and commercial biocontrol stakeholders must be strengthened to ensure that genomic discoveries translate effectively into actionable field practices. As sequencing costs continue to decline and analytical tools become more accessible, NGS is poised to become a routine component of integrated pest management programs, accelerating the transition toward data-driven and ecologically sustainable crop protection.

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CHAPTER 4

COMPARATIVE ANALYSIS OF LEAF MORPHOLOGY IN FOUR *QUERCUS* SPECIES

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1. INTRODUCTION

The genus *Quercus*, one of the most prominent and ecologically influential components of temperate-zone forests in the Northern Hemisphere, is notable for its wide distribution and high species diversity. Globally comprising more than 500 species, the main centers of diversification of this genus are the Sierra Madre Occidental of Mexico and East and Southeast Asia (Govaerts et al., 1998; Denk et al., 2017). The representation of approximately 250 species in the Americas and around 125 species in Asia and Malaysia, together with more limited yet ecologically critical populations in Europe, North Africa, and Macaronesia, reflects the complex biogeographic history of *Quercus* (Govaerts et al., 1998). Türkiye also constitutes an important center of diversity for this genus, hosting 18 native oak species (Yaltırık, 1984). The broad morphological and genetic variation observed in oaks is closely associated with weak reproductive barriers among many species (Bacilieri et al., 1995; Manos et al., 1999; Samuel, 1999). Extensive hybridization is commonly observed among species within the same section, and in many regions, species occur as mosaic-like mixed populations. While this pattern supports the high adaptive capacity of oaks, it also results in complex variation structures that complicate taxonomic classification. The ability of oaks to rapidly adapt to diverse climatic and edaphic conditions, together with their root system characteristics, leaf litter production, and contributions to soil organic matter cycling, has led to their recognition as "ecosystem engineer" species (McShea and Healy, 2002; Johnson et al., 2019). These functional roles within ecosystems place the genus *Quercus* in a critical position with respect to both biodiversity and forest dynamics. The extensive root systems of oak species and their litterfall processes, which enrich soil organic matter, make substantial contributions to the maintenance of nutrient cycling and soil fertility in forest ecosystems (Crow, 1988; Johnson et al., 2009). Therefore, the genus *Quercus* represents a fundamental component not only in terms of woody plant diversity but also in sustaining key ecosystem functions.

In the biogeographic regions of Europe, Anatolia, and the Caucasus, oaks constitute one of the principal components of forest cover. The phylogenetic and morphological diversity of *Quercus* species in Western Eurasia is of key importance for understanding the paleoclimatic history of the region and the evolutionary development of forest structure (Denk and Grimm, 2010). Anatolia is particularly notable for the dominance of oak species within maquis, pseudomaquis, and broadleaved forest formations. Similarly, the occurrence of different oak species across both humid and relatively dry microclimates in the Caucasus demonstrates the broad environmental tolerance of this genus (Yaltırık, 1984). Across Europe, oaks are regarded as structural elements of many forest types and play a major role in maintaining habitat diversity and continuity (Mölder et al., 2019).

Oaks also have strategic economic importance. Species such as *Quercus robur*, *Q. petraea*, and *Q. cerris* have long been preferred for furniture, veneer, construction, and shipbuilding due to their high-density, durable, and long-lasting wood. In addition, acorns represent one of the primary food resources for wildlife and directly influence the population dynamics of many mammal and bird species. Oak forests further provide critical habitats for a wide range of insects, fungi, and lichens, thereby making a strong contribution to biological diversity within forest ecosystems (Smallwood and Peters, 1986; Eaton et al., 2016). For these reasons, oaks represent one of the central tree groups in European and Western Asian forestry in terms of both economic value and habitat-enhancing functions.

In Türkiye, the genus *Quercus* constitutes one of the most important forest components in terms of both species richness and spatial extent. According to data from the General Directorate of Forestry, oak forests account for approximately 30% of the country's total forest area and exhibit a wide distribution (OGM, 2021). Extensive oak communities dominated by different species occur in Central Anatolia, the Aegean, Marmara, and Eastern Anatolia regions. Oak forests are of high silvicultural importance, particularly due to their functions in erosion control, regulation of water regimes, conservation of soil fertility, and provision of fuelwood in rural areas. Moreover, the difficulties encountered in species identification and the high degree of morphological variation among oaks in Türkiye render this group increasingly critical from both scientific research and applied forestry perspectives (Yaltırık, 1984; Kaya and Raynal, 2001; Atalay, 2014).

Oak species exhibit remarkable diversity in leaf morphology due to their broad ecological tolerances and high phenotypic plasticity. This variability represents a fundamental indicator both for taxonomic discrimination among species and for assessing the adaptive responses of populations to environmental conditions. Comprehensive morphometric studies on *Quercus petraea* and *Q. robur*, two widespread European species, have demonstrated that traits such as petiole length, lobe depth, sinus angles, and leaf width show statistically robust differences between the two species (Kremer et al., 2002). Similar studies conducted in Türkiye have likewise revealed that leaf shape and size ratios provide high discriminatory power for classification in species such as *Q. robur*, *Q. petraea*, *Q. frainetto*, and *Q. hartwissiana* (Borazan and Babaç, 2003).

One of the major factors complicating the taxonomy of the genus *Quercus* is the widespread occurrence of natural hybridization and introgressive individuals. The formation of hybrid zones in sympatric areas by many species renders the biological species concept controversial for this genus (van Valen, 1976) and leads to blurred morphological boundaries among taxa. In both Europe and Western Asia, the presence of individuals exhibiting intermediate traits of parental species clearly illustrates the role of hybridization in generating taxonomic uncertainty (Muir and Schlötterer, 2005; Curtu et al., 2007). Consequently, leaf characters are regarded as indispensable indicators for evaluating phenotypic variation and identifying hybrid individuals in oaks (Stace, 1989; Jensen et al., 1984).

In recent years, advances in morphometric approaches—particularly geometric morphometrics—have enabled high-resolution analyses of leaf shape, providing a powerful tool for both species delimitation and the identification of environmental adaptation patterns. Studies on Chinese oaks have demonstrated that geometric morphometrics achieves high classification accuracy in discriminating closely related species and reliably reveals shape variation associated with habitat differences (Viscosi et al., 2009; Liu et al., 2018). Research conducted on populations originating from geographically distinct regions has further confirmed the presence of significant variation in quantitative traits such as leaf length, width, and area, with populations from Azerbaijan providing a strong example of this pattern (Aliyeva et al., 2021). Morphometric analyses are also of critical importance for the detection of hybrid individuals; studies from European forests have reported the successful discrimination of hybrids using both classical and geometric metrics (Bruschi et al., 2000; Viscosi et al., 2009). Collectively, these findings demonstrate that leaf morphology constitutes a key tool in the genus *Quercus* for taxonomic discrimination as well as for elucidating hybridization processes and environmental adaptation mechanisms.

Oak species exhibit remarkable diversity in leaf morphology as a consequence of their broad ecological tolerances and high phenotypic plasticity. This variability serves as a fundamental indicator both for taxonomic discrimination among species and for evaluating the adaptive responses of populations to environmental conditions. Comprehensive morphometric studies on *Quercus petraea* and *Q. robur*, two widespread European species, have demonstrated that traits such as petiole length, lobe depth, sinus angles, and leaf width exhibit statistically robust differences between the two species (Kremer et al., 2002). Similar studies conducted in Türkiye have likewise shown that leaf shape and size ratios possess high discriminatory power for classification in species such as *Q. robur*, *Q. petraea*, *Q. frainetto*, and *Q. hartwissiana* (Borazan and Babaç, 2003).

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Nevertheless, studies on oak leaf morphology have largely focused on a limited number of species groups and, in Europe, have concentrated predominantly on the *Q. robur*–*Q. petraea* species pair. In regions with high species diversity such as Türkiye and the Caucasus, comprehensive morphometric studies comparing multiple oak species within a unified methodological framework remain scarce. Research conducted in Türkiye has likewise often been restricted to specific populations and therefore does not fully capture the broad species diversity present in the region (Borazan and Babaç, 2003).

The comparison of four ecologically and taxonomically important species—*Q. cerris*, *Q. hartwissiana*, *Q. petraea*, and *Q. robur*—within a single dataset addresses a clear gap in the existing literature. The majority of morphometric studies on oak leaves have focused primarily on leaf shape, outline, and size. Research based on geometric morphometric methods has demonstrated that leaf shape reflects interspecific differentiation with high resolution and is particularly effective in distinguishing sympatric species (Viscosi et al., 2009; Liu et al., 2018). However, the combined evaluation of functional traits such as vein angle alongside classical and geometric morphometric measurements remains rare. Vein angle may be considered a physiological indicator potentially associated with water transport, photosynthetic efficiency, mechanical stability, and growth orientation of the leaf. Therefore, the assessment of vein angle together with classical morphometric parameters such as leaf length, width, and area in these four oak species is expected to provide a valuable contribution to the literature. Given the high phenotypic plasticity and complex interspecific relationships within the genus *Quercus* (Denk and Grimm, 2010), such a comprehensive interspecific analysis is likely to yield important insights into both oak systematics and species-specific ecological adaptations.

The aim of this study is to compare the main morphological characteristics of leaves from *Quercus cerris*, *Q. hartwissiana*, *Q. petraea*, and *Q. robur* in order to elucidate structural differences among these species.

2. MATERIAL AND METHOD

The study was conducted on natural oak species located on the Kanuni Campus of Karadeniz Technical University (Figure 1). Accordingly, *Q. cerris*, *Q. hartwissiana*, *Q. petraea*, and *Q. robur* were selected as representative species. Leaf samples were collected at a minimum of 50 leaves per individual. The samples were taken from the outer, light-exposed portions of the tree crowns.

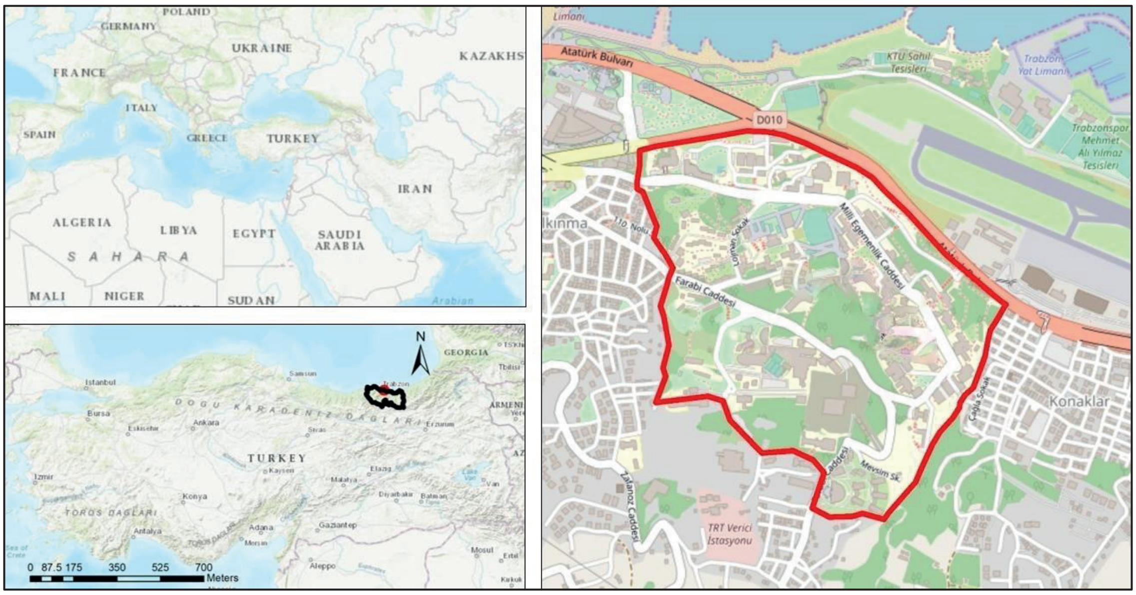

Figure 1. Geographical location of the study area

In this study, morphological traits including leaf length, leaf width, leaf area, leaf vein angle, and leaf shape index were measured. Leaf vein angle was obtained by measuring three different sections of the leaf, namely the basal, median, and apical parts. The ratio of leaf length to the corresponding leaf width was used to calculate the leaf shape index (Jeong et al., 2011; Wang and Zhang, 2012). Leaf samples were scanned at a resolution of 1200 dpi using a flatbed scanner (Hewlett-Packard Scanjet G4010). Subsequent measurements were performed using Image Analysis Software (ImageJ). This software has been widely applied in various scientific studies to analyze variation in leaf traits (Bayramzadeh et al., 2008; Atar, 2022).

The data were analyzed using the SPSS statistical software package version 26.0. For each species, descriptive statistical parameters were calculated to assess the degree of variation in each measured trait. Analysis of variance (ANOVA) was employed to determine whether statistically significant differences existed among species with respect to the measured morphological characters. In addition, Duncan’s multiple range test was applied to identify homogeneous groups.

3. RESULTS

Descriptive statistics and analysis of variance (ANOVA) results for leaf length, leaf width, leaf vein angle, leaf area, and leaf shape index of *Quercus cerris*, *Q. hartwissiana*, *Q. petraea*, and *Q. robur* are presented in Table 1.

Table 1. The results of analysis of variance and descriptive statistics concerning the values of leaf characteristics

Leaf Characters	Species	Mean	SD	SE	Minimum	Maximum	*P*-value (F)
LL (cm)	*Q. Cerris*	10.52	1.28	0.24	7.79	14.22	0.000 (F: 8.392)
	Q. hartwissiana	10.30	0.99	0.18	8.25	12.13	
	Q. petraea	11.70	1.13	0.22	9.33	13.89	
	Q. robur	10.42	1.17	0.24	8.27	12.44	
LW (cm)	*Q. Cerris*	5.72	0.90	0.17	4.31	8.21	0.036 (F: 2.955)
	Q. hartwissiana	5.93	0.73	0.13	4.47	7.40	
	Q. petraea	6.22	0.67	0.13	5.23	7.58	
	Q. robur	6.30	0.81	0.17	4.73	8.27	
LVA (°)	*Q. Cerris*	43.48	4.68	0.88	35.34	54.61	0.000 (F: 34.711)
	Q. hartwissiana	44.22	4.44	0.82	36.36	55.62	
	Q. petraea	35.69	3.63	0.71	28.38	41.28	
	Q. robur	48.05	4.78	0.99	36.92	56.63	
LA (cm^2)	*Q. Cerris*	32.95	8.42	1.59	22.63	60.80	0.000 (F: 16.840)
	Q. hartwissiana	40.86	6.96	1.29	26.05	55.57	
	Q. petraea	48.16	7.96	1.56	32.98	62.52	
	Q. robur	38.36	8.54	1.78	25.71	61.73	
LSI	*Q. Cerris*	1.85	0.22	0.04	1.48	2.32	0.000 (F: 7.161)
	Q. hartwissiana	1.75	0.19	0.03	1.39	2.19	
	Q. petraea	1.89	0.17	0.03	1.60	2.33	
	Q. robur	1.66	0.16	0.03	1.36	1.99	

LL: Leaf length, LW: Leaf width, LVA: Leaf vein angle, LA: Leaf area, LSI: Leaf shape index, SD: Standard deviation, SE: Standard error

The results indicate that statistically significant differences were detected among the oak species for all examined leaf morphological characters ($p < 0.05$). With respect to leaf length, the highest mean value was recorded in *Q. petraea* at 11.70 cm, with minimum and maximum values ranging from 9.33 to 13.89 cm. Mean leaf length was determined as 10.52 cm (7.79–14.22 cm) in *Q. cerris*, 10.42 cm (8.27–12.44 cm) in *Q. robur*, and 10.30 cm (8.25–12.13 cm) in *Q. hartwissiana*. The analysis of variance for this parameter was significant (F = 8.392; p < 0.001), indicating that *Q. petraea* was distinguished from the other species particularly in terms of both mean value and range of variation. In terms of leaf width, the highest mean value was measured in *Q. robur* at 6.30 cm, with values ranging between 4.73 and 8.27 cm. The mean leaf width was 6.22 cm (5.23–7.58 cm) in *Q. petraea*, 5.93 cm (4.47–7.40 cm) in *Q. hartwissiana*, and 5.72 cm (4.31–8.21 cm) in *Q. cerris*. These interspecific differences were found to be statistically significant (F = 2.955; p = 0.036), demonstrating that leaf width varies depending on species.

A pronounced differentiation among species was observed with respect to leaf vein angle, and differences for this trait were highly significant (F = 34.711; $p < 0.001$). The highest mean vein angle was recorded in *Q. robur* at 48.05°, with values ranging from 36.92° to 56.63°. The mean vein angle was 44.22° (36.36–55.62°) in *Q. hartwissiana*, 43.48° (35.34–54.61°) in *Q. cerris*, and markedly lower in *Q. petraea*, with a mean of 35.69° (28.38–41.28°). These results indicate that vein angle represents a highly discriminative morphological trait among the studied species.

Significant differences were also detected among species in terms of leaf area (F = 16.840; $p < 0.001$), with the highest mean value observed in *Q. hartwissiana* at 40.86 cm^2. This was followed by *Q. robur* (38.36 cm^2; 25.71–61.73 cm) and *Q. petraea* (38.16 cm^2; 32.98–62.52 cm), whereas *Q. cerris* exhibited the lowest mean leaf area at 32.95 cm² (22.63–60.80 cm). Such variation in leaf area may be interpreted as reflecting species-specific morphological responses to environmental conditions.

Regarding the leaf shape index (LSI), the highest mean value was recorded in *Q. petraea* (1.89), with values ranging from 1.60 to 2.33. Mean LSI values were 1.85 (1.48–2.32) in *Q. cerris*, 1.75 (1.39–2.19) in *Q. hartwissiana*, and 1.66 (1.36–1.99) in *Q. robur*. These differences were statistically significant (F = 7.161; $p < 0.001$), indicating that leaf shape constitutes a strong indicator for the morphological differentiation of oak species. Overall, all examined leaf morphological traits exhibited clear and significant variation among the oak species, demonstrating that these characteristics can be effectively used to reveal morphological and ecological differences among taxa. The results of the Duncan multiple range test, conducted to identify species groupings based on the examined leaf characters, are presented in Figure 2.

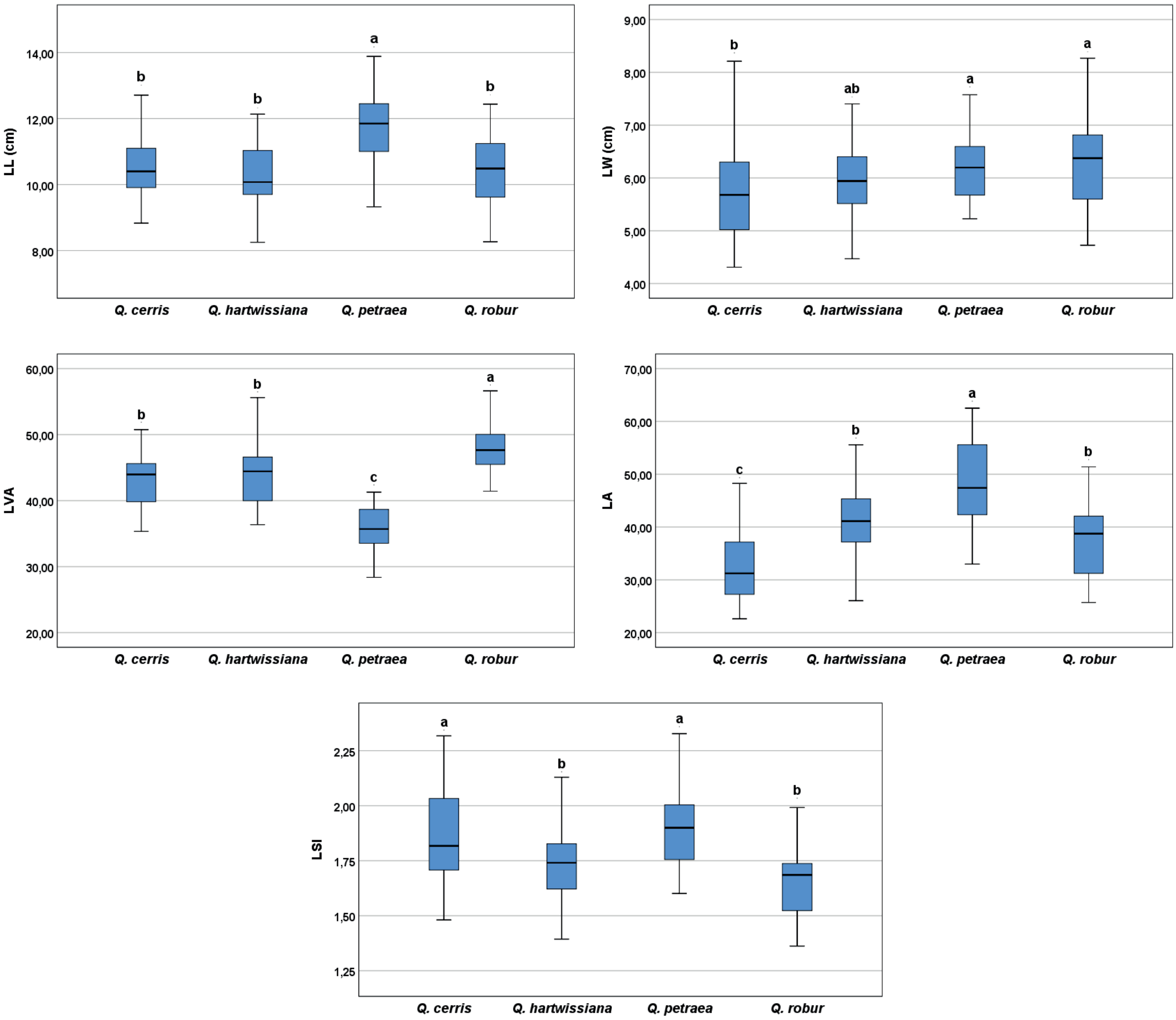

Figure 2. Duncan test results for leaf characters according to species

The results of Duncan's multiple range test presented in Figure 2 reveal clear and consistent groupings among the oak species with respect to the examined leaf morphological characters. For leaf length (LL), *Q. petraea* was statistically placed in the highest group (a), whereas *Q. cerris*, *Q. hartwissiana*, and *Q. robur* were grouped together (b), with no significant differences detected among these three species. This pattern indicates that *Q. petraea* is distinctly separated from the other species in terms of leaf length.

With respect to leaf width (LW), *Q. robur* and *Q. petraea* formed the highest group (a), while *Q. cerris* was assigned to a lower group (b). *Q. hartwissiana* occupied an intermediate position (ab), overlapping with both groups. This result suggests a gradual, rather than discrete, differentiation among species for leaf width. Species separation was more pronounced for leaf vein angle (LVA). *Q. robur* formed the uppermost group (a) with the highest values, whereas *Q. cerris* and *Q. hartwissiana* clustered together in an intermediate group (b). In contrast, *Q. petraea* constituted a distinct lower group (c) with the smallest vein angle values. This clear separation supports the use of vein angle as a strong morphological indicator for species discrimination. In terms of leaf area (LA), *Q. petraea* occupied the highest group (a), followed by *Q. hartwissiana* and *Q. robur* in an intermediate group (b), while *Q. cerris* was positioned in the lowest group (c). These results demonstrate that leaf area varies markedly among species. For the leaf shape index (LSI), Duncan test results indicated that *Q. cerris* and *Q. petraea* were grouped together in the upper group (a) with higher index values, whereas *Q. hartwissiana* and *Q. robur* formed a second group (b) characterized by lower values.

Overall, the Duncan test results corroborate the findings of the analysis of variance, indicating clear interspecific differentiation for parameters such as leaf length, vein angle, and leaf area, while leaf width and leaf shape index exhibit more gradual and overlapping groupings. This pattern suggests that the examined morphological characters differ in their discriminatory power for separating oak species.

4. DISCUSSION AND CONCLUSION

The genus *Quercus* is considered one of the most taxonomically complex tree genera due to weak reproductive barriers and widespread hybridization in sympatric distribution areas. This situation often results in indistinct morphological boundaries among species and considerable interspecific overlap (Bacilieri et al., 1995; Kremer and Petit, 1993). In this context, leaf morphology has long been used as a fundamental and practical tool for the discrimination of oak species; however, it has been emphasized that single characters are frequently insufficient, and that the combined evaluation of multiple morphological parameters provides more reliable results (Jensen et al., 1984; Kremer et al., 2002).

In the present study, *Q. cerris*, *Q. hartwissiana*, *Q. petraea*, and *Q. robur* differed significantly with respect to leaf length, leaf width, leaf vein angle, leaf area, and leaf shape index. In particular, the clear separation of *Q. petraea* from the other species in terms of leaf length indicates that this trait may serve as a strong indicator for species discrimination. Similarly, large-scale studies conducted across Europe have reported that leaf size–based distinctions between *Q. petraea* and *Q. robur* can be observed consistently across different geographical regions (Kremer et al., 2002). However, the partial overlap observed among species for certain traits, such as leaf width, suggests that these characters may be more sensitive to environmental factors and phenotypic plasticity.

Leaf vein angle emerged as one of the parameters providing the clearest interspecific separation in this study. The occurrence of wider vein angles in *Q. robur* and markedly narrower angles in *Q. petraea* indicates that this character conveys a distinct morphological signal for species differentiation. These findings are consistent with previous studies emphasizing the importance of venation patterns and leaf architecture in oak species discrimination (Viscosi et al., 2009; Borazan and Babaç, 2003). Viscosi et al. (2009), using geometric morphometric approaches, demonstrated that venation structure and leaf shape constitute strong components supporting interspecific differentiation.

The results obtained for leaf area also point to species-specific ecological strategies. The larger leaf areas observed in *Q. petraea* and *Q. hartwissiana* suggest that these species may have developed strategies aimed at enhancing light capture and increasing photosynthetic surface area. In contrast, the lower leaf area values recorded for *Q. cerris* indicate that this species may be adapted to different ecological conditions. Such interspecific differentiation in leaf area is consistent with studies emphasizing the influence of environmental conditions and local adaptation on leaf morphology in *Quercus* species (Bruschi et al., 2000; Yücedağ and Gailing, 2013).

Differences observed in the leaf shape index further indicate that species are differentiated in terms of leaf proportions and overall leaf architecture. However, the presence of overlapping values for this parameter in some species suggests that a single ratio-based trait may not be sufficient for reliable species identification. Indeed, Borazan and Babaç (2003) reported that characters related to leaf shape and size among white oaks may exhibit wide variation due to hybridization and gene flow, thereby necessitating the use of multivariate analyses.

The results of Duncan's multiple range test are consistent with the findings of the analysis of variance, showing that certain traits—particularly leaf length, vein angle, and leaf area—produce clearer groupings among species, whereas leaf width and leaf shape index display more gradual and overlapping patterns. This pattern aligns with the effects of hybridization and shared ancestral variation on morphological characters within the genus *Quercus* (Bacilieri et al., 1995; Yücedağ and Gailing, 2013), and further underscores the need to use multiple morphological indicators jointly rather than relying on single traits for species discrimination.

Overall, this study demonstrates that leaf morphological characters provide robust information supporting interspecific differentiation in oaks, while also showing that the overlaps observed in certain traits are a natural consequence of the well-documented genetic and ecological complexity of the genus *Quercus*. Therefore, species discrimination based on leaf morphology should involve the combined evaluation of as many characters as possible and, where appropriate, be supported by molecular data.

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CHAPTER 5

INSECT BIODIVERSITY IN A CHANGING WORLD: PATTERNS, DRIVERS, AND CONSERVATION CHALLENGES

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1. Introduction

Biodiversity, short for "biological diversity," refers to the total variety of living organisms, including plants, animals, fungi, and microorganisms, as well as the genetic differences within these species and the ecosystems they form (Linhares et al., 2022). It is a multidimensional concept, typically described at three main levels as genetic diversity, species diversity, an ecosystem diversity. There is no single, universally accepted definition or metric for biodiversity due to its complexity and the multiple levels at which it operates (Scheiner et al., 2025). While species richness (the number of species) is a common measure, comprehensive assessments also consider genetic, functional, and phylogenetic diversity (Scheiner et al., 2025).

Genetic diversity is the variation within species, including differences among individuals and populations (Linhares et al., 2022; Wani, 2024). Species diversity refers to the number and abundance of different species in a given area (Linhares et al., 2022; Spiridonov & Lovejoy, 2023; Wani, 2024;). And ecosystem diversity is the variety of habitats, communities, and ecological processes (Linhares et al., 2022; Jadhav et al., 2025; Wani, 2024).

Biodiversity is essential for ecosystem health, resilience, and the provision of ecosystem services such as food, clean water, air, climate regulation, and medicine (Linhares et al., 2022; Jadhav et al., 2025). High biodiversity supports robust, stable, and resilient ecosystems, which are crucial for human well-being and survival (Linhares et al., 2022; Jadhav et al., 2025). It Genetic diversity is variation within species, including differences among individuals and populations Species diversity means the number and abundance of different species in a given area Biodiversity is essential for ecosystem health, resilience, and the provision of ecosystem services such as food, clean water, air, climate regulation, and medicine (Linhares et al., 2022; Jadhav et al., 2025). High biodiversity supports robust, stable, and resilient ecosystems, which are crucial for human well-being and survival (Linhares et al., 2022; Jadhav et al., 2025). It encompasses the full range of life forms, their genetic makeup, and the ecosystems they create. It is vital for ecosystem function and human survival, but is currently threatened by human activities, making its conservation a global priority.

Insect biodiversity encompasses the diversity of all insect species, which make up more than half of all described animal species on Earth. Estimates suggest there are over one million described insect species, with total numbers (including undescribed and cryptic species) possibly reaching several million or even higher (Xu & Zhang, 2025; Sollai & Solari, 2022;). This diversity includes differences at the genetic, species, and functional levels, reflecting the wide range of adaptations insects have developed to thrive in nearly every habitat on the planet (Xu & Zhang, 2025; Sollai & Solari, 2022).

Insects are crucial for ecosystem functioning being the most diverse and abundant group of organisms on Earth. They act as pollinators, decomposers, pest controllers, and serve as food for many other animals. Their activities support nutrient cycling, plant reproduction, and the stability of food webs in terrestrial and freshwater ecosystems (Xu & Zhang, 2025; Sollai & Solari, 2022; Abirami et al., 2024). Insects also have significant economic and societal impacts, both positive (e.g., pollination, pest control) and negative (e.g., as pests or disease vectors) (Xu & Zhang, 2025; Sollai & Solari, 2022; Abirami et al., 2024). Insect biodiversity is measured by assessing species richness (the number of species), genetic diversity, and the variety of ecological roles (functional diversity) insects fulfill (Sollai & Solari, 2022; Wang et al., 2022). Studies show that insect diversity varies greatly across regions, habitats, and environmental conditions, with tropical forests and structurally complex habitats often supporting the highest diversity (Fan et al., 2024)

Despite their importance, much of insect biodiversity remains poorly known, especially among small-bodied and highly diverse groups. Many insect species are threatened by habitat loss, climate change, pollution, and other human activities, leading to concerns about widespread declines in abundance and diversity (Srivathsan et al., 2022). Conservation and further research are urgently needed to better understand and protect insect biodiversity (Millard et al., 2025).

On the other hand, recent studies have reported alarming declines in insect abundance, biomass, and diversity, raising concerns about increasing ecological consequences (Wagner, 2020). While these declines are uneven across species, regions, and ecosystems, collectively they suggest that insect biodiversity is under unprecedented pressure. Insect biodiversity is the foundation of terrestrial and many aquatic ecosystems, supporting ecological balance and human well-being, but it faces significant threats that require urgent attention.

This chapter synthesizes current knowledge on global patterns of insect biodiversity, the major environmental drivers affecting insect communities, and the emerging conservation priorities needed to safeguard this critical component of global biodiversity.

2. Global Patterns of Insect Biodiversity

Insect biodiversity is not evenly distributed across the globe; instead, it follows distinct spatial and environmental patterns. For example, studies in China have shown that south-western and south-eastern regions harbour higher insect biodiversity and contain many older evolutionary lineages, acting as "museums" of diversity, while north western regions have lower diversity and younger lineages, serving as "cradles" for new species. These patterns are strongly influenced by environmental factors. Higher mean annual temperature and precipitation generally increase insect diversity, while higher altitudes tend to decrease it. Human activities, such as cultivating diverse vegetation, can also enhance insect diversity in certain areas, and mixed forests often support high genetic diversity among insects (Fan et al., 2024; Li et al., 2021).

2.1.1. Spatial Patterns and Environmental Gradients

Insect diversity often peaks at low elevations and declines with increasing altitude, with temperature and seasonality being key drivers (Neves et al., 2024). In tropical regions, mountains can act as both "museums" (preserving old lineages) and "cradles" (generating new diversity), especially for groups like Hemiptera (Li et al., 2021; Neves et al., 2024). In grasshopper communities, for instance, species richness and diversity indices decrease significantly with increasing altitude, and these changes are closely linked to temperature, moisture, and soil properties (Li et al., 2024). In steppe ecosystems, insect diversity can show complex patterns, such as an "n-shaped" distribution along latitudinal gradients, and is influenced by climate, grazing intensity, and plant diversity (Song et al., 2023).

Structurally diverse habitats, such as heterogeneous forests or areas with varied vegetation, support higher insect richness and evenness compared to more uniform environments (Habel et al., 2021; Sinclair et al., 2024). Open, low-vegetation areas can be biodiversity hotspots for flying insects (Sinclair et al., 2024).

Intensive agriculture and urbanization generally reduce insect abundance and richness, especially when combined with climate warming. However, nearby natural habitats can buffer these losses, particularly in low-intensity agricultural systems (Outhwaite et al., 2022; Sinclair et al., 2024).

Insect richness is highest in tropical regions, particularly in rainforests, savannas, and mountainous areas with heterogeneous microhabitats (Basset et al., 2012). Coleoptera, Lepidoptera, Hymenoptera, and Diptera dominate species counts, although many lineages such as parasitoid wasps, fungus gnats, and soil-dwelling taxa remain poorly documented (Forbes et al., 2018).

Despite considerable progress, global insect diversity remains vastly underestimated. Recent estimates suggest that up to 5.5 million insect species may exist, although only about one million have been formally described (Stork, 2018). Under sampled habitats, including forest canopies, subterranean systems, and tropical soils, likely harbour the largest proportion of undiscovered taxa (Basset et al., 2012).

2.1.2. Temporal Patterns and Community Dynamics

Long-term monitoring programs have identified substantial declines in biomass and abundance across multiple ecosystems. For instance, a 27-year study from Germany reported a 75% reduction in flying insect biomass in protected areas (Hallmann et al., 2017). Meta-analyses indicate that freshwater insects show partial recovery or stability in some regions, while terrestrial insects remain in decline globally (van Klink et al., 2020).

Still, decline patterns are heterogeneous: some taxa (e.g., dragonflies, certain butterflies) recover with habitat restoration, while many specialists and endemic taxa continue to suffer (Wagner et al., 2021). Temporal variability emphasizes the need for standardized, long-term monitoring across regions and taxonomic groups.

Temporal patterns are also important. Insect richness, abundance, and biomass can remain stable or even increase over short periods in some habitats, but long-term trends may differ depending on environmental changes and habitat types. Habitat type, weather, and vegetation are major predictors of these temporal patterns (Gebert et al., 2023).

a. **Seasonal and Interannual Variation:** Insect communities show strong seasonal and year-to-year fluctuations in abundance, richness, and composition, often driven by climate variability and resource availability (Gebert et al., 2023; Baranov et al., 2020).
b. **Long-Term Trends:** While some studies report declines in insect diversity, others find stable or even increasing trends over short periods, highlighting the need for long-term, multi-taxa monitoring (Gebert et al., 2023; Baranov et al., 2020).
c. **Dominant Taxa:** A small number of insect families (especially within Diptera and Hymenoptera) consistently dominate local communities worldwide, despite high species turnover at the site level (Srivathsan et al., 2022; Sinclair et al., 2024).
d. **Functional Diversity:** Both taxonomic and functional diversity are influenced by landscape and climate factors, with functional diversity reflecting the range of ecological roles insects play (Liu et al., 2025; Song et al., 2023).

Table 1. Summary of major insect biodiversity patterns and their drivers.

Pattern/Driver	Main Findings	Citations
Elevation/Latitude	Richness peaks at low elevations, declines upward	(Engels et al., 2019; Li et al., 2021; Neves et al., 2024;)
Habitat Heterogeneity	Increases richness and evenness	(Sinclair et al., 2024; Habel et al., 2021)
Land Use & Climate Change	Reduce diversity, especially in tropics	(Outhwaite et al., 2022; Sinclair et al., 2024)
Dominant Families	20 families >50% of local diversity globally	(Srivathsan et al., 2022; Sinclair et al., 2024)
Temporal Turnover	High seasonal/interannual species turnover	(Gebert et al., 2023; Baranov et al., 2020)

Overall, insect biodiversity patterns are shaped by a combination of climate, habitat heterogeneity, elevation, human activities, and historical factors. Understanding these patterns is crucial for conservation planning and predicting how insect communities may respond to environmental changes (Fan et al., 2024; Zhao et al., 2023; Song et al., 2023; Li et al., 2021; Li et al., 2024).

3. Drivers of Change in Insect Biodiversity

3.1 Habitat Loss and Fragmentation

Habitat conversion, driven primarily by agriculture, urbanization, and forestry, is consistently identified as the strongest driver of insect decline (IPBES, 2019). Fragmentation reduces population connectivity, increases edge effects, and favours generalist species over specialists (Haddad et al., 2015). Monoculture expansion simplifies landscapes, reducing floral resources, nesting sites, and microclimatic heterogeneity needed by diverse insect communities. The reduction in total habitat area leads to lower species richness, abundance, and genetic diversity among insect populations, with these negative effects observed across a range of ecosystems and taxa (Multigner et al., 2025;). Habitat loss also disrupts ecological interactions, such as pollination and herbivory, which can have cascading consequences for ecosystem functioning (Ojija, 2024).

The effects of habitat fragmentation where remaining habitat is divided into smaller, more isolated patches are more nuanced and remain a subject of scientific debate. At the patch scale, fragmentation typically reduces local (α) diversity, especially in small or isolated patches, and can disrupt gene flow, leading to population declines and increased vulnerability to extinction (Perrin et al., 2025; Wang et al., 2024). Specialist species and those with poor dispersal abilities are particularly susceptible to these negative impacts (Wang et al., 2024; Rossetti et al., 2017). Fragmentation can also alter insect behaviour, such as increasing movement-related activities in search of suitable habitats, which may represent adaptive responses but can also reduce reproductive success (Marcantonio et al., 2023).

However, at the landscape scale, fragmentation can sometimes increase overall (γ) diversity by promoting species turnover (β-diversity) between patches, especially when the total amount of habitat remains high. This is because multiple small patches may support a greater variety of species across the landscape than a single large patch, due to differences in microhabitats and reduced competition (Perrin et al., 2025; Smith et al., 2024). Yet, when habitat amount is low, fragmentation tends to exacerbate biodiversity loss (Bosco et al., 2023).

Meta-analyses and systematic reviews indicate that the negative effects of fragmentation are generally more pronounced when combined with habitat loss, and that the relative importance of fragmentation versus habitat amount depends on spatial scale, species traits, and ecological context (Perrin et al., 2025; Ojija, 2024; Multigner et al., 2025; Rossetti et al., 2017; Bosco et al., 2023). Some studies suggest that habitat quality and total area are more critical than fragmentation per se for maintaining insect communities (Bosco et al., 2023).

In summary, habitat loss almost always reduces insect biodiversity, while the effects of fragmentation are context-dependent—negative at small scales or low habitat amounts, but potentially positive for landscape-level diversity when sufficient habitat remains. Conservation strategies should prioritize preventing habitat loss and maintaining connectivity, while also considering the value of both large and small habitat patches to support diverse insect communities (Perrin et al., 2025; Ojija, 2024; Multigner et al., 2025; Rossetti et al., 2017; Smith et al., 2024; Cardoso et al., 2020; Bosco et al., 2023).

3.2 Climate Change

Climate change significantly affects insect biodiversity through rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events. These changes have led to widespread declines in insect abundance and species richness, particularly in regions experiencing both climate warming and intensive land use, such as tropical areas. In these regions, insect abundance and diversity have dropped by nearly 50% and 27%, respectively, compared to less-disturbed habitats. However, the presence of natural habitats can help buffer some of these negative effects, especially in low-intensity agricultural landscapes (Outhwaite et al., 2022).

Long-term studies reveal that climate change can cause complex and sometimes nonlinear responses in insect communities. For example, a 42-year study of freshwater insects found an 81.6% decline in abundance, but also increases in species richness and diversity, as well as shifts in community structure and phenology, such as earlier and prolonged emergence periods. These findings highlight that climate change can simultaneously drive declines in some metrics while increasing turnover and diversity in others, depending on the context and timescale (Neff et al., 2022; Engelhardt et al., 2022).

Insects respond to climate change by shifting their geographic ranges, often moving to higher latitudes or elevations. Cold-adapted and habitat-specialist species are particularly vulnerable, while warm-adapted and generalist species may expand their ranges. These shifts can disrupt ecological interactions, such as pollination and food web dynamics, and may lead to the breakdown of mutualistic relationships, as seen in cases where heat-sensitive symbionts are lost (Engelhardt et al., 2022; Souza et al., 2024).

The severity of climate change impacts on insects is projected to increase with greater warming. Limiting global temperature rise to 1.5°C, rather than 2°C or higher, could reduce the number of insect species losing more than half their range by two-thirds, underscoring the importance of climate mitigation for insect conservation (Warren et al., 2018).

Overall, climate change is reshaping insect biodiversity worldwide, with effects that vary by region, habitat, and species traits. These changes threaten essential ecosystem services provided by insects, such as pollination and nutrient cycling, and highlight the urgent need for conservation strategies that address both climate change and habitat preservation (Outhwaite et al., 2022; Warren et al., 2018; Neff et al., 2022; Engelhardt et al., 2022; Souza et al., 2024).

3.3 Pesticides and Chemical Pollution

Pesticides directly reduce insect abundance and species richness by causing mortality, impairing development, and disrupting physiological and behavioral functions in both target and non-target species. Insects have experienced sharper declines in abundance and diversity than birds or plants, with some studies reporting up to a 76% decline in flying insects and a 78% decline in ground-foraging arthropods in areas of intensive pesticide use (Quandahor et al., 2024; Beaumelle et al., 2023). These chemicals also contaminate pollen, nectar, and nesting sites, leading to impaired foraging, reproduction, and colony health among pollinators such as bees and butterflies (Khan, 2025; Ojija & Bacaro, 2024). Sublethal exposures can reduce learning, navigation, and immune function increase disease susceptibility and further weaken populations (Feldhaar & Otti, 2020).

Indirectly, pesticides disrupt ecological interactions and food webs. Herbicides reduce plant diversity and floral resources, which in turn diminishes food availability for pollinators and natural enemies of crop pests. The loss of natural predators and competitors can trigger pest outbreaks, while aquatic insect communities are particularly vulnerable to pesticide runoff, with significant reductions in taxonomic richness and shifts toward more pollution-tolerant species (Ito et al., 2020; Stehle &

Schulz, 2015). Soil invertebrate diversity is also eroded, especially when multiple or broad-spectrum pesticides are used, threatening ecosystem health and nutrient cycling (Beaumelle et al., 2023).

Other chemical pollutants, such as heavy metals and industrial byproducts, further threaten insect biodiversity by causing lethal and sublethal effects, impairing immune systems, and increasing vulnerability to pathogens. These pollutants can interact with pesticides, amplifying negative impacts on insect health and community stability (Feldhaar & Otti, 2020; John et al., 2025). Chemical pollution from industrial waste, microplastics, and heavy metals also affects insect physiology and survival, though these impacts remain underexplored.

Pesticides and chemical pollution are among the most serious threats to insect biodiversity, causing widespread declines through direct toxicity, disruption of ecological interactions, and degradation of habitat quality. Reducing pesticide use, adopting integrated pest management, and mitigating chemical pollution are critical for conserving insect diversity and the essential ecosystem services insects provide (Quandahor et al., 2024; Khan, 2025; Beaumelle et al., 2023; John et al., 2025).

3.4 Invasive Species and Biological Interactions

Invasive alien insects and plants disrupt native insect communities through competition, predation, and habitat modification. Invasive insects often outcompete or displace native species by exploiting similar resources, leading to changes in community structure and sometimes local extinctions, especially as their introduced range expands (Fortuna et al., 2022; Kenis et al., 2008; Géron et al., 2023). Invasive plants can alter the availability and quality of resources for native insects, causing shifts in herbivore and pollinator communities, and sometimes reducing native insect abundance and diversity (Ojija, 2024). The introduction of invasive species can also trigger cascading effects, destabilizing food webs and ecosystem functions, particularly in isolated or species-poor environments such as islands (Géron et al., 2023).

Biological interactions including competition, predation, mutualism, and host-parasite relationships shape insect diversity and distribution. Invasive species can disrupt these interactions by introducing new competitors, predators, or pathogens, or by altering mutualistic relationships (e.g., pollination or symbiosis with microorganisms) (Fortuna et al., 2022; Kenis et al., 2008;). For example, invasive herbivores may interfere with native herbivore-natural enemy dynamics, diverting predators or parasitoids and weakening biological control processes (Fortuna et al., 2022; Kenis et al., 2008). Invasive species can also introduce novel pathogens, threatening the health and diversity of native insects. The complexity and strength of these interactions often determine the resilience or vulnerability of native insect communities to invasion and environmental change (Ojija, 2024).

Invasive species and altered biological interactions significantly impact insect biodiversity by reshaping community composition, disrupting ecological networks, and threatening ecosystem stability. Effective conservation requires understanding these dynamics and managing both invasive species and the integrity of native biological interactions (Ojija, 2024; Fortuna et al., 2022; Kenis et al., 2008; Géron et al., 2023).

3.5 Light and Noise Pollution

Light and noise pollution are increasingly recognized as significant drivers of insect biodiversity loss, particularly in urban and human-altered landscapes. Artificial light at night (ALAN) has emerged as a major concern, with mounting evidence that it disrupts insect populations at multiple levels. Meta-analyses and global reviews indicate that urbanization, which includes the proliferation of artificial lighting, results in substantial declines in insect abundance and species richness, estimated at 42% and 40% reductions, respectively, compared to conserved areas. These declines are not uniform across all insect groups or regions, but the overall trend is clear: ALAN interferes with critical behaviours such as development, movement, foraging, and reproduction, and can increase predation risk by making insects more visible to predators. The impact of ALAN is not limited to direct mortality; it also disrupts seasonal adaptations, such as diapause in moths, which is essential for overwintering survival. Even dim light, like skyglow, can prevent diapause induction, particularly in mid-latitude regions, making populations more vulnerable to decline. Furthermore, ALAN alters species interactions and community composition, with cascading effects on ecosystem functioning that extend beyond the illuminated areas themselves. The shift to broad-spectrum LED lighting, while energy-efficient, may exacerbate these impacts due to its spectral properties, and mitigation strategies such as dimming, shielding, and spectral modification are urgently needed to reduce harm to insect populations (Vaz et al., 2023; Merckx et al., 2023).

Noise pollution, though less extensively studied in the context of insects, is also emerging as a threat to insect biodiversity, especially among pollinators. Field studies have demonstrated a negative correlation between noise levels and pollinator diversity, with noisier urban sites supporting fewer pollinator species. Anthropogenic noise interferes with insect communication, mating, and foraging by masking or distracting from natural acoustic cues, which can alter species interactions and reduce individual fitness. Reviews of the literature highlight that while the effects of noise pollution on mammals, birds, and fish are well-documented, there is a notable research gap regarding invertebrates, including insects. Nevertheless, the available evidence suggests that noise pollution can disrupt ecological processes and contribute to the decline of insect populations, particularly in urban environments where multiple stressors often interact. The combined effects of light and noise pollution, along with habitat loss and fragmentation, can further hinder insect dispersal and metapopulation dynamics, increasing the risk of local extinctions (Franks & Farquhar, 2024; Classen-Rodríguez et al., 2021).

Both light and noise pollution are significant, though differently studied, contributors to the ongoing decline in insect biodiversity. Light pollution is a well-established driver, with robust evidence linking it to population declines, disrupted life cycles, and altered community structures. Noise pollution, while less thoroughly investigated in insects, shows clear negative effects on pollinator diversity and behaviour, warranting further research and immediate mitigation efforts. Addressing these forms of pollution is critical for conserving insect populations and maintaining the essential ecosystem services they provide (Classen-Rodríguez et al., 2021; Merckx et al., 2023; Vaz et al., 2023; Franks & Farquhar, 2024).

4. Conservation Challenges and Priorities

4.1 Improving Monitoring and Data Gaps

Addressing monitoring and data gaps in insect biodiversity requires a multifaceted approach that combines technological innovation, standardization, capacity building, and inclusive collaboration. Traditional insect monitoring methods, such as malaise traps, light traps, and visual surveys, have provided valuable long-term data but are often labour-intensive, taxonomically biased, and limited in spatial and temporal coverage. Recent advances in molecular techniques (e.g., DNA metabarcoding and megabarcoding), computer vision, autonomous acoustic monitoring, and radar-based remote sensing are revolutionizing the field by enabling large-scale, automated, and fine-grained monitoring of insect communities. Integrating these technologies—rather than developing them in isolation—can greatly improve taxonomic and spatio-temporal resolution, making it feasible to monitor insect biodiversity globally and in near real-time. However, to maximize their impact, these new methods must be harmonized with existing monitoring schemes and data standards to ensure compatibility and continuity with historical datasets, which are essential for tracking long-term trends (Van Klink et al., 2024; Penel et al., 2025).

A major challenge is the lack of data from the most biodiverse regions, particularly in the tropics and the Global South, where financial, infrastructural, and technical barriers are significant. To address this, there is a strong call for the development and deployment of frugal, accessible monitoring technologies—such as mobile phone-based identification apps, low-cost sensors, and simplified data collection protocols—that can be widely adopted in resource-limited settings. Building local capacity through training, community engagement, and the empowerment of local experts is crucial for sustainable monitoring efforts. International collaborations and equitable partnerships between the Global North and South can help bridge gaps in expertise, technology, and funding, while also ensuring that monitoring programs are contextually relevant and inclusive (Van Klink et al., 2024; Brydegaard et al., 2024).

Standardization and data sharing are also critical. The adoption of best practices and standardized protocols for sampling, metadata collection, and data management increases the interoperability and utility of insect biodiversity data. Digital tools, open-access databases (such as GBIF), and adherence to FAIR (Findable, Accessible, Interoperable, Reusable) data principles facilitate the aggregation, analysis, and dissemination of data across regions and disciplines. Citizen science initiatives, when integrated with expert-led surveys, can rapidly expand spatial and taxonomic coverage, as demonstrated in urban environments where combined efforts achieved near-complete species documentation in a short time. However, ensuring data quality and validation remains essential, and hybrid approaches that combine molecular, morphological, and image-based identification are recommended to minimize errors and biases (Zheng et al., 2025; Svenningsen & Schigel, 2024).

Finally, addressing data gaps requires sustained investment in taxonomy, monitoring infrastructure, and analytical capacity, especially in underrepresented regions. Policy frameworks should incentivize data sharing, support the development of global monitoring networks, and recognize the importance of insects in ecosystem functioning and conservation planning. Only through coordinated, inclusive, and technologically advanced strategies can the global community close the critical data gaps in insect biodiversity and inform effective conservation action (Van Klink et al., 2024; Brydegaard et al., 2024).

4.2 Protecting and Restoring Habitats

Protecting and restoring habitats are among the most effective strategies for conserving and enhancing insect biodiversity. These actions counteract the negative impacts of habitat loss, fragmentation, and degradation, which are primary drivers of global insect declines. Restoration of natural habitats such as forests, grasslands, and wetlands, promotes the recovery of insect communities by increasing habitat availability, structural complexity, and plant diversity. These factors provide essential resources and microhabitats for a wide range of insect taxa, supporting their abundance, diversity, and ecological functions such as pollination, decomposition, and pest control (Tudor et al., 2023; Lange et al., 2023; Dong et al., 2025). Studies show that restored landscapes can resemble reference (undisturbed) communities within a decade, with insect assemblages shifting from dominance by generalists to more specialized and functionally diverse groups as restoration progresses (Tudor et al., 2023; Lange et al., 2023). High plant diversity in restored areas accelerates the transition to native insect communities and stabilizes them over time (Lange et al., 2023). In agricultural and urban landscapes, the presence of nearby natural or semi-natural habitats mitigates the negative effects of land use and climate change, supporting higher insect abundance and species richness (Outhwaite et al., 2022; Ojija & Bacaro, 2024).

Landscape heterogeneity, variation in habitat types and structures, further enhances insect biodiversity by providing a mosaic of resources and conditions that support different species and functional groups (Tudor et al., 2023). Both large, well-connected patches and smaller, isolated patches contribute to overall diversity, with connectivity facilitating recolonization and gene flow among populations (Ojija, 2024; Perrin et al., 2025; Dong et al., 2025). Restoration efforts that reduce isolation and increase habitat complexity are particularly effective in fragmented landscapes, helping to buffer insect populations against local extinctions and environmental fluctuations (Perrin et al., 2025).

Protected areas play a crucial role as refuges for rare and threatened insect species, but their effectiveness depends on the inclusion of diverse habitat types and the management of key habitat features, such as microhabitats and floral resources. Many high-diversity habitats remain under-protected, highlighting the need to expand and better manage protected areas to cover critical insect habitats (Sinclair et al., 2024). Even small-scale interventions, such as planting wildflower strips or restoring verges, can locally boost pollinator abundance and diversity, especially when implemented at sufficient density across landscapes (Donkersley et al., 2023).

Protecting and restoring habitats, by increasing habitat area, diversity, and connectivity, are proven, scalable solutions for reversing insect declines and sustaining ecosystem services. These actions benefit not only insects but also broader ecological health and human well-being. Long-term success depends on integrating restoration with landscape planning, adaptive management, and the expansion of protected areas to encompass key insect habitats.

4.3 Reducing Chemical Inputs

Reducing the use of chemical inputs—especially synthetic pesticides and fertilizers—has a significant positive effect on insect biodiversity. Extensive research shows that the widespread application of pesticides is a primary driver of insect declines, leading to reduced abundance, species richness, and altered community structure across both terrestrial and aquatic ecosystems. Pesticides not only directly kill target pest species but also harm non-target insects, including pollinators, natural enemies of pests, and soil fauna, thereby destabilizing ecological networks and reducing the resilience of agroecosystems (Wan et al., 2025; Deynze et al., 2024). For example, large-scale studies in agricultural regions have linked increased pesticide use, particularly neonicotinoids, to substantial declines in butterfly and bee populations, with cascading effects on pollination and food webs (Deynze et al., 2024).

Reducing chemical inputs can slow or even reverse these declines. Studies indicate that lowering pesticide and fertilizer use is associated with increased abundance and diversity of beneficial insects, such as pollinators and natural enemies, and can promote the regrowth of declining groups like bees and butterflies (Quandahor et al., 2024). Sustainable management strategies, such as integrated pest management (IPM), organic farming, and diversification of crops and habitats, further enhance these benefits by reducing reliance on chemicals and supporting a more complex and stable insect community (Quandahor et al., 2024; Billaud et al., 2020). Additionally, reducing chemical inputs helps maintain soil health and the diversity of soil invertebrates, which are crucial for nutrient cycling and ecosystem functioning (Beaumelle et al., 2023).

However, the effects of reducing chemical inputs can vary depending on the degree of reduction and the specific context. Moderate reductions in fertilizer use may not significantly impact crop yields or insect diversity, but drastic reductions could affect productivity if not accompanied by other sustainable practices (Zou et al., 2024; Li et al., 2022). Intercropping and increasing habitat heterogeneity can compensate for lower chemical inputs by supporting natural pest control and enhancing insect diversity (Li et al., 2022). Overall, reducing chemical inputs is a key strategy for conserving insect biodiversity, sustaining ecosystem services, and promoting resilient agricultural landscapes (Quandahor et al., 2024; Beaumelle et al., 2023; Billaud et al., 2020; Deynze et al., 2024).

4.4 Addressing Climate Change and Increasing Resilience

Restoring insect biodiversity in the context of climate change requires urgent, coordinated action on multiple fronts. The decline of insects is driven by a combination of habitat loss, pollution, invasive species, climate change, and overexploitation, all of which are exacerbated by human activities. To address these challenges, scientists advocate for a global roadmap that includes immediate measures such as reducing greenhouse gas emissions, reversing agricultural intensification, and minimizing the use of synthetic pesticides and fertilizers. Transitioning to agro-ecological practices and promoting diversified, locally adapted land use can help create more resilient landscapes for insects. Increasing landscape heterogeneity and maintaining natural areas within agricultural and urban environments provide essential microhabitats, especially during extreme climatic events like droughts and heatwaves (John et al., 2024; Outhwaite et al., 2022).

Protecting and restoring natural habitats is fundamental for both climate mitigation and insect conservation. Preserving large, interconnected areas of natural habitat can buffer the negative impacts of climate change and intensive agriculture, supporting higher insect abundance and diversity. In landscapes where natural habitat is scarce, insect populations suffer greater declines, highlighting the importance of habitat connectivity and restoration efforts (Outhwaite et al., 2022; Reddy et al., 2025). Nature-based solutions, such as rewilding, urban greening, and ecological restoration, not only sequester carbon but also enhance ecosystem resilience and provide refuges for insects. These approaches should be integrated into broader climate and biodiversity policies to maximize co-benefits (Reddy et al., 2025).

Sustainable land management practices, including integrated pest management, organic farming, and reduced chemical inputs, are crucial for building resilience in insect populations. These strategies help maintain ecosystem services such as pollination and pest control, which are vital for food security and ecological stability. Additionally, fostering public awareness, education, and community engagement is essential for the success of conservation initiatives. Citizen science programs can enhance monitoring efforts and promote behavioral changes that benefit insect biodiversity (Reddy et al., 2025).

Finally, adaptive management and long-term monitoring are necessary to ensure that conservation strategies remain effective in the face of evolving climate and ecological conditions. Policymakers, scientists, and land managers must collaborate to implement evidence-based solutions, prioritize vulnerable species and habitats, and invest in research and capacity building. By taking these comprehensive actions, society can combat climate change, build resilience, and restore the rich diversity of insect life that underpins healthy ecosystems (John et al., 2024; Outhwaite et al., 2022; Reddy et al., 2025; Pörtner et al., 2023).

4.5 Public Engagement and Policy

Effective conservation of insect biodiversity requires both robust policy frameworks and meaningful public participation, organized in a way that integrates scientific knowledge, stakeholder interests, and community action.

Policies should be designed to specifically address the needs of insects, moving beyond a traditional focus on vertebrates. This involves developing species-specific action plans, expanding protected areas, and incorporating insects into broader biodiversity strategies. Policies must also set measurable and achievable conservation targets for insects, ensure regular monitoring, and adapt to new scientific findings. Importantly, policies should address the main drivers of insect decline—such as habitat loss, pesticide use, and invasive species—by promoting habitat connectivity, sustainable land use, and strict regulation of harmful practices. International conventions, national biodiversity strategies, and local action plans all play a role, but must be coordinated and inclusive of insect diversity across functional groups, not just charismatic pollinators (Duffus et al., 2023).

Public participation is essential for successful insect conservation. This can be achieved through educational programs that build action competence, empowering individuals and communities to take practical steps in their own gardens, neighborhoods, and workplaces. Citizen science initiatives, such as biodiversity monitoring and local conservation projects, allow the public to contribute valuable data and foster a sense of stewardship. Engaging stakeholders—including farmers, land managers, policymakers, and local authorities—in dialogue and decision-making ensures that diverse perspectives are considered and that conservation measures are practical and widely supported. Transdisciplinary approaches, where scientists, citizens, and policymakers collaborate, help bridge knowledge gaps and create solutions tailored to local contexts (Zheng et al., 2025; Egerer et al., 2024).

To overcome barriers to engagement, communication strategies should address knowledge gaps, misaligned values, and low self-efficacy. This includes using accessible language, highlighting the benefits of insect conservation, and providing clear calls to action. Community-based programs, outreach activities, and partnerships with NGOs can further mobilize public support and advocacy for policy change (Egerer et al., 2024).

In summary, organizing public participation and policies for insect biodiversity conservation requires integrating science-based policy, inclusive stakeholder engagement, targeted education, and community-driven action. This collaborative approach ensures that conservation efforts are effective, adaptive, and supported at all levels of society (Duffus et al., 2023; Egerer et al., 2024; Zheng et al., 2025;).

5. Conclusion

Insect biodiversity represents one of the most fundamental components of global ecosystems, shaping ecological networks, enabling energy flow, and sustaining essential ecosystem services that directly and indirectly support human well-being. Throughout this chapter, the evidence has made clear that insects are not merely the most species-rich group of organisms on Earth; they are also among the most functionally irreplaceable. Their taxonomic, genetic, and functional diversity is unparalleled, reflecting an evolutionary trajectory shaped by climatic variability, historical biogeography, habitat heterogeneity, and species interactions (Xu & Zhang, 2025; Sollai & Solari, 2022). Yet despite this ecological and evolutionary prominence, insect biodiversity is undergoing profound and multifaceted pressures that threaten its stability across nearly all biomes. Understanding these threats, and the patterns underlying them, is essential for developing conservation strategies capable of slowing and ultimately reversing biodiversity loss.

One of the key themes emerging from the synthesis of global literature is that insect biodiversity is structured by highly distinct spatial and temporal patterns. Richness tends to peak in regions with warm climates, high precipitation, and structurally complex habitats such as tropical forests and mountainous areas with varied microhabitats (Fan et al., 2024; Li et al., 2021). Altitudinal gradients consistently demonstrate declining richness with rising elevation, driven by temperature, seasonality, and resource availability (Neves et al., 2024; Li et al., 2024). Habitat heterogeneity, whether in forests, grasslands, wetlands, or agricultural mosaics, enhances both species richness and functional diversity (Sinclair et al., 2024; Habel et al., 2021). At the same time, insect assemblages exhibit strong seasonal and interannual variability, reflecting climate fluctuations, resource cycles, and disturbance regimes (Gebert et al., 2023; Baranov et al., 2020). These spatiotemporal dynamics underscore that insect biodiversity is far from static; instead, it is continually shaped by environmental gradients and historical contingencies that determine where species persist, diversify, or decline.

The global patterns summarized in this chapter also reveal that insect biodiversity is profoundly underestimated. With only about one million species formally described out of an estimated 5.5 million or more (Stork, 2018), the majority of insect diversity remains uncharacterized, particularly in hyperdiverse but understudied taxa such as parasitoid wasps, Diptera families, soil-dwelling microarthropods, and canopy specialists (Basset et al., 2012; Forbes et al., 2018). Vast numbers of species likely inhabit inaccessible or under-sampled habitats including forest canopies, subterranean systems, tropical soils, and freshwater springs (Basset et al., 2012). As a result, contemporary estimates of insect decline are inevitably conservative, given the absence of baseline data for many taxa and regions. This knowledge gap highlights the urgent need for expanded taxonomic research, enhanced monitoring networks, and large-scale integrative approaches that combine molecular, morphological, and ecological data (Van Klink et al., 2024; Penel et al., 2025). Without such efforts, many species may disappear before they are even discovered.

The drivers of change affecting insect biodiversity are diverse, interlinked, and overwhelmingly anthropogenic. Habitat loss and fragmentation remain among the most pervasive and damaging pressures. Conversion of natural ecosystems into agricultural, urban, or industrial landscapes reduces habitat area, simplifies vegetation structure, and disrupts ecological interactions (IPBES, 2019; Haddad et al., 2015). Habitat loss almost always results in declines in abundance, richness, and genetic diversity, with the most severe effects observed in specialist species and those with limited dispersal capacity (Wang et al., 2024; Rossetti et al., 2017). Fragmentation effects are more complex, sometimes reducing local diversity but increasing landscape-level β-diversity when total habitat area remains high (Perrin et al., 2025; Smith et al., 2024). When habitat amount is low, however, fragmentation exacerbates biodiversity loss (Bosco et al., 2023). The consistent message across studies is that habitat amount, quality, and connectivity are central determinants of insect persistence.

Climate change acts synergistically with habitat degradation. Insects are highly sensitive to temperature and precipitation patterns, and warming has already triggered shifts in phenology, distribution, and community structure (Engelhardt et al., 2022; Neff et al., 2022). Cold-adapted, montane, and specialist taxa are particularly vulnerable, while generalist and warm-adapted species may expand their ranges (Neves et al., 2024). Climate-driven disruptions extend beyond individual species, altering mutualistic relationships, trophic interactions, and food web stability. For example, changes in emergence timing and thermal tolerance can disrupt pollinator–plant interactions or destabilize predator–prey dynamics (Engelhardt et al., 2022). Extreme weather events—including heatwaves, droughts, and flooding—further intensify these stresses, often leading to rapid population collapses (Souza et al., 2024). Projections indicate that limiting warming to 1.5°C would prevent two-thirds of potential range losses for insects, emphasizing the urgency of climate mitigation (Warren et al., 2018).

Chemical pollution, particularly pesticides, represents another critical driver. Numerous studies have documented significant declines in insect abundance, richness, and reproductive success in association with pesticide exposure (Quandahor et al., 2024; Beaumelle et al., 2023). Neonicotinoids, pyrethroids, fungicides, and herbicides affect both target and non-target species, impairing foraging, navigation, immunity, and reproductive performance (Khan, 2025; Feldhaar & Otti, 2020). Pollinators are especially affected through contamination of pollen, nectar, and nesting substrates (Ojija & Bacaro, 2024). Aquatic insects face additional risks from pesticide runoff, which alters community composition and reduces taxonomic richness (Stehle & Schulz, 2015; Ito et al., 2020). Chemical pollutants, including heavy metals and industrial waste, further compromise insect health and interact with pesticides to amplify negative effects (John et al., 2025). Reducing pesticide use, diversifying cropping systems, and adopting integrated pest management and agroecological practices offer promising avenues to reverse these trends (Deynze et al., 2024; Billaud et al., 2020).

Invasive species and altered biotic interactions also contribute to insect biodiversity loss. Invasive insects and plants modify habitat structure, compete for resources, introduce novel pathogens, and disrupt ecological networks (Fortuna et al., 2022; Géron et al., 2023). These invasions often intensify in fragmented or degraded landscapes where native species are already weakened. Mutualisms involving pollinators, herbivores, and symbionts may break down when climate or land-use changes alter species distributions (Kenis et al., 2008). Such disruptions can destabilize food webs and reduce ecosystem resilience.

Light and noise pollution are increasingly recognized as emerging threats. Artificial light at night alters insect behavior, reproduction, dispersal, and diapause induction, often increasing predation pressure and disrupting ecological interactions (Merckx et al., 2023; Vaz et al., 2023). Even low levels of skyglow can interfere with nocturnal insects far from urban centers. Noise pollution, though less studied, has demonstrable effects on pollinator diversity and communication (Franks & Farquhar, 2024). These stressors often coincide with urbanization, compounding the impacts of habitat loss and climate change (Vaz et al., 2023).

Against this backdrop of complex and interacting drivers, conservation efforts must be multifaceted and grounded in robust scientific evidence. Monitoring remains a foundational challenge. Traditional methods—malaise traps, light traps, pitfall traps, and visual surveys—are invaluable but limited in spatial and taxonomic scope (Van Klink et al., 2024). High-throughput sequencing, metabarcoding, automated imaging, radar, and acoustic sensors promise unprecedented scalability and precision (Penel et al., 2025; Brydegaard et al., 2024). Yet these approaches require standardization, data integration, and global accessibility. Addressing gaps in the tropics and Global South is especially urgent, given these regions' disproportionate share of global insect diversity (Van Klink et al., 2024). Capacity building, equitable partnerships, and low-cost monitoring technologies are essential for inclusive biodiversity assessment (Brydegaard et al., 2024).

Habitat protection and restoration are central to conservation. Restoring structurally diverse habitats increases insect abundance, richness, and functional diversity, often enabling communities to resemble reference ecosystems within a decade (Lange et al., 2023; Tudor et al., 2023). Landscape heterogeneity and connectivity enhance resilience, enabling recolonization and gene flow (Perrin et al., 2025; Dong et al., 2025). Even small interventions—such as wildflower strips, hedgerows, and urban green pockets—can significantly support pollinators and beneficial insects when deployed at landscape scales (Donkersley et al., 2023). Protected areas, though essential, must be strategically expanded and effectively managed to include diverse habitat types important for insects (Sinclair et al., 2024).

Reducing chemical inputs is equally crucial. Studies show that declines in butterflies, bees, and other taxa can be slowed or reversed by decreasing pesticide use, diversifying crops, and improving soil health (Quandahor et al., 2024; Beaumelle et al., 2023). Agroecological approaches integrate ecological principles with farming practices, promoting resilient landscapes that support both biodiversity and food production (Li et al., 2022; Zou et al., 2024). These strategies benefit not only insects but entire agroecosystems.

In the context of climate change, enhancing habitat resilience is paramount. Natural and semi-natural habitats buffer populations against extreme events, while maintaining ecological corridors allows species to track shifting climatic niches (Outhwaite et al., 2022; Reddy et al., 2025). Nature-based solutions such as rewilding, wetland restoration, and urban greening offer co-benefits for carbon sequestration and biodiversity conservation (Pörtner et al., 2023). Adaptation strategies must incorporate long-term monitoring, adaptive management, and prioritization of vulnerable species and ecosystems.

Finally, conservation efforts must involve public engagement and policy integration. Public awareness, education, and citizen science initiatives expand monitoring capacity and foster stewardship (Zheng et al., 2025; Egerer et al., 2024). Policy frameworks should include insect-focused measures, regulate harmful chemicals, protect critical habitats, and integrate insects into biodiversity strategies at local, national, and global levels (Duffus et al., 2023). Transdisciplinary collaboration among scientists, policymakers, land managers, farmers, and communities, ensures that conservation strategies are both scientifically sound and socially feasible.

In summary, insect biodiversity is at a pivotal moment. It is simultaneously vast, essential, and deeply threatened. Yet the scientific knowledge, technological innovations, and conservation tools necessary to safeguard it are rapidly advancing. The challenge now is to integrate these insights into a cohesive global response that addresses both immediate threats and long-term systemic drivers of change. Protecting insect biodiversity is not solely a conservation goal; it is a prerequisite for sustaining the ecological processes that support life on Earth. Through coordinated action, informed policy, technological innovation, and inclusive collaboration, it remains possible to secure a future in which insect diversity continues to thrive and sustain the world’s ecosystems.

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CHAPTER 6

BREEDING OF NEW FISH SPECIES FOR STOCK ENHANCEMENT

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1. Introduction

The history of aquaculture dates to Ancient Egypt around 2500 BC. Tombstones depict people retrieving tilapia from ponds. Carp farming, practiced using traditional methods by the Chinese since 2000 BC, has spread to countries such as Malaysia, the Philippines, Cambodia, Thailand, and Vietnam. Fish farming in brackish water ponds in the Philippines and eel farming in Japan have very old roots (FAO, 1987). Carp farming in Europe was carried out within monasteries throughout the Middle Ages. The development of aquaculture began to gain momentum after WWII (Yayan, 2015). Breeding of many fish species and other aquatic organisms such as crustaceans in marine and inland waters has become widespread in many parts of the world with the development of production and feed technologies in aquaculture.

Seafood has significant social, economic, and environmental benefits in addition to being an important and healthy food source for humans. Aquaculture production creates new employment opportunities, migration from rural to urban areas is reduced, fisheries pressure on wild fish populations is reduced, certain types of wastewaters are purified through aquatic plants and mollusks, and negative impacts on nature are reduced through integrated and polyculture production (Bert, 2007).

The amount of fish caught from oceans, seas, and inland waters has been declining in recent years due to overfishing. Demand for seafood has steadily increased, at the same time aquaculture production has also increased accordingly. Aquaculture has been identified as the fastest-growing food production sector in the world by the Food and Agriculture Organization (Subasinghe et al., 2009). China is the world's largest aquaculture producer, and several Asian countries also rank among the top ten. Asian countries account for 90% of global aquaculture production (Tatlıdil et al., 2009). The development of the aquaculture sector and the continued increase in aquaculture production depend on increasing the number of cultured species, improving sector management and production systems, expanding the market, and optimizing regulations.

2. Global Aquaculture and Fisheries Production

It is generally accepted that sustainable production from fisheries worldwide will not exceed 100 million metric tons. However, a steady increase in production through aquaculture has also led to a sustained increase in total production despite the stagnation in fisheries (Çakmak et al., 2011). Production systems range from fisheries to aquaculture. They provide numerous environmental, economic, and social benefits and services, contributing to the sustainability of healthy diets and aquatic biodiversity globally.

The sales value of fisheries is $157 billion, and aquaculture is $296 billion in 2022 (FAO, 2024; URL-1; URL-2). According to the 2024 State of World Fisheries and Aquaculture (SOFIA) report by the Food and Agriculture Organization of the United Nations (FAO), aquaculture production surpassed fisheries production for the first time. The fisheries and aquaculture industry produced 223.2 million metric tons in 2022. Global aquaculture production reached 130.9 million metric tons. Today, a small number of countries dominate aquaculture production. The top 10 aquaculture producers account for approximately 90% of total production: China, Indonesia, India, Vietnam, Bangladesh, the Philippines, South Korea, Norway, Egypt, and Chile (FAO, 2024; URL-2).

There is a need to produce food more efficiently and responsibly due to limited resources. According to the FAO, aquaculture represents 17% of the world's animal protein intake. When comparing the ability of an animal to convert feed into meat, fish convert feed to meat at the highest rate (URL-3; URL-4; URL-5).

Increasing aquaculture production is essential to addressing food security and nutrition challenges. Global annual per capita consumption of seafood is projected to rise from 9.1 kg in 1961 to 20.7 kg in 2022. It is estimated that 89% of all aquaculture products are consumed directly, with the remainder consumed as inedible fish meal and fish oil. About 22% increase in current production is needed to maintain current per capita consumption of 20.7 kg by 2050 (FAO, 2024; URL-6).

Total aquaculture and fisheries production in Türkiye was 1.010.346 metric tons in 2023. Aquaculture production was 556.287 metric tons, and per capita seafood consumption was 7.2 kg. Seafood exports were recorded at $1,709,398,874 (BSGM, 2024). The increase in the amount of aquaculture products obtained in Türkiye every year has led to a significant increase in the amount of seafood exported. These exports have significantly contributed to the economy.

3. Importance of Alternative Fish Species Breeding

Rainbow trout, sea bream and sea bass are widely farmed in Türkiye. In addition, species such as tuna and mussels are also cultivated. Since the number of species produced in aquaculture is minimal, culturing new and alternative species is important for sustainability. One of the key elements of sustainable aquaculture production is increasing product diversity. If intensively farmed species create market saturation, the solution is to enter the market with alternative products. On the other hand, aquaculture plays a significant role in stock enhancement which is crucial for supporting the stocks of fish species facing extinction in wild and for ensuring the sustainability of fisheries.

3.1. Stock enhancement

Stock enhancement is the technique of releasing hatchery raised aquatic species into natural ecosystems to increase populations and support fisheries. This technique supports fish stocks, improves recreational and commercial fishing opportunities, and restores declining fish populations (URL-7). In this technique, aquatic organisms are cultivated under hatchery conditions and then released into the wild because of high mortality in the early stages of the life cycle. Survival rate can exceed 90% in hatchery conditions while survival is approximately 5% in the wild due to some natural factors such as floods, inundations, turbidity, predatory etc. (Aksungur et al., 2006).

The history of stock enhancement dates to the 1860s. Initially, studies focused on anadromous salmon in the Pacific. By the 1900s, efforts to establish coastal marine fish populations had become widespread. Increasing industrialization, urbanization, and intensive fishing, particularly between 1920 and 1940, negatively impacted stocks. The dramatic declines in fishing, known as the salmon crisis in 1947, led to the development of a series of measures (Lichatowich, 1999; Aksungur et al., 2006; Doremus & Frank, 2009). In Japan, approximately 15–20% of total annual fish production is achieved through the release of hatchery-based fish (Zengin, 2001). Fish are raised to smolt size and released into the sea at river mouths in Canada and the United States, while in Japan and Northern European countries, fish weighing 1 g or smaller, or smolt size, which are hatchery raised, are released into stream environment (Sedgwick, 1990).

The leading countries implementing stocking programs include Norway, Iceland, the United Kingdom, the United States, Canada, Japan, Denmark, Spain, Sweden, France, Ireland, and some countries in the Indo-Pacific region. Japan is a leader in this area, having conducted direct stocking and experimental studies on approximately 80 species (Zengin, 2010). The main species widely used in commercial breeding programs for stock enhancement around the world are *S. salar, O. Keta, O. kisutch, O. nerka*, *P. olivaceus*, *P. maxima*, *P. major*, *A. japonicus*, *S. quinqueradiata*, *G. morhua*, *M. cephalus*, *P. japonicus, M. ensisi, P. semiltacus*, *P. yassoensis*, *Haliotis sp*, *R. philippinarum*, *P. trituberculatus*. Of these species, 7 are salmon, 20 are marine fish and 25 are invertebrates (Salvanes, 2001).

Today, fish stocking enhancement are conducted to replenish depleted and collapsed natural stocks, to inoculate fish in areas where they are not yet available or in newly constructed ponds, to sport fishing, or to contribute to the regional economy. Stock enhancement can ensure the rational utilization of our inland water resources for aquatic products (Çakmak et al., 2010).

3.2. Stock Enhancement Practices in Türkiye

The first fish stock enhancement in Türkiye began with mosquitofish released into the marshes of Lake Amik by the French for biological control. In subsequent years, stock enhancements were followed by zander, carp, rainbow trout, pearl mullet, crucian carp, tench, and tilapia (Elp & Şen, 2006; Yılmaz et al., 2011). It is aimed to enrich the fish stocks of aquatic environments through stock enhancement studies carried out from time to time and periodically in the lakes, ponds, and dam lakes of Türkiye. These studies carried out by the General Directorate of State Hydraulic Works, the Ministry of Food, Agriculture and Livestock, and the National Parks units of the Ministry of Forestry have generally involved the stock enhancement of mirror and common carp to develop inland water fisheries. Some undesirable fish species such as *C. carassius*, *C. gibelio*, *P. paroa*, *L. gibbosus*, *A. boyeri* were also introduced into the environment during the stock enhancement of common carp. On the other hand, some economically important fish species such as *S. lucioperca*, *C. laveratus*, *T. tinca*, *T. zilli*, and *O. mykiss* have been deliberately introduced to some of natural lakes to increase lake productivity (Yılmaz et al., 2011).

The General Directorate of State Hydraulic Works carries out stock enhancement activities in the dam lakes and ponds under its responsibility. In addition, the Ministry of Agriculture and Forestry General Directorate of Fisheries and Aquaculture (BSGM) carries out stock enhancement activities in many natural lakes and dam lakes across Türkiye. A total of 5.540.000 juvenile carps were released to water bodies for stock enhancement in 28 provinces in 2002, this number was 6.085.000 in 60 provinces in 2017 (Table 1). A total of 79.840.000 juvenile carps were released for stock enhancement between 2002 and 2017 (Anonymous, 2018). 15.155.000 carp, 3.750.000 shabout, 65.000 sea bass, 20,000 sea bream, 15.000 meagre, 420.000 Tigris scraper and 1.000 grouper were released into water resources in 2020 (BSGM, 2021). 54.018.450 juvenile carps were released into 1.011 water bodies in 73 provinces in 2021 (BSGM, 2024).

Table **1.** *Fish stock enhancement of the Ministry of Agriculture and Forestry General Directorate of Fisheries and Aquaculture (Anonymous, 2018).*

Years	Number of provinces	Number of water sources	Number of fish
2002	28	200	5.540.000
2003	48	274	5.920.000
2004	57	338	6.000.000
2005	48	315	6.485.000
2006	49	317	6.550.000
2007	55	326	4.450.000
2008	56	330	4.730.000
2009	58	401	4.100.000
2010	58	451	5.150.000
2011	62	449	4.550.000
2012	39	498	3.500.000
2013	49	554	4.250.000
2014	32	328	4.030.000
2015	52	378	3.500.000
2016	55	541	5.000.000
2017	60	591	6.085.000
		Total	**79.840.000**

3.3. Aquaculture Studies in Türkiye

3.3.1. Black Sea Trout

Studies conducted by the Trabzon Central Research Institute of Fisheries aim to introduce Black Sea trout to the private sector. Stock management, feeding, and breeding have been implemented. The goal is to establish an infrastructure for breeding and selection (Çakmak et al., 2008).

3.3.2. Sturgeon

Sturgeon culture is successfully carried out in many countries, including Russia, the United States, Iran, France, Hungary, Bulgaria, Ukraine, and Azerbaijan. In these countries, some of the artificially produced fry are raised in ponds as food fish, while the majority are released into the wild to enrich fishing grounds and replenish natural stocks. Research studies on sturgeons aim to determine the genetic distribution of species on coasts and to establish broodstock stocks and conduct breeding in Türkiye. Commercial facilities are aiming to import broodstock and eggs from abroad for breeding purposes (Aksungur & Çakmak, 2008). Today, there are sturgeon farming facilities that produce commercial fish in Türkiye.

3.3.3. Bluefin Tuna

As carnivorous species, bluefin tuna feeds on species such as *A. alosa*, *S. aurita*, *C. harengus*, *S. japonicus*, *L. vulgaris*, and *S. officinalis*. Bluefin tuna began to be farmed in Japan in the 1970s and in some Mediterranean countries in the early 1990s. Since this fish is obtained from nature through fishery, the sustainability of production is possible with the continuous and balanced use of natural stocks. ICCAT (International Commission for the Conservation of Atlantic Tunas) is one of the leading international organizations established for this purpose. Unlike sea bream and sea bass, tuna farming is not carried out from the larval stage onwards, but rather by stocking and growing the captured fish. The farming activity is driven by demand from Japan, the most important market for this fish. Cage culture facilities were established in Croatia (6), in Australia (16), in Mexico and USA (5), in Spain (6), in Malta (4), in Morocco (2), in Japan (18) and in Türkiye (6). This migratory fish is intensively fished for rearing between Türkiye and Cyprus during April and May. Currently, purse seine fishing gear is used for wild-caught rearing. The caught tunas (~115 cm and 30 kg) are transferred to cages and stocked at 2–3 kg/m^3. They are fed with 5% of their body weight (sardines, anchovies, shad, mackerel) for 6–8 months and are marketed between November and January after gaining approximately 30% weight (Aksungur & Çakmak, 2008).

3.3.4. Turbot

The most comprehensive research in this area in Türkiye was conducted at the Trabzon Central Research Institute of Fisheries between 1998 and 2002. Approximately 30,000 fries were produced from turbot (*Psetta maxima*) breeding stock obtained through fishery in the Eastern Black Sea. In the research, useful results such as initial adaptation, growth and migration for the improvement of the decreasing turbot population were obtained. Proposals for a new management strategy for the rehabilitation of turbot stocks and fisheries along the Turkish Black Sea coast have been made (Zengin et al., 2006).

3.3.5. Greater Amberjack

It is widely cultivated, particularly in Japan and other Far Eastern countries. Because larval rearing is problematic, fry captured from the wild are raised in net cages. Semi-controlled rearing can be done in naturally occurring lagoons and similar areas (such as lagoons, ponds, etc.) near the coastline. In such areas, fries are raised entirely from natural habitats, and rearing occurs alongside other fish. In larval rearing, only 5 to 10% of the larvae survive until the end of the larval stage (Aksungur & Çakmak, 2008).

3.3.6. Flounder

In the study conducted by Aydın et al. (2013), adaptation to culture conditions, survival rate, feed intake and survival rate and growth according to sex of *Platichthys flesus luscus* caught from wild by bottom trawling were determined. In the first trial, survival rates declined rapidly in the first months, reaching 23.5% at the end of the 9-month trial. In the second trial, survival rates remained high for the first 3 months, reaching 11% for females and 19% for males at the end of the 11-month trial. Weight loss occurred during the first five months of adaptation, but as the fish adapted to the diet, they showed rapid growth. Despite high mortality rates, gonadal development was observed in the adapted fish.

3.3.7. Other Marine Fish Species

Studies and research are being carried out on different marine species through private sector-state cooperation in Türkiye, and some of the studied species are being produced commercially. Some of the species such as *S. aurata, D. labrax, A. regius, D. dentex, D. gibbosus, P. puntazzo, P. pagrus,* *S. pagrus, D. vulgaris, D. sargus, U. cirrosa, S. umbra, P. maxima, M. cephalus, L. mormyrus, S. dumerilii, Thunnus sp., E. aeneus, S. solea, B. barbatus* are produced at commercial level, while some are only studied at the level of adaptation of broodstock fish (URL-8). It may be difficult to obtain eggs from the broodstock of some species despite hormone application. On the other hand, techniques for larval period feeding need to be developed (Aksungur & Çakmak, 2008).

3.3.8. Trouts

In addition to the intensive marine fish farming in the Aegean and Mediterranean regions, rainbow trout production accounts for approximately half of aquaculture production. Along with rainbow trout farming, brown trout is one of the most widely distributed freshwater fish species in the region encompassing Europe, Asia, and North Africa. With its widespread distribution, brown trout has also been successfully introduced to regions where it is not naturally found (Baki et al., 2011).

Studies on the biology of brown trout, including egg production and the release of juveniles into the wild, were conducted at the Istanbul University Hydrobiology Institute in the 1950s, and at the General Directorate of National Parks of the Ministry of Forestry hatcheries with FAO support in the 1970s (Tatar, 1983; Okumuş, 2003). Brown trout, which is still commercially farmed in a few farms in Türkiye, has been cultivated and introduced to forest water resources since 2004 by the General Directorate of Nature Conservation and National Parks of the Ministry of Environment and Forestry to restore depleted natural trout stocks (Akkan, 2009).

3.3.9. *Capoeta sp.*

Gün & Kızak (2019) studied the adaptation of captured *Capoeta umbla* broodstocks to fish tanks for domestication and tested different substrates. A total of 320 fish were caught on October 2018 in Tatar Reservoir. At the end of study, the survival rates were recorded as 81.25%, 12.5% and 5% for earthen, sandy and artificial grass tanks, respectively.

Studies on the production possibilities of *C. umbla* for stock enhancement purposes were carried out on a project basis by the Elazığ Fisheries Research Institute, affiliated to the General Directorate of Agricultural Research and Policies of the Ministry of Agriculture and Forestry. A doctoral thesis was conducted within this project. In the thesis of Gün (2022), reproductive performance by hormonal induction, embryonic development of eggs, larval growth characteristics by applying different feeding protocols and growth characteristics of juvenile fish at different stocking densities were studied under controlled conditions for *C. umbla*. Two different induction agents (ovopel and ovaprim) were applied at different doses to ensure ovulation in broodstocks that have reached reproductive maturity. After the latent period, which lasted for about 3 days, the highest ovulated females were determined in the ovopel groups. It has been observed that ovaprim and ovopel can be used effectively to stimulate reproduction in *C. umbla*. Embryonic development took approximately 144 - 146 hours at 18-19ºC. The yolk-sac is finished in the 9th day. Feeding protocols that included live food gave better results. High stocking densities were found to be disadvantageous for growth of *C. umbla* fry. According to the results, the production of Tigris scraper is possible under controlled conditions by applying aquaculture techniques.

Figure **1.** *Male C. umbla (Original).*

Figure **2.** *Female C. umbla (Original).*

Figure **3.** *Tubercles on the male C. umbla (Original).*

Figure **4.** *Intramuscular injection of induction agent (Original).*

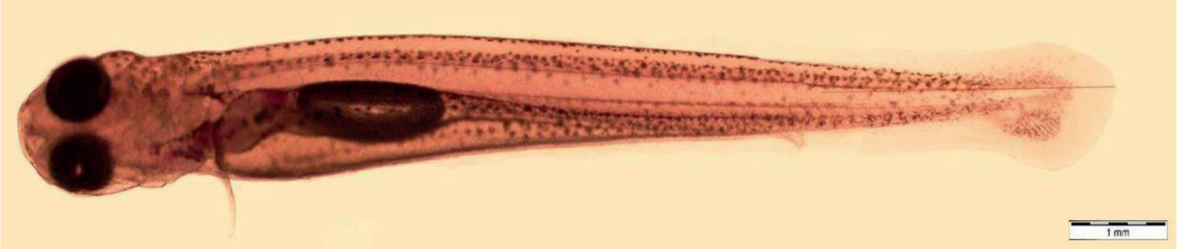

Figure **5.** *A 7-day-old C. umbla prelarva with partially consumed food sac (Original).*

Capoeta pestai is a Cyprinidae species endemic to Lake Eğirdir and of high economic value. Although this species is widespread in Lake Eğirdir, its population has rapidly declined due to excessive fishing pressure. Solutions to this problem can only be achieved through the implementation of aquaculture methods, which preserve and support the natural balance, reduce hunting pressure, meet nutritional requirements, and ensure production (Demir, 2017). The studies on *C. pestai* of the Eğirdir Fisheries Research Institute are carried out on a project basis and the studies are continuing.

3.3.10. Common Chub

Studies on common chub (*Squalius cephalus*) are being carried out on a project basis at the Elazığ Fisheries Research Institute, affiliated to the General Directorate of Agricultural Research and Policies of the Ministry of Agriculture and Forestry, and the studies are continuing.

3.3.11. Pike

The pike (*Esox lucius*) is Europe's most widely recognized carnivorous freshwater fish, playing a crucial ecological role in controlling various fish populations in natural waters. It is also a sportfishing species of considerable economic importance. However, pike populations are in significant decline in Europe and Türkiye due to overfishing pressure and the progressive degradation of natural breeding grounds (Szabo, 2008). Pike occurs naturally in rivers, lakes, and dam reservoirs in central and northern Türkiye and have high aquaculture potential. Advances in hormone treatments, artificial fertilization methods, and the understanding of pre- and postlarval stages make them a highly likely species for rearing in the coming years (Gökçek et al., 2011).

3.3.12. Catfish

Catfish is a fish of great importance in fisheries. It grows quickly, has a delicious meat, surpasses many other fish species in commercial value and is therefore adaptable to farming conditions. It is a species of great economic value both in the stock enhancement and in commercial fishing. Catfish must be given due importance both to protect fish stocks in natural waters and to effectively utilize the increasingly widespread aquaculture efforts (Yüngül & Dörücü, 2023).

3.3.13. Eel

Wild-caught elvers are grown and cultured in Italy, France, and Denmark. It has been determined that the fishing method has a significant impact on fish survival rates (Çakmak & Aksungur, 2008). Studies on the production possibilities of European and African eels are ongoing in studies conducted by the Mediterranean Fisheries Research, Production and Training Institute.

3.3.14. Anatolian minnow

The Eğirdir Fisheries Research Institute is conducting a project to investigate the production possibilities of the Anatolian minnow, to rear it as an alternative species, and to supplement natural stocks. This project explores the possibilities of introducing an alternative species to the inland aquaculture sector (Erbatur, 2016).

3.3.15. Shabout and Mangar

Studies on Shabout and Mangar were conducted by the Elazığ Fisheries Research Institute between March 2008 and October 2009 on *Luciobarbus esocinus* and *Barbus grypus* captured from Keban Dam Lake in Elazığ. Gonadosomatic index values were found to be at their highest in March and to decrease rapidly from this month onwards. Condition factor values were determined to increase up to age group V and to decrease after this age (Uslu, 2016).

4. Conclusion

Fisheries and aquaculture are crucial in meeting the animal protein needs of the rapidly growing global population. Fisheries production remains relatively constant, while the amounts vary from year to year. On the other hand, significant increases in fisheries cause harsh pressure on the natural fish stocks. Aquaculture production is rapidly increasing globally, but there has been only a slight increase in species diversity. To ensure the continued growth in the number of species produced through aquaculture, researchers must conduct further research on alternative species in aquaculture and introduce new species to the sector.

Fish stock enhancement in dam lakes located on the Euphrates and Tigris River systems, which are crucial for inland fisheries in Türkiye, should prioritize high-commercially valuable native species such as *Capoeta* sp., *A. grypus*, *L. esocinus*, *L. xanthopterus*, *L. mystaceus*, and *S. cephalus*. Furthermore, increasing the farming of commercially important omnivorous fish species can significantly contribute to sustainable aquaculture. Aquaculture practices with omnivorous species are more economical, environmentally friendly, and ecologically sound than those with carnivorous species.

As a result, in any external intervention into ecosystems, it would be appropriate to seek the opinion of experts on the subject. A strategy for the implementation of fish stock enhancement programs and the establishment of scientific monitoring committees is of high importance.

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CHAPTER 7

CLIMATE CHANGE IMPACTS ON FISH POPULATIONS

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Introduction

Climate change is increasingly recognized as one of the most pervasive and transformative forces affecting aquatic ecosystems and the human societies that depend on them. Driven primarily by anthropogenic greenhouse gas emissions, climate change has resulted in sustained increases in global air and ocean temperatures, altered precipitation and hydrological regimes, ocean acidification, and widespread deoxygenation of marine and freshwater systems (IPCC, 2021; Pörtner et al., 2021). These changes are occurring at rates unprecedented in the recent geological past, challenging the adaptive capacity of biological systems and undermining the ecological foundations of fisheries and aquaculture worldwide.

Fisheries and aquaculture occupy a central position at the interface of environment, economy, and food security. Globally, aquatic foods provide more than 3.3 billion people with at least 20% of their average animal protein intake and are a critical source of essential micronutrients, including omega-3 fatty acids, iron, zinc, and vitamin A (Golden et al., 2016; FAO, 2022). The sector supports the livelihoods of nearly 60 million people directly and many more indirectly through processing, trade, and associated services, with small-scale fisheries playing a particularly important role in low- and middle-income countries (Allison et al., 2009; FAO, 2022). Consequently, climate-driven disruptions to fisheries and aquaculture have far-reaching implications for nutrition, poverty alleviation, and sustainable development.

Aquatic ecosystems are inherently sensitive to climate change because key physical and chemical properties of water, temperature, oxygen solubility, stratification, and carbonate chemistry, are tightly coupled to biological processes (Pörtner & Peck, 2010; Deutsch et al., 2015). Fish and invertebrates are ectothermic organisms whose metabolic rates, growth, reproduction, and survival are strongly temperature dependent. Even modest shifts in thermal regimes can therefore alter individual performance, population dynamics, and species interactions, with cascading effects on ecosystem structure and productivity (Poloczanska et al., 2016; Pörtner et al., 2017).

Over the past two decades, a rapidly expanding body of empirical, experimental, and modeling research has documented clear biological responses to climate change across marine and freshwater systems. Observed impacts include poleward and depth-related shifts in species distributions, changes in phenology, altered growth and recruitment patterns, increased frequency of disease outbreaks, and reorganization of food webs (Perry et al., 2005; Poloczanska et al., 2013; Free et al., 2019). These ecological responses are already influencing fisheries yields, economic performance, and management outcomes in many regions, underscoring that climate change is not a future threat but a present-day driver of change (Barange et al., 2018; Pinsky et al., 2018).

Climate change also interacts strongly with other anthropogenic stressors, particularly fishing pressure, habitat degradation, and pollution. Overfishing reduces population size, age structure, and genetic diversity, thereby lowering resilience to climate variability and extremes (Berkeley et al., 2004; Hsieh et al., 2006). Habitat loss and degradation, including destruction of coral reefs, mangroves, and freshwater wetlands, further constrain the ability of fish populations to adapt or shift distributions in response to changing environmental conditions (Barbier et al., 2011; Roberts et al., 2017). These cumulative impacts highlight the need to consider climate change within a broader framework of multiple stressors affecting aquatic ecosystems.

From a socio-economic perspective, climate change introduces new dimensions of risk and uncertainty into fisheries governance. Many management systems are based on historical baselines and assume relatively stable relationships between environmental conditions, stock productivity, and harvest levels, assumptions increasingly violated under climate change (Planque et al., 2010; Pinsky & Mantua, 2014). Climate-driven redistribution of fish stocks across national boundaries challenges existing allocation agreements and raises issues of equity, access, and international cooperation

(Blasiak et al., 2017; Pinsky et al., 2018). These challenges are particularly acute for small-scale fisheries and climate-vulnerable regions, where adaptive capacity is limited and dependence on aquatic resources is high (Allison et al., 2009; Bennett et al., 2021).

Despite the growing recognition of climate change as a major driver of change in fisheries and aquaculture, significant gaps remain in our understanding of mechanisms, cumulative impacts, and effective responses. While large-scale models provide valuable insights into potential future trajectories, uncertainties persist regarding how physiological stress translates into population-level outcomes, how multiple stressors interact, and how governance systems can adapt to non-stationary conditions (Pörtner et al., 2017). Addressing these gaps requires integrative, interdisciplinary approaches that link climate science, ecology, economics, and social sciences.

The objective of this chapter is to provide a comprehensive synthesis of current scientific knowledge on the potential impacts of climate change on fish populations, with a particular emphasis on mechanisms, population-level responses, and socio-economic consequences. Drawing on scientific literature, global assessments, and synthesis reports, the chapter examines how physical and chemical changes in aquatic environments affect fish populations.

Physical and Chemical Drivers of Climate Change in Marine and Freshwater Systems

Climate change affects fisheries fundamentally through alterations in the physical and chemical properties of marine and freshwater environments. Unlike many terrestrial systems, aquatic ecosystems are tightly governed by temperature-dependent processes, gas solubility, stratification dynamics, and biogeochemical cycles, making them particularly sensitive to climate forcing (Pörtner & Peck, 2010; IPCC, 2021). Three interrelated drivers, warming, ocean acidification, and deoxygenation, are now recognized as the dominant climate-mediated stressors shaping contemporary and future aquatic ecosystems and fisheries (Pörtner et al., 2014; Breitburg et al., 2018).

These drivers do not operate in isolation. Instead, they interact across spatial and temporal scales, producing complex and often non-linear biological responses. Understanding their mechanistic foundations is essential for linking climate change to observed and projected impacts on fish physiology, population dynamics, ecosystem structure, and fisheries productivity (Deutsch et al., 2015; Pörtner et al., 2017).

The global climate system has warmed unequivocally, with aquatic systems absorbing the majority of excess heat generated by anthropogenic greenhouse gas emissions. The ocean alone has taken up more than 90% of the additional heat accumulated in the Earth system since the mid-20th century, leading to widespread warming of surface and subsurface waters (IPCC, 2021; Cheng et al., 2022). Mean sea surface temperatures have increased by approximately 0.88°C since 1900, with accelerated warming observed over the past four decades (IPCC, 2021).

Warming is spatially heterogeneous. Tropical oceans exhibit relatively small absolute temperature increases but experience disproportionately large biological impacts because resident species often live close to their upper thermal limits (Deutsch et al., 2015; Sunday et al., 2017). In contrast, high-latitude and polar regions are warming at rates two to four times the global average, driving rapid physical and ecological transformations (Fossheim et al., 2015; IPCC, 2021). Freshwater systems, including lakes and rivers, are also warming rapidly, often exceeding local air temperature trends due to changes in ice cover, hydrology, and land use (O’Reilly et al., 2015; Woolway et al., 2020).

Temperature exerts a dominant influence on fish physiology because fishes are ectotherms whose metabolic rates increase exponentially with temperature (Pörtner & Farrell, 2008). Warming elevates maintenance metabolism, increasing energetic demands for survival and reducing the energy available for growth, reproduction, and immune function (Pörtner et al., 2017). These effects are commonly conceptualized through the framework of oxygen- and capacity-limited thermal tolerance, which links thermal limits to constraints on aerobic performance (Pörtner & Peck, 2010).

At sublethal temperatures, warming can accelerate growth and development up to an optimum, beyond which performance declines sharply due to limitations in oxygen supply, enzyme function, and cellular stability (Deutsch et al., 2015; Pörtner et al., 2017). Chronic exposure to elevated temperatures reduces aerobic scope, impairs cardiac performance, and increases vulnerability to additional stressors such as hypoxia and disease (Farrell, 2007; Sandblom et al., 2016).

Physiological stress induced by warming propagates upward to population and ecosystem levels. Elevated temperatures often reduce body size at maturity, shorten lifespan, and alter reproductive schedules, contributing to declines in population productivity (Daufresne et al., 2009; Audzijonyte et al., 2020). These changes can reduce fisheries yields by lowering biomass production and increasing interannual variability (Free et al., 2019).

Warming also restructures ecosystems by altering species interactions and food-web dynamics. Differential thermal sensitivities among predators, prey, and competitors can modify trophic transfer efficiency and destabilize established community structures (Dell et al., 2013; Poloczanska et al., 2016). At larger scales, warming drives poleward and depth-related range shifts, reshaping regional species assemblages and redistributing fisheries resources across jurisdictions (Perry et al., 2005; Pinsky et al., 2013).

Ocean acidification results from the absorption of anthropogenic carbon dioxide (CO_2) by seawater. Since the industrial revolution, the global ocean has absorbed approximately 25-30% of emitted CO_2, leading to a decrease in average surface ocean pH of about 0.1 units, a 30% increase in hydrogen ion concentration (Doney et al., 2009; IPCC, 2021). Continued emissions are projected to cause further declines in pH, with particularly rapid changes in high-latitude and upwelling regions (Orr et al., 2005; IPCC, 2021).

Acidification alters the carbonate system by reducing the availability of carbonate ions required for calcium carbonate formation. While early research focused on calcifying organisms, it is now clear that acidification also affects non-calcifying taxa, including fishes, through multiple physiological and ecological pathways (Heuer & Grosell, 2014).

Fish regulate internal acid–base balance through ion exchange mechanisms in gills and other tissues. Elevated CO_2 levels challenge this regulatory capacity, leading to increased energetic costs and potential disruptions to neural and sensory function (Heuer & Grosell, 2014). Laboratory experiments have demonstrated that acidification can impair olfaction, auditory processing, and behavior in fish larvae and juveniles, with consequences for predator avoidance, habitat selection, and survival.

Acidification can also affect growth, development, and aerobic performance, particularly when combined with warming or hypoxia (Pörtner et al., 2014; Boyd et al., 2018). Although species-specific responses are common, evidence suggests that early life stages are especially sensitive, raising concerns about recruitment success under future ocean conditions (Frommel et al., 2012 2013, 2014; Baumann & Doherty, 2013).

At ecosystem scales, acidification influences food-web structure by affecting plankton communities, benthic habitats, and trophic interactions (Doney et al., 2012; Kroeker et al., 2013). Changes at the base of the food web can propagate to higher trophic levels, altering energy transfer efficiency and fisheries productivity (Pörtner et al., 2017).

For fisheries, acidification poses particular risks to shellfish-dependent systems and mixed fisheries where early life stages of fish overlap with acidification hotspots (Cooley & Doney, 2009; Kroeker et al., 2013). The interaction of acidification with warming and deoxygenation further complicates projections, as combined stressors can produce synergistic impacts exceeding those of individual drivers (Boyd et al., 2018; Pörtner et al., 2021).

Deoxygenation is an increasingly prominent consequence of climate change, driven by reduced oxygen solubility in warmer water, enhanced stratification that limits vertical mixing, and altered nutrient dynamics that promote eutrophication (Breitburg et al., 2018; IPCC, 2021). Since the mid-20th century, global oceanic oxygen inventories have declined by approximately 2%, with much larger losses observed in coastal zones and oxygen minimum zones (Stramma et al., 2012; Breitburg et al., 2018).

Freshwater systems are similarly affected, with warming, nutrient runoff, and altered hydrology contributing to widespread hypoxia in lakes, reservoirs, and rivers (Jenny et al., 2016; Woolway et al., 2020). These trends are projected to intensify under continued climate change.

Oxygen availability directly constrains aerobic metabolism in fishes. Hypoxia reduces aerobic scope, limits activity, and forces trade-offs between maintenance, growth, and reproduction (Claireaux & Chabot, 2016; Pörtner et al., 2017). Many species respond behaviorally by avoiding low-oxygen habitats, leading to habitat compression and increased overlap with predators or fishing gear (Prince & Goodyear, 2006; Stramma et al., 2012).

Chronic or repeated hypoxia exposure can impair growth, reduce reproductive output, and increase mortality, particularly when combined with warming (Deutsch et al., 2015; Breitburg et al., 2018). These effects disproportionately affect large-bodied and highly active species with high oxygen demands, contributing to shifts in community composition (Pauly & Cheung, 2018).

Deoxygenation alters population dynamics by reducing suitable habitat volume, increasing density-dependent interactions, and elevating vulnerability to fishing (Breitburg et al., 2018). Habitat compression can lead to higher catchability even as populations decline, masking stock depletion and increasing the risk of overfishing (Prince & Goodyear, 2006; Pörtner et al., 2017).

At ecosystem scales, expanding hypoxic zones restructure food webs by excluding sensitive species and favoring hypoxia-tolerant taxa, often reducing biodiversity and ecosystem resilience (Stramma et al., 2012; Breitburg et al., 2018). These changes have profound implications for fisheries productivity, stability, and management.

A defining feature of climate change in aquatic systems is the co-occurrence and interaction of warming, acidification, and deoxygenation. These drivers are mechanistically linked and often act synergistically, intensifying physiological stress and ecological disruption (Pörtner et al., 2014; Boyd et al., 2018). For example, warming increases metabolic oxygen demand while simultaneously reducing oxygen supply, exacerbating hypoxia stress (Deutsch et al., 2015).

Multi-stressor experiments and synthesis studies demonstrate that combined exposure frequently produces non-additive effects, including reduced tolerance limits, altered energy allocation, and increased mortality (Boyd et al., 2018; Pörtner et al., 2021). These interactions challenge single-stressor management approaches and highlight the need for integrated frameworks that consider cumulative climate impacts.

In summary, warming, ocean acidification, and deoxygenation represent the primary physical and chemical pathways through which climate change affects aquatic ecosystems and fisheries. These drivers operate through well-established physiological mechanisms that scale up to influence population dynamics, ecosystem structure, and fisheries productivity. Their interactions amplify impacts and increase uncertainty, underscoring the need for mechanistic, multi-stressor approaches in climate-fisheries science and management.

Impacts of Climate Change on Fish Populations

Climate change influences fish populations through a suite of interconnected mechanisms operating across physiological, demographic, spatial, and evolutionary scales. Changes in temperature, oxygen availability, and carbonate chemistry alter individual performance, which in turn affects growth, reproduction, survival, and ultimately population dynamics. These biological responses are further shaped by species interactions, habitat constraints, and fishing pressure, resulting in complex and often non-linear population-level outcomes (Pörtner et al., 2017).

Understanding population responses is central to assessing climate impacts on fisheries because population productivity, resilience, and spatial structure determine the amount of biomass available for harvest and the stability of yields over time (Barange et al., 2018; Free et al., 2019). Fish growth reflects the balance between energy intake and metabolic expenditure, both of which are strongly temperature dependent. Warming generally increases metabolic rates, raising maintenance costs and reducing the fraction of assimilated energy available for somatic growth (Deutsch et al., 2015). While moderate warming can enhance growth up to a species-specific thermal optimum, chronic exposure to elevated temperatures typically leads to reduced growth efficiency and smaller adult body size (Daufresne et al., 2009; Audzijonyte et al., 2020).

Empirical analyses across marine and freshwater systems show consistent declines in mean body size with increasing temperature, a pattern often referred to as the temperature-size rule (Daufresne et al., 2009). Smaller body size has important population-level consequences because fecundity, competitive ability, and survival often scale nonlinearly with size (Barneche et al., 2018). As a result, warming-induced size reductions can lower population reproductive output and productivity even when abundance remains unchanged.

Warming-induced increases in metabolic demand interact strongly with oxygen availability to constrain growth. As temperature rises, oxygen solubility declines while metabolic oxygen demand increases, reducing aerobic scope and limiting growth potential (Deutsch et al., 2015; Pörtner et al., 2017). Hypoxia further exacerbates these constraints, particularly in stratified coastal and freshwater systems where oxygen depletion is already pronounced (Breitburg et al., 2018).

Growth suppression under combined warming and hypoxia has been documented in multiple species, with consequences for age-at-maturity, size structure, and cohort strength (Claireaux & Chabot, 2016; Pauly & Cheung, 2018). These bioenergetic constraints represent a key mechanistic link between climate change and reduced population productivity.

Reproduction is particularly sensitive to temperature because gametogenesis, spawning timing, and embryonic development occur within narrow thermal windows (Pörtner et al., 2017). Elevated temperatures can disrupt endocrine regulation, reduce gamete quality, and shorten spawning seasons, leading to declines in reproductive output (Donelson et al., 2014).

In exploited populations, increased recruitment variability complicates management by undermining the predictability of stock–recruitment relationships and increasing the risk of overfishing during periods of low productivity (Planque et al., 2010; Pinsky & Mantua, 2014). Shifts in spawning phenology have been widely observed, with many species spawning earlier in the year in response to warming (Poloczanska et al., 2016). While phenological shifts may initially maintain synchrony with environmental conditions, they can also increase the risk of mismatch between larval stages and prey availability, particularly under rapid or unpredictable climate change (s).

Early life stages, eggs, larvae, and juveniles, are often the most climate-sensitive phases of the life cycle. Elevated temperature, acidification, and hypoxia can increase mortality, reduce growth, and impair sensory and swimming performance during these stages (Houde, 2008; Frommel et al., 2012; Baumann & Doherty, 2013). Because recruitment variability is a dominant driver of population dynamics in many fish species, small changes in early life-stage survival can have disproportionate effects on adult population size (Houde, 2008).

Climate change may also alter the spatial and temporal overlap between larvae and suitable nursery habitats, further influencing recruitment success (Planque et al., 2010; Peck et al., 2013). These processes contribute to increased interannual variability in recruitment and greater uncertainty in population trajectories under climate change.

Long-term time series reveal that climate variability can synchronize recruitment fluctuations across populations, reducing the buffering effect of spatial heterogeneity and increasing the risk of regional-scale population declines (Hsieh et al., 2006; Anderson et al., 2013). Climate change is expected to intensify this synchronization by increasing the spatial coherence of temperature anomalies and extreme events (Free et al., 2019).

One of the most robust biological responses to climate change is the redistribution of fish populations in space. Numerous studies document poleward and depth-related shifts in species distributions as fish track suitable thermal and oxygen conditions (Perry et al., 2005; Pinsky et al., 2013). Average poleward shifts of marine species exceed 50 km per decade, with faster rates observed in rapidly warming regions (Poloczanska et al., 2013).

Depth shifts are also common, particularly in demersal species that move into deeper, cooler waters to avoid thermal stress (Dulvy et al., 2008; Baudron et al., 2020). These shifts alter habitat use, exposure to fishing gear, and interactions with other species, reshaping population dynamics and fisheries catch composition.

Deoxygenation and warming can compress suitable habitat vertically and horizontally, forcing fish into narrower depth ranges or coastal corridors (Prince & Goodyear, 2006; Stramma et al., 2012). Habitat compression increases density-dependent interactions, intensifies predation pressure, and often elevates catchability, creating the illusion of stable or increasing abundance even as populations decline (Pörtner et al., 2017; Breitburg et al., 2018).

For fisheries, habitat compression can mask stock depletion and increase the risk of overexploitation, particularly when management relies on catch-based indicators rather than independent abundance estimates (Prince & Goodyear, 2006; Free et al., 2019).

Climate change reshapes prey-predator interactions by differentially affecting the physiology, behavior, and distribution of interacting species (Gilman et al., 2010; Dell et al., 2013). Warming can increase metabolic demand and feeding rates of predators while simultaneously reducing prey availability or size, altering energy flow through food webs (Pörtner et al., 2017).

Temporal and spatial mismatches between predators and prey can further destabilize population dynamics, either weakening trophic interactions or intensifying predation pressure depending on the direction of change (Durant et al., 2007; Thackeray et al., 2016).

As species redistribute, communities undergo turnover, with warm-adapted species replacing cold-adapted taxa in many regions (Engelhard et al., 2014; Fossheim et al., 2015). This reorganization can alter trophic structure, reduce mean body size, and change ecosystem functioning, often with implications for fisheries yields and stability (Daufresne et al., 2009; Audzijonyte et al., 2020). Novel species assemblages may lack coevolutionary history, leading to unpredictable interactions and increased variability in population dynamics (Williams & Jackson, 2007).

Population resilience depends on life-history diversity, spatial structure, and genetic variation. Climate change erodes these attributes by truncating age structure, synchronizing dynamics, and reducing habitat availability (Hsieh et al., 2006; Anderson et al., 2013). Overfishing exacerbates these effects by selectively removing large, fecund individuals that buffer recruitment variability (Berkeley et al., 2004; Barneche et al., 2018).

Reduced resilience increases the likelihood of abrupt population declines and slows recovery following disturbance, particularly under continued climate stress (Pörtner et al., 2017; Free et al., 2019).

Fish populations may respond to climate change through phenotypic plasticity and evolutionary adaptation, but both processes have limits. While short-term acclimatization can buffer moderate change, rapid warming may exceed plastic capacity, particularly in long-lived or slowly reproducing species (Donelson et al., 2012; Seebacher et al., 2015).

Evolutionary adaptation depends on genetic diversity and effective population size, both of which are often reduced in exploited populations (Hutchings & Fraser, 2008; Hoffmann & Sgrò, 2011). Climate-driven changes in connectivity can further constrain adaptation by disrupting locally adapted gene complexes (Selkoe et al., 2015).

Species with narrow thermal tolerance, specialized habitat requirements, or restricted geographic ranges face elevated extinction risk under climate change (Sunday et al., 2012; Comte & Olden, 2017). Freshwater fishes are particularly vulnerable due to limited dispersal opportunities and strong dependence on hydrological regimes.

Climate change increasingly interacts with overfishing, habitat loss, and pollution to drive cumulative risk, emphasizing the need for integrated conservation and management approaches (Barange et al., 2018; IPBES, 2019).

In synthesis, climate change affects fish populations through interconnected impacts on growth, reproduction, recruitment, distribution, species interactions, and resilience. These population-level responses underpin observed and projected changes in fisheries productivity and stability. By increasing variability, reducing resilience, and reshaping spatial structure, climate change challenges traditional assumptions of fisheries sustainability and underscores the need for climate-informed management.

Climate-driven changes in fish populations translate directly into impacts on fisheries yields, economic performance, and food security. Because fisheries operate at the interface between ecological productivity and human demand, even modest biological changes can propagate rapidly through markets, livelihoods, and nutrition systems (Barange et al., 2018; Free et al., 2019). Climate change therefore reshapes not only where and how fish are caught, but also who benefits from fisheries and who bears the costs of environmental change.

Fisheries yields are determined by the productivity, spatial distribution, and accessibility of fish populations, all of which are sensitive to climate change (Pörtner et al., 2017). Warming, deoxygenation, and acidification affect growth rates, recruitment success, and mortality, thereby altering stock biomass and sustainable harvest levels (Stock et al., 2011; Deutsch et al., 2015). These effects operate alongside fishing pressure, often amplifying the consequences of exploitation when productivity declines (Free et al., 2019).

Process-based global models consistently project declines in maximum sustainable yield (MSY) under continued warming, particularly in tropical regions where species already operate near thermal limits (Cheung et al., 2010; Barange et al., 2018). Even where total biomass does not decline sharply, shifts toward smaller body sizes and lower trophic levels can reduce the economic and nutritional value of catches (Pauly & Cheung, 2018; Audzijonyte et al., 2020).

One of the most significant climate impacts on fisheries yields is the redistribution of catch potential across latitudes. Projections indicate substantial declines in tropical catch potential, often exceeding 20-40% by mid-century under high-emissions scenarios, while some temperate and polar regions may experience short-term gains as species shift poleward (Cheung et al., 2010; Free et al., 2019).

Empirical observations already confirm these trends, with fisheries in high-latitude regions gaining access to new species, while tropical fisheries experience declining abundance and diversity (Pinsky et al., 2013; Fossheim et al., 2015). These changes challenge existing management systems and exacerbate global inequities, as regions most dependent on fisheries often face the largest losses (Allison et al., 2009; Barange et al., 2018).

Beyond changes in mean yield, climate change increases interannual and decadal variability in fisheries production. Marine heatwaves, hypoxia events, and anomalous circulation patterns can cause abrupt recruitment failures or mass mortality, leading to sudden declines in catches (Oliver et al., 2018; Smale et al., 2019).

Increased variability undermines predictability, complicating harvest planning and increasing the risk of overfishing during low-productivity periods (Planque et al., 2010; Pinsky & Mantua, 2014). Fisheries that lack responsive management frameworks are particularly vulnerable to these shocks, which can erode long-term sustainability even when average yields appear stable (Anderson et al., 2013).

As fish stocks shift geographically, economic benefits and losses are redistributed among countries and fishing sectors. Nations at higher latitudes may gain access to valuable stocks, while tropical and developing countries face disproportionate economic losses (Cheung et al., 2010; Blasiak et al., 2017). These shifts challenge historical allocation agreements and raise questions of fairness and compensation.

Transboundary and highly migratory stocks are particularly affected, as climate-driven redistribution can destabilize cooperative management arrangements and increase the risk of conflict (Spijkers & Boonstra, 2017; Pinsky et al., 2018). Without adaptive governance, economic competition over shifting resources may undermine sustainability and international cooperation.

Small-scale fisheries are especially vulnerable because they often rely on local stocks, have limited access to capital, and lack the capacity to follow shifting species distributions (Béné, 2006). Climate impacts on fisheries therefore have profound social consequences that extend beyond economics to affect cultural identity and community cohesion.

Climate-driven declines in fisheries productivity threaten nutritional benefits by reducing availability, increasing prices, or shifting consumption toward less nutritious alternatives (Golden et al., 2016). These impacts are particularly concerning in regions already facing malnutrition and limited dietary diversity. Projected declines in nearshore fisheries productivity in tropical regions could reduce per capita fish consumption, exacerbating micronutrient deficiencies and increasing health risks, particularly for women and children (Golden et al., 2016). These outcomes highlight the intersection of climate change, food security, and social justice.

Climate change raises fundamental questions of equity and justice in fisheries. Regions that have contributed least to global emissions often face the greatest losses in fisheries productivity and food security (Allison et al., 2009; Barange et al., 2018). At the same time, some high-latitude nations may benefit from shifting stocks, highlighting asymmetries in climate impacts and adaptive capacity. Addressing these inequities requires governance frameworks that incorporate climate justice principles, support vulnerable communities, and promote fair allocation of benefits and burdens (Blasiak et al., 2017; Bennett et al., 2021). International cooperation and climate finance mechanisms will be essential for enabling adaptation in the most affected regions.

Conclusion

In conclusion, climate change reshapes fisheries yields, economic performance, and food security through interconnected ecological and socio-economic pathways. Declines and redistribution of productivity, increased variability, and heightened uncertainty challenge traditional fisheries management and exacerbate global inequities. These impacts underscore the need for adaptive, inclusive governance and integrated food-system approaches that link fisheries sustainability with nutrition and social well-being.

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