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Climate change impacts on forest and soil ecosystems: Microbial responses, carbon cycling, and future perspectives

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ABSTRACT: Global climate change is profoundly altering the structure and functioning of forest ecosystems by modifying temperature and precipitation regimes, increasing the frequency of extreme climatic events, and disrupting soil biological processes. This review synthesizes current knowledge on the impacts of climate change on forest and soil ecosystems, with particular emphasis on soil microbial communities, microbial biomass, microbial processes, nutrient cycling, and carbon sequestration. Relevant findings from recent international studies, together with regional observations and climate projections for Türkiye and the Mediterranean Basin, were critically evaluated to identify current knowledge and future research priorities. The reviewed evidence indicates that rising temperatures, prolonged drought, and altered precipitation patterns modify soil moisture, pH, organic carbon inputs, and nutrient availability, resulting in substantial changes in microbial diversity, community composition, and ecosystem functioning. Climate-induced disturbances, including wildfires, pest outbreaks, and vegetation shifts, further accelerate carbon losses and reduce ecosystem resilience, particularly in Mediterranean forests that are highly vulnerable to environmental stress. The review also highlights that microbial responses differ among forest types according to vegetation characteristics, stand age, soil properties, and topographic conditions. Overall, the evidence highlights soil microbial functioning as a key component linking climate stress to forest productivity, nutrient cycling, and carbon sequestration. Long-term monitoring and multidisciplinary approaches integrating climatic, vegetation, soil, and microbial processes are therefore needed to improve predictions and support adaptive forest and land-management strategies under future climate scenarios.

Keywords: Climate change; forest ecosystems; soil microbial communities; carbon sequestration; forest resilience

İklim değişikliğinin orman ve toprak ekosistemleri üzerindeki etkileri: Mikrobiyal tepkiler, karbon döngüsü ve gelecek perspektifleri

ÖZET: Küresel iklim değişikliği, sıcaklık ve yağış rejimlerini değiştirerek, aşırı iklim olaylarının tetikler ve toprak biyolojik süreçlerini bozarak orman ekosistemlerinin yapısını ve işleyişini derinden değiştirmektedir. Bu derleme, iklim değişikliğinin orman ve toprak ekosistemleri üzerindeki etkilerine ilişkin mevcut bilgileri, özellikle toprak mikrobiyal toplulukları, mikrobiyal biyokütle, mikrobiyal süreçler, besin döngüsü ve karbon tutulumu üzerinde durarak sentezlenmektedir. Son uluslararası çalışmalardan elde edilen bulgular, bölgesel gözlemler ve Türkiye ve Akdeniz Havzası için iklim projeksiyonlarıyla birlikte, mevcut bilgileri ve gelecekteki araştırma önceliklerini belirlemek için eleştirel olarak değerlendirilmiştir. İncelenen kanıtlar, yükselen sıcaklıkların, uzun süreli kuraklığın ve değişen yağış modellerinin toprak nemini, pH'ı, organik karbon girdilerini ve besin kullanılabilirliğini değiştirdiğini ve bunun da mikrobiyal çeşitlilikte, topluluk bileşiminde ve ekosistem işleyişinde önemli değişikliklere yol açtığını göstermektedir. Orman yangınları, zararlı böcek salgınları ve bitki örtüsü değişimleri de dâhil olmak üzere iklim kaynaklı bozulmalar, özellikle çevresel strese karşı oldukça savunmasız olan Akdeniz ormanlarında karbon kayıplarını daha da hızlandırmakta ve ekosistem direncini azaltmaktadır. İnceleme ayrıca, mikrobiyal tepkilerin bitki örtüsü özellikleri, ağaç yaşı, toprak özellikleri ve topografik koşullara göre orman tipleri arasında farklılık gösterdiğini vurgulamaktadır. Genel olarak, elde edilen kanıtlar, toprak mikrobiyal işlevinin iklim stresi ile orman verimliliği, besin döngüsü ve karbon tutulumu arasında bağlantı kuran kilit bir bileşen olduğunu vurgulamaktadır. Bu nedenle, gelecekteki iklim senaryoları altında tahminleri iyileştirmek ve uyarlanabilir orman ve arazi yönetimi stratejilerini desteklemek için iklim, bitki örtüsü, toprak ve mikrobiyal süreçleri entegre eden uzun vadeli izleme ve çok disiplinli yaklaşımlara ihtiyaç duyulmaktadır.

Anahtar kelimeler: İklim değişikliği; orman ekosistemleri; toprak mikrobiyal toplulukları; karbon tutulumu; orman direnci

INTRODUCTION

Global warming has become a major concept that has been on the agenda of the entire world, especially in the last 2 decades, with international conferences, agreements, and symposiums being organized to find solutions. The reason for this is that carbon dioxide and other greenhouse gases, which are the main causes of global warming, have significantly altered the chemical composition of the Earth's atmosphere compared to 100-150 years ago (Battaglia et al., 2021; Babur et al., 2022a). In recent years, there have been significant increases in the levels of carbon dioxide and methane, along with synthetic chemicals that contribute to the greenhouse effect despite not naturally occurring in the atmosphere. While these gases enable sunlight to reach the Earth's surface, they prevent the reflected thermal radiation from escaping back into space, which drives the greenhouse effect. But, they prevent the heat waves generated by the arrival of these rays on the Earth's surface from escaping back into the upper layers of the atmosphere through the greenhouse effect. In fact, these gases keep the world warm and maintain livable temperatures as long as their levels do not exceed a certain threshold. However, the disproportionate increase in greenhouse gas concentrations traps a larger fraction of the long wave thermal radiation re-emitted by the Earth's surface. This continuous trapping of thermal energy exacerbates global warming and accelerates broader climate change. Currently, a major issue debated among scientists is the potential impacts of a 1-2ºC rise in global temperature on forests, agricultural production, sea levels, and the existence and diversity of living organisms. Unfortunately, scientists cannot predict how fast this change process will be, how long it will last, or where it will lead humanity.

The soil diversity is directly related to ecosystem. Ecosystem diversity can be described as a dynamic whole formed by the functional interaction between living organisms, such as animal, plant, and microorganism communities, and the non-living elements such as soil, water, air, and minerals (Laureto et al., 2015). Biological diversity is an important historical accumulation that has formed since the emergence of living organisms on Earth, encompassing genetic diversity and ecosystem diversity. Both biological diversity and ecosystems form the life support units of the world, ensuring the functioning of ecological balance as a whole (Anonymous, 2024). In fact, the exchange of matter and energy between living and non-living elements depends on this diversity. However, the negative impact of global climate change on ecosystems and biological diversity can lead to the extinction of some species, the relocation or migration of others, and population increases in certain species (Weiskopf et al., 2020). This climate change could cause a series of severe ecological consequences with unpredictable long-term outcomes, such as changes in natural biological diversity, changes in the interactions of organisms with each other and their environment, and possible disruptions in the ecological food chain.

Forest ecosystems play a critical role in regulating the global climate through carbon sequestration, nutrient cycling, and energy exchange; these processes are largely managed by soil microorganisms (Babur et al., 2025; Akbaş et al., 2026). Changes in temperature, precipitation patterns, and the frequency of extreme events caused by climate change directly affect the structure, biomass, and activity of the soil microbial community, altering organic matter decomposition and nutrient mineralization rates (Babur et al., 2021a). These microbial responses can enhance or limit soil carbon storage and create feedback mechanisms that can amplify or mitigate climate change impacts (Lionello et al., 2014; Ozlu et al., 2022a). Therefore, understanding the interactions between forest ecosystems and soil microbial dynamics under changing climate conditions is crucial for predicting ecosystem resilience and developing mitigation and adaptation strategies against climate change. This study will present information on the factors triggering global warming and their effects on microorganisms and their activities, which are sensitive indicators of soils forming the basis of forest ecosystems.

Although numerous studies have examined the effects of climate change on forests, soils, and microbial communities separately, an integrated synthesis focusing on their interactions remains limited. This review therefore aims to synthesize current evidence on climate-driven changes in forest and soil ecosystems by integrating findings related to soil microbial processes, nutrient cycling, carbon dynamics, and ecosystem resilience. Furthermore, this review identifies major knowledge gaps and proposes future research priorities for sustainable forest management under changing climatic conditions.

MATERIALS AND METHODS

Literature Search Strategy and Study Selection

This review was conducted using a structured literature search framework adapted from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency and reproducibility of the study selection process. Scientific literature was retrieved from three major databases: Web of Science Core Collection (n = 165), Scopus (n = 180), and Google Scholar (n = 75). A total of 420 articles published between 2000 and 2025 were initially identified using combinations of the keywords climate change, global warming, forest ecosystem, forest soil, soil microorganisms, microbial biomass, soil enzyme activity, carbon sequestration, nutrient cycling, and forest resilience. Only peer-reviewed English-language studies focusing on forest ecosystems were considered.

Following the removal of 76 duplicate records, 344 unique publications remained for title screening. After screening titles for relevance to the objectives of this review, 198 studies were retained for abstract and full-text evaluation. Full-text assessment was subsequently performed using predefined inclusion and exclusion criteria, resulting in 112 potentially eligible publications. Finally, 79 peer-reviewed studies were selected for qualitative synthesis and included in this review.

Studies were included if they (i) investigated the effects of climate change on forest ecosystems, forest soils, or soil microbial communities; (ii) reported experimental, observational, or review-based evidence related to carbon cycling, nutrient dynamics, microbial activity, or ecosystem functioning; and (iii) were published in peer-reviewed journals. Conference abstracts, dissertations, duplicate publications, and studies not directly related to forest soil ecosystems or climate change were excluded. The overall study selection process is illustrated in Figure 1.

History of Global Climate Change

Climate change emerged before human history and, with the world undergoing different periods of change, has transformed into forms quite different from its original state. Our world has continuously changed, reaching its current state, which is the final form in which humans can live.

In the 1200s, particularly in regions with temperate climates, the Earth faced natural disasters such as droughts and floods as a result of climatic changes. During these periods, humans, powerless in their struggle against nature, were forced to adapt to it. They even designed their settlements according to climate and natural events, sometimes have to abandon their homes and migrate. In the 15th century, stable climatic conditions are known to have prevailed (Graham et al., 2011). By the mid-1550s, a 300-year climate cooling period had already begun. Experts have even named this period the Little Ice Age (Grove, 1988). Subsequently, the 1800s saw severe famine and it reached deadly proportions in Europe. By the end of the 1800s, there had been a 0.5- ^{o}C increase in the global average temperature. This increase was followed by a 25-year cooling period. Today, the global average temperature is exhibiting an upward trend once again. It has been observed that the eight hottest years on record have occurred since 1978. Furthermore, measurements taken in both the northern and southern hemispheres indicate that 1998 was the hottest year on record since 1860. The history of climate change on Earth is very old, but it is known that anthropogenic effects on the climate began with the Industrial Revolution. Figure 1 shows a diagram of global temperature change over the last 800,000 years.

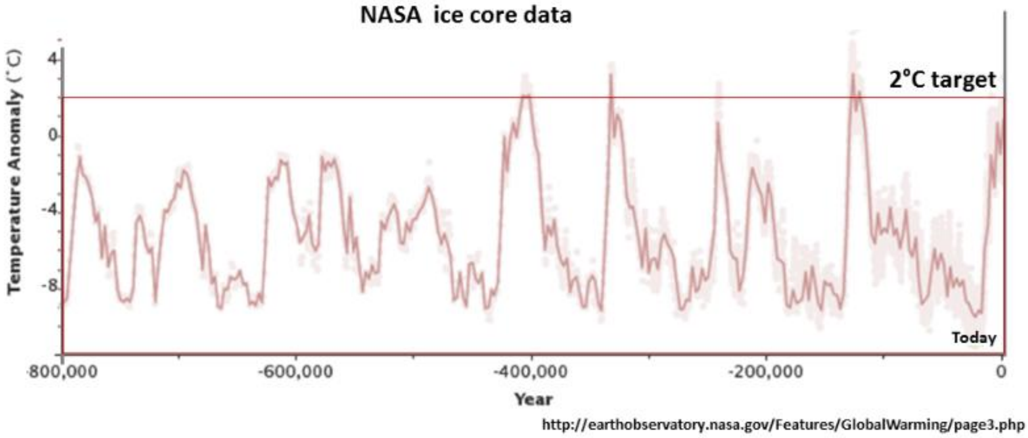

Figure 1. The global temperature change that has been ongoing for 800,000 years is indicated in the diagram by NASA (URL.1).

A study indicated that atmospheric CO_2 levels had reached their highest point in 15 million years (Anonymous, 2009). Rapid industrialization and high energy demand have led to an increase in the type and amount of harmful gases released into the atmosphere (Figure 2). Since the 1970s, global emissions of greenhouse gases, including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), have increased by 75% (Smith et al., 2014). The gases accumulating in the atmosphere have caused a rise in temperature through the greenhouse effect, presenting humanity with a global threat in the form of climate change and an increase in extreme weather events. In contrast, international efforts to prevent global climate change date back only 50 years (Ozlu et al., 2022a).

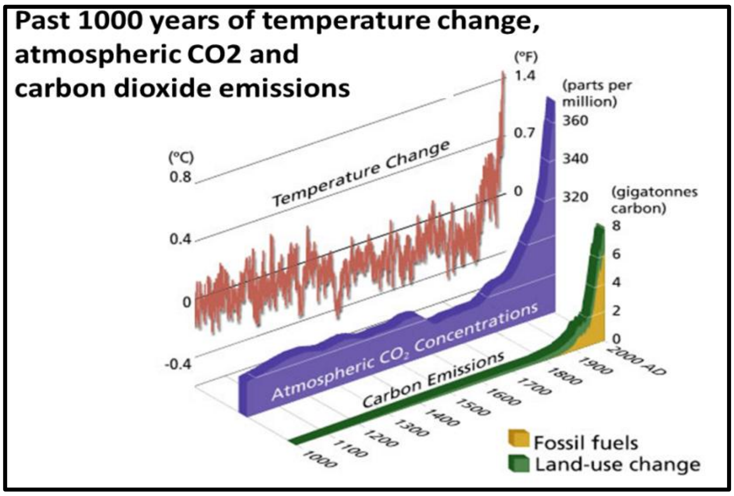

Figure 2. Diagram showing atmospheric CO_2 and temperature increase together (URL. 2)

The effects of climate change in Turkey

When we talk about global climate change, the first things that come to mind are unpredictable weather events and negative phenomena such as high temperatures. Global climate change has become a common problem for many ecologically sensitive countries, particularly our country and those located in the Mediterranean basin. Research indicates that temperature increases will continue worldwide over the next half-century (NASA, URL.1), and that Turkey will suffer greater damage from this change than it does now. NASA (URL.1) has stated that the summer of 2023 was the hottest summer on record for Earth. It has stated that it was at least 0.23 ^{o}C hotter than other summers recorded by NASA. Similar effects are observed in Türkiye, a large part of which borders the Mediterranean Sea. This implies that Türkiye will experience losses in efficiency and production—i.e., direct financial losses—in agriculture, industry, tourism, the economy, and many other sectors. Worse still are other negative effects such as changes in soil structure, the alteration or transformation of ecosystems due to drought, and the loss of species. Turkey, which has soil suitable for agriculture, is already becoming a basin that is beginning to dry up. In addition, our water shortage in terms of irrigation and drinking/domestic water has increased and will continue to increase (Figure 3). Similarly, droughts in the Central Anatolia region have caused many lakes to dry up (Figure 4). Rainfall will decrease, leading to unstable and irregular winter and summer seasons. This will directly complicate the supply of clean water and sufficient food; ultimately, deteriorating ecosystems and dwindling resources will pose catastrophic threats to humanity.

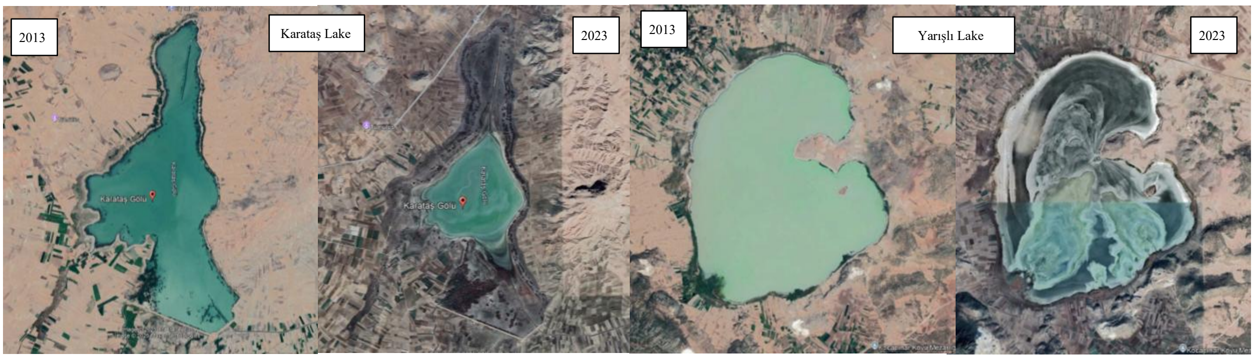

Figure 3. It shows how much the water reservoirs of the Karataş and Yarışlı lakes in the Mediterranean basin have decreased in August 2023 compared to August 2013.

Figure 4. This shows how much the water reservoirs of the Düden lakes in the basin decreased in October 2023 compared to 2013.

Türkiye's annual average temperature map and the projected temperature increase map for the next century are shown in Figures 5 and 6. According to research, if global warming continues at the same rate, temperatures in western Turkey will rise by 5 to 6 degrees and by 3 to 4 degrees in Central and Eastern Anatolia and Southeastern Anatolia during the summer months. Temperatures will also rise by 2 to 3 degrees during the winter months. Rainfall in the Black Sea Region will increase by 10 to 20 percent, while in the south it will decrease by up to 30 percent. Although the temperature increase will remain limited over the next 15 to 20 years, a rapid increase in temperature is predicted towards the end of the 2030s. Although it varies by region, overall temperatures are projected to increase by 4°C in winter and 6°C in summer. Across Türkiye, an increase of between 2.5°C and 4°C in the annual average temperature is predicted. Although rainfall is expected to increase in eastern Northern Anatolia, it is expected to decrease across Turkey as a whole. These factors will lead to a significant decrease in water resources, causing drought and desertification, loss of agricultural productivity, an increase in the number and impact of forest fires, and loss of biodiversity. Indeed, it has been noted that in recent year, due to the increase in temperatures during the summer months, a significant number of fires have been recorded in red pine forests, both in terms of quantity and quality (Babur et al., 2022b).

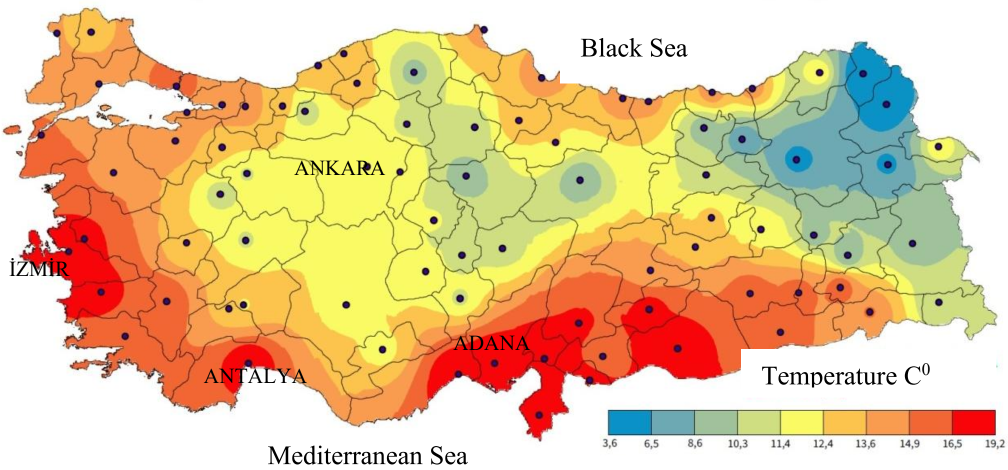

Figure 5. Türkiye's average annual temperature distribution (URL. 3)

The temperature difference values obtained from the HadGEM2-ES global model using the dynamic downscaling method based on the RCP4.5 scenario show an increasing trend compared to the 1971-2000 reference period in Türkiye. Assuming this increase continues, an increase of 2-3 °C is expected between 2013 and 2040, particularly in the summer season in our North-West and South-East regions, while this increase will generally be around 1-1.5 °C in the winter season. In the 2041-2070 periods, temperatures are projected to increase by at least an average of 1 °C in all seasons compared to the previous period (Figure 6).

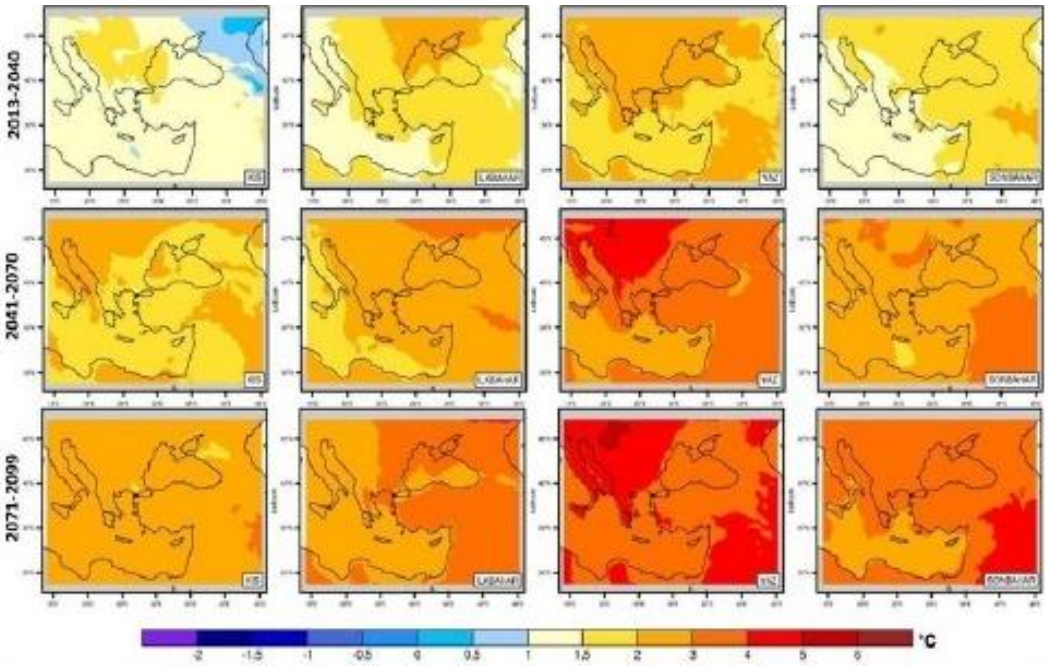

Figure 6. Temperature difference map for the periods 2013-2040, 2041-2070, and 2071-2099 in future scenarios based on climate data from 1971-2000 for all seasons (URL.4)

Potential impacts of climate change on some ecosystems worldwide

Climate Change Effects on Boreal Forests and Their Role in the Global Carbon Cycle

The northern taiga (boreal) forests, which cover one-third of the Earth's surface in the northern regions of Canada, Alaska, Europe and Russia, constitute the largest terrestrial biome on Earth. They play a crucial role in regulating the global carbon cycle. These high-latitude ecosystems store vast quantities of carbon in their vegetation, soils and permafrost layers, accounting for a significant proportion of the global terrestrial carbon reserve (Tagesson et al., 2020). It is estimated that boreal forests contain 30–40% of the world's terrestrial carbon, much of which is stored in organically rich soils and peatlands that formed in cold climates where decomposition processes are slow (URL.1). As well as sequestering carbon, these forests filter rainwater and snowmelt, and support high levels of biodiversity. The biggest threat to taiga forests today is deforestation through logging. In particular, vast areas of Siberia's forests were cleared and destroyed during the Soviet era. Large-scale deforestation has also occurred, and continues to occur, in Scandinavia and Canada.

Global warming has brought about serious, irreversible threats. The increase in temperature is causing drought and an increase in forest fires. While Bengston (2021) points to a 3°C increase as a critical threshold for the extinction of northern forests, Suz et al. (2021) report that even low levels of warming can prevent boreal forests from regenerating. This is because climate change reduces plants' resistance to biotic and abiotic pests, leaving them vulnerable to secondary pests (Laz et al., 2019). Bark beetles, generally considered secondary pests, cause widespread damage to spruce trees, particularly as temperatures rise, resulting in the death of spruce forests (Jenkins et al., 2014). The spruce beetle (*Ips typographus*) is a North American insect that has lived exclusively on spruce bark for thousands of years. In healthy forests, they are always found in small numbers and play an important role in decomposing dead trees within the forest ecosystem. However, in recent years, increasing temperatures, an earlier spring and a progressively longer summer have led to a significant increase in the spruce beetle population (Şimşek et al., 2010). An increase in insect populations can lead to a shortage of dead trees on which to feed. This causes the insects to infest and kill healthy trees in the vicinity. The insects lay their eggs near the vascular tissues of spruce tree trunks, which carry water and nutrients. The newly hatched larvae feed on these tissues, which hinders the transport of water and nutrients to the upper parts of the tree, eventually killing it. Provided the insect population is not excessive and the tree is not weakened by other factors, it can counteract the damage by releasing abundant resin. However, in recent years, increasing drought and longer summer seasons have led to excessive insect populations in trees with reduced resistance. This can result in significant financial losses for forests worldwide. For instance, between 1990 and 2000, an extensive outbreak of spruce beetles resulted in the death of spruce trees across 1.19 million hectares of forest in Alaska. It is estimated that around 30 million trees died during the period of intensification of the outbreak (Werner et al., 2006).

The excessive proliferation of the spruce beetle and the subsequent loss of forest cover create a domino effect. Global climate change and the lengthening of the warm season lead to an overpopulation of these beetles. The beetles destroy forests, reducing the forests' ability to sequester atmospheric carbon, leaving more carbon dioxide in the air, leading to further warming. These events, observed in regions near the Arctic where temperatures are rising more than in other areas, are no coincidence. A temperature increase of 0.8-1.6 degrees Celsius is already causing critical thresholds to be crossed in natural systems (Climate Analytics, 2024). What further ecological disasters humanity will face in the coming years is a very serious matter that even scientists cannot predict.

Figure 7 shows data on changes in the Earth's temperature, as recorded by four different space and research centers since the 1880s. Figure 8 illustrates the impact of both natural and human factors on global temperature change.

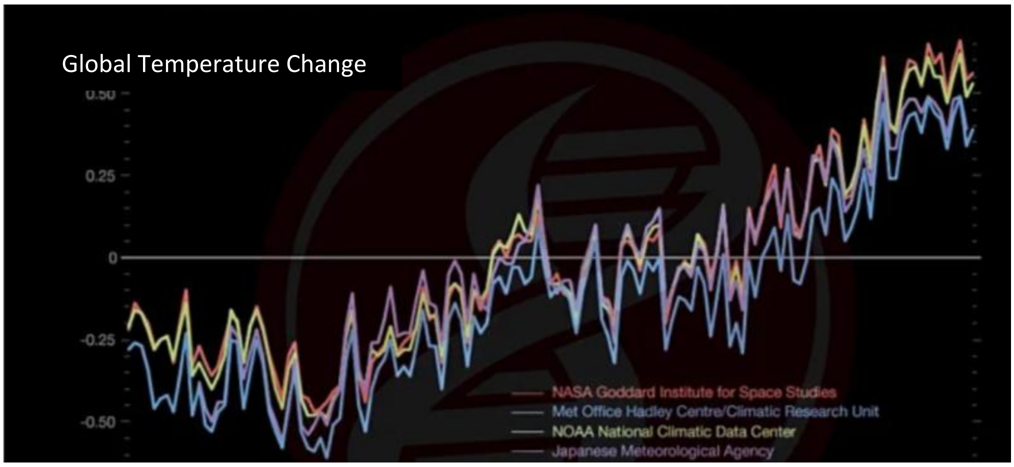

Figure 7. Earth's temperature collected by four different space and research centers since the 1880s.

In Figure 7 the red graph is from NASA's Goddard Institute for Space Studies, the blue graph is from the Met Office Hadley Centre for Climate Research, the green graph is from the National Oceanic and Atmospheric Administration's National Climatic Data Center, and the purple graph is from the Japan Meteorological Agency (From NASA).

Figure 8 shows the effects of natural and human activities on changes in global temperatures. It particularly highlights how severely human impact has increased over the past 40 years (Walsh et al., 2014).

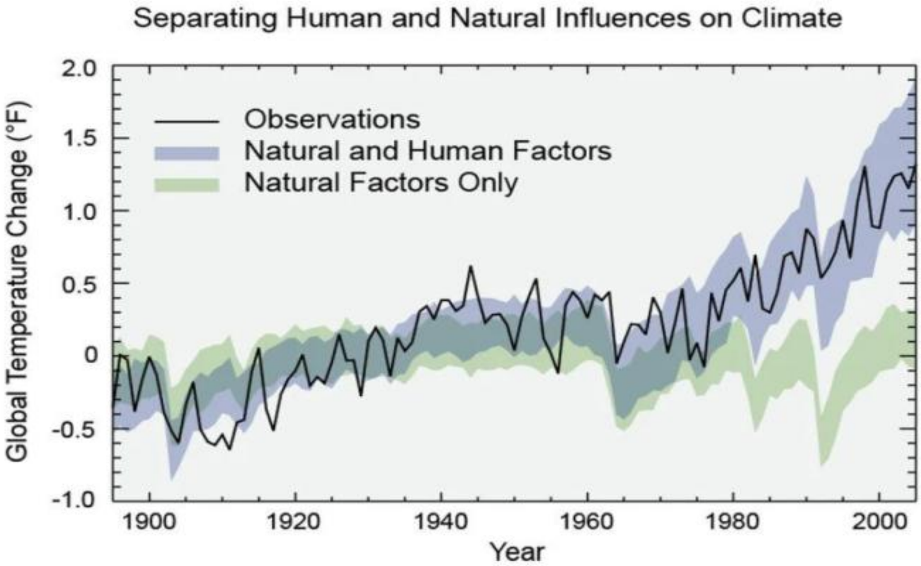

Figure 8. Human activities on changes in global temperatures.

In conclusion, the sustainability and stability of taiga ecosystems are closely linked to global climate regulation and management practices. However, increasing temperatures, thawing permafrost, drought stress and more frequent and intense wildfires are rapidly altering the structure and functioning of taiga forests due to climate change. These disruptions can accelerate the release of carbon stored in soils and biomass, potentially transforming taiga forests from long-term carbon sinks into net carbon sources and creating a positive feedback loop that exacerbates global warming further (Eckdahl et al., 2022). The increasing frequency and intensity of wildfires due to climate change has particularly been identified as one of the most significant mechanisms destabilizing the carbon stocks of taiga ecosystems. Fires rapidly release large amounts of previously stored carbon into the atmosphere, while also altering ecosystem recovery dynamics and carbon sequestration potential (Philiphs et al., 2022). Therefore, it is crucial to understand how taiga forests respond to climate change in order to predict future carbon cycle feedbacks and develop effective forest management and climate mitigation strategies.

Effects on subtropical and Mediterranean forests

Subtropical and Mediterranean forests cover more than 25 million hectares of woodland. They also cover more than 50 million hectares of other wooded areas (FAO, 2025; Wang et al., 2010). Subtropical and Mediterranean forests differ significantly from other forest ecosystems due to their high biodiversity, ecological productivity and socioeconomic importance. These forests therefore deserve special consideration. They support a wide variety of plant and animal species, while also providing vital services such as carbon sequestration, soil conservation, and water regulation (Anonymous, 2018; Wang et al., 2010). Despite covering only a small part of the Earth's surface, Mediterranean-type ecosystems are considered areas of high global biodiversity due to their species richness and endemism.

However, these ecosystems are becoming increasingly susceptible to the effects of global climate change and related environmental degradation due to their vulnerability.

Subtropical and Mediterranean forests are characterized by high temperatures, marked seasonal droughts and intense variability in climate parameters. The environmental conditions in the Mediterranean region make these forests particularly vulnerable to climate change, especially rising temperatures, prolonged droughts and altered rainfall patterns (Marques et al., 2010; Babur et al., 2025b). Recent studies have demonstrated that escalating droughts and extreme weather events can have a significant impact on forest productivity, species composition, and the functioning of ecosystems (Bouwman et al., 2025; Tijerín-Triviño et al., 2025). Prolonged drought stress can reduce photosynthetic activity, inhibit tree growth, and increase tree mortality rates in many Mediterranean forest species. Such sharp changes can alter forest structure (e.g. species composition, canopy closure and growth parameters) and lead to shifts in species distribution, potentially reducing ecosystem resilience and biodiversity (Paroissien et al., 2014).

In such sensitive and fragile regions, another significant consequence of climate change is an increase in the number and severity of secondary ecological pests, such as forest fires, pest infestations and soil degradation (Dindaroğlu et al., 2021; 2023). Mediterranean forests are naturally adapted to periodic fire regimes; however, climate-induced droughts and temperature increases are causing forest fires to exceed natural thresholds. Large, severe fires can lead to significant losses of biomass, SOC and vegetation, thereby reducing forests' capacity to sequester carbon (Babur et al., 2022b). Furthermore, repeated disturbances can hinder ecosystem recovery and accelerate soil degradation processes, particularly in regions where water is scarce. Forests in the Mediterranean basin are shown in Figure 9, and projections for extreme temperatures and drought in 2030 are shown in Figure 10.

Although research on forest responses to climate change has expanded considerably, important knowledge gaps remain regarding the long-term responses of subtropical and Mediterranean forests to increasingly frequent and severe climatic stress. In Mediterranean forests, drought responses are strongly context dependent and can vary with species composition, stand structure, antecedent conditions, and site characteristics, while the belowground mechanisms governing water acquisition and post-drought recovery remain incompletely understood (Mas et al., 2024; Italiano et al., 2024). Climate-driven changes may also interact with edaphic conditions and nutrient availability, with potentially important consequences for forest functioning and stability. Indeed, soil carbon and nutrient cycling in Mediterranean forests are closely linked to plant functional traits and community composition (Prieto-Rubio et al., 2023), while evidence from subtropical forests indicates that soil nutrient availability, particularly phosphorus, can regulate the long-term stability of tree-community dynamics (Liang et al., 2024). Moreover, climatic controls can substantially modify soil nitrogen transformations and their responses to environmental change across forest biomes (Zhang et al., 2024). A better understanding of these interconnected climate–soil–vegetation processes is therefore essential for predicting ecosystem trajectories and developing adaptive forest-management strategies capable of maintaining ecosystem functioning and resilience under future climatic conditions.

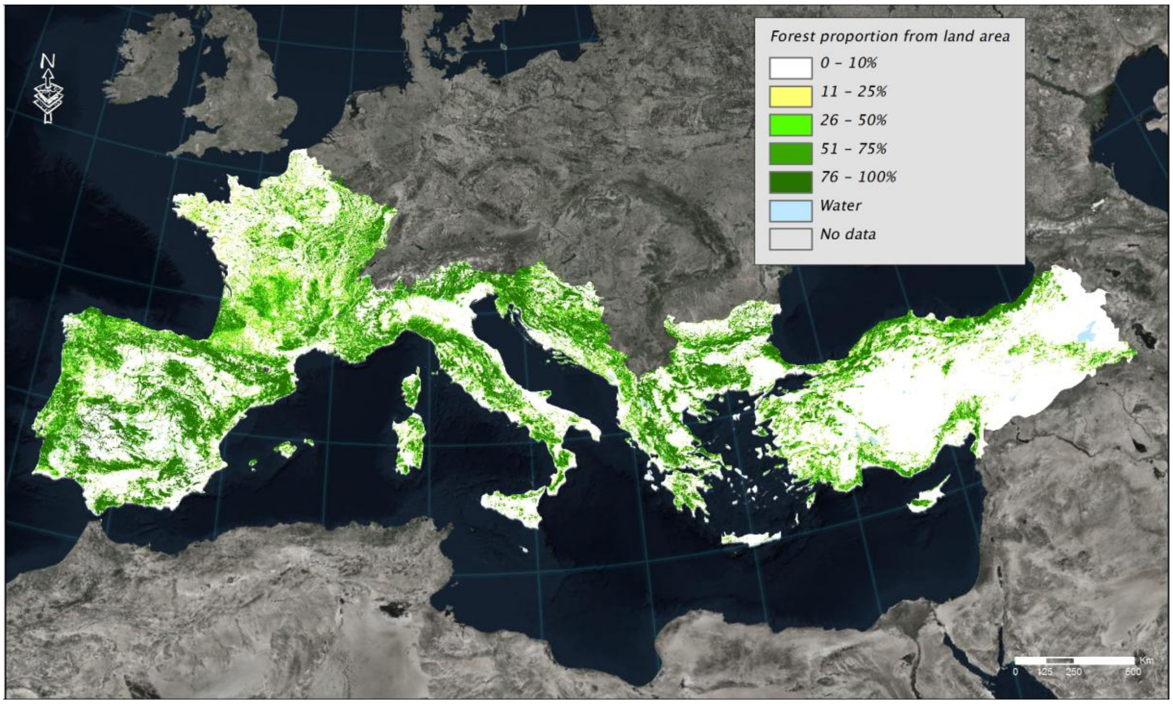

Figure 9. The map showing forest cover, as published by the Joint Research Centre (Kempeneers et al., 2011).

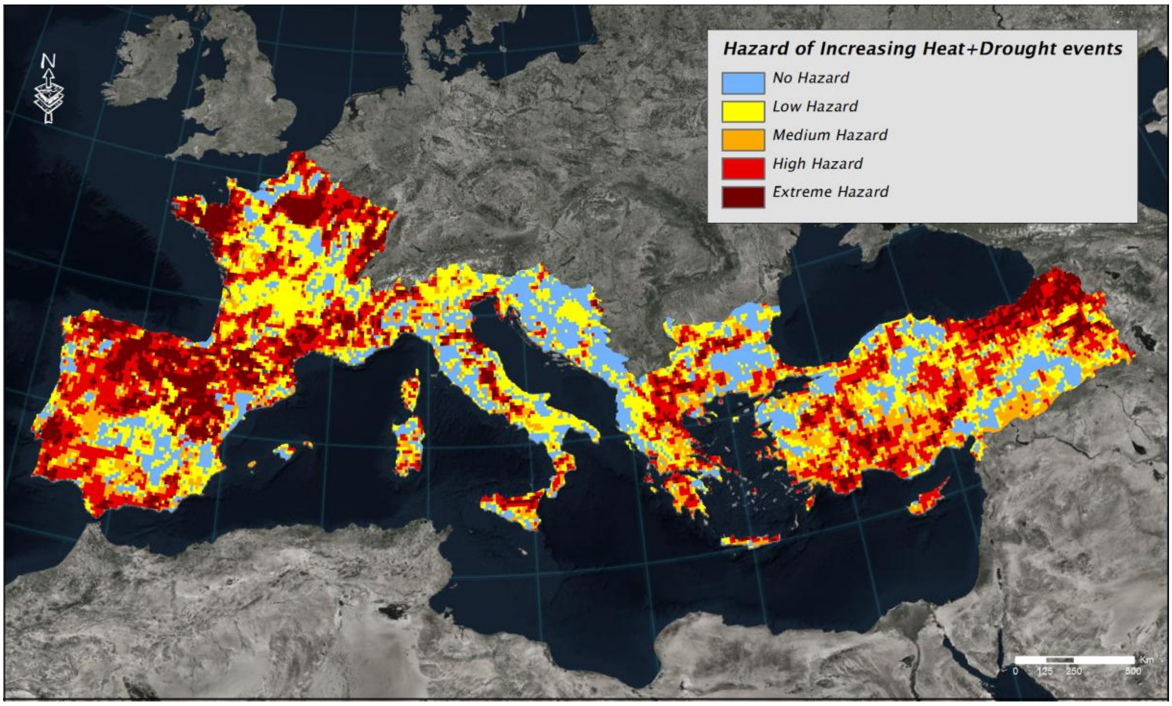

Figure 10. Increasing hazard of heat and droughts by 2030. Source: elaborations by authors from Bucchignani et al. (2014).

Climate changes on Eastern USA

In the United States, forests cover around 740 million acres — approximately one-third of the country's total land area (USDA, 2025). These forests provide society with numerous benefits and services, including clean water and air, recreational opportunities, wildlife habitats, carbon sequestration, climate regulation and a variety of forest products. However, climate change directly and indirectly impacts forest growth and productivity through changes in temperature, precipitation, weather patterns and other factors. It can significantly impact forest health by affecting the structure and function of forest ecosystems and increasing threats such as pest outbreaks, fires, anthropogenic events and drought.

As mentioned above, forests are facing the impact of climate change. This includes the disappearance of vulnerable species, the introduction of new species and land degradation. There is also an increased risk of wildfires and air pollution. For example, significant changes are predicted in many parts of the United States. Figure 11 shows that, in the north-east of the United States, the currently dominant maple-beech-birch forest type (shaded red) is projected to shift to oak-pine and oak-hickory forest types in the near future due to rising temperatures, under a lower emission scenario. While it is difficult to determine the impact values of the individual factors causing this, their combined effect leads to significant losses of forest area. As these changes are likely to continue in the coming years, some of the products and services that forests provide may be put at risk.

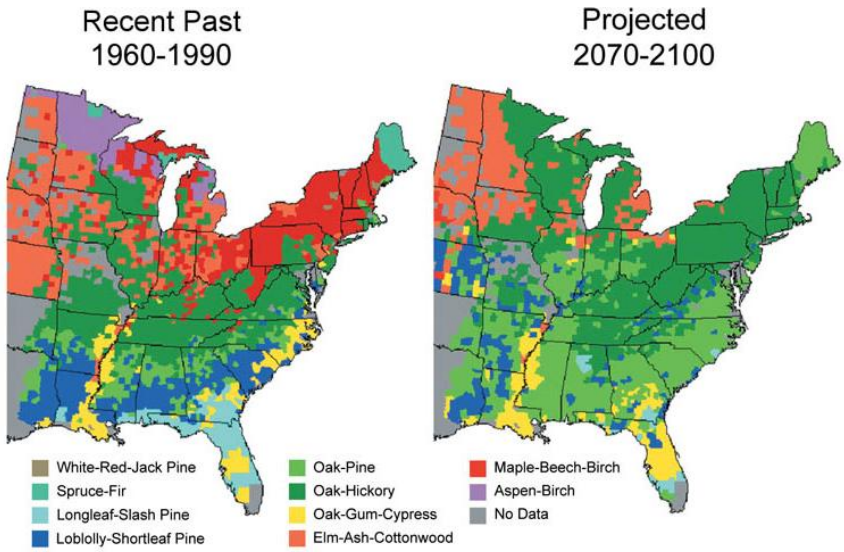

Figure 11. A map showing that, according to a study, many of the current plant species in America could be replaced by different species in the coming years. (Source: USGCRP, 2009).

Climate change impact on forest growth and productivity.

Climate change is likely to affect forest growth and productivity in a variety of ways. The most significant negative impacts of climate change on forests are rising temperatures, rainfall anomalies, and increased carbon dioxide (CO_2) levels.

Rising temperatures and longer heat periods generally lead to longer growing seasons. However, this also alters the geographic ranges of some tree species. The habitats of some species are likely to shift northwards or to higher altitudes. If conditions in the current geographic location of the species are no longer suitable within the ecological requirement ranges of the habitat, these species will be at risk locally or regionally. For instance, species currently found only near the forest line on mountaintops in certain regions may perish due to dehydration caused by higher temperatures, as they are unable to relocate to greater altitudes. Climate change will increase the risk of drought in some regions while increasing the risk of extreme rainfall and flooding in others. Rising temperatures affect the seasonal availability of water by altering the timing of snowmelt. While many trees are drought-tolerant to a certain degree, rising temperatures could make future droughts more damaging than those experienced in the past (Dubrovský et al., 2013; García-Ruiz et al., 2013). Furthermore, drought increases the risk of wildfires because dry trees and shrubs provide fuel for them. Drought also reduces trees' ability to produce sap, making them more susceptible to insect and fungal pests.

Carbon dioxide is essential for photosynthesis, the process by which green plants use sunlight to grow. When they are given sufficient water and nutrients, increases in atmospheric CO_2 can boost the productivity of trees, which could potentially alter the distribution of tree species. Growth is greatest in nutrient-rich soils without water limitations, decreasing as productivity and the water supply are reduced.

Soil and Climate Change

The topsoil of terrestrial ecosystems (the top 30 centimetres) contains approximately twice as much carbon as the entire atmosphere (Okolo et al., 2019). After the oceans, soils represent the second largest global carbon pool, storing significantly more carbon than the atmosphere and all terrestrial vegetation combined. These facts demonstrate the importance of healthy soils for food production and efforts to mitigate the negative effects of climate change (Anonymous, 2017).

Climate change's effect on soil

Climate change is rapidly altering soil systems by disrupting the physical, chemical, and biological processes that regulate the functioning of biotic and abiotic elements within ecosystems. Rising temperatures can accelerate organic matter decomposition, leading to a decrease in SOC stocks and a reduction in carbon sequestration potential (Wu et al., 2025). Simultaneously, prolonged droughts and irregularities and changes in rainfall patterns affect soil moisture regimes, impacting nutrient availability, microbial activity, and plant-soil interactions (Zia et al., 2021; Oishy et al., 2025). The increasing frequency of extreme and variable weather events can further exacerbate soil erosion, aggregate disintegration, and nutrient loss, ultimately degrading soil structure and fertility. Furthermore, climate-induced changes in vegetation and root dynamics can alter subsurface carbon inputs and microbial community composition, leading to chain reactions in soil biochemical cycles (Babur et al., 2022; Cai et al., 2023). Soils play critical roles in climate change mitigation and climate regulation. However, the literature highlights the need for sustainable soil management practices that enhance soil resilience and protect ecosystem services, as Mediterranean soils are particularly vulnerable to degradation driven by climatic and anthropogenic pressures (Lagacherie et al., 2018; Ferreira et al., 2022).

Researchers have identified the global and European soil-related effects of climate change. For instance, the latest report by the European Environment Agency (EEA) on climate change, its impacts and vulnerability in Europe reveals that soil moisture in the Mediterranean region has decreased significantly since 1950, whereas it has increased in certain areas of Northern Europe. Similar effects are predicted by the models developed as long as the average temperature increase continues (Anonymous, 2017). Ongoing decreases in soil moisture can dramatically impact food production by increasing the need for irrigation in agriculture, potentially leading to lower yields and even desertification. A total of 13 EU member states have declared themselves affected by desertification. Despite this, a recent report by the European Court of Auditors concluded that Europe's efforts to combat desertification and land degradation lack consistency.

Changes in seasonal temperatures can affect the productivity of plants and animals, as well as altering their annual reproductive cycles (Walsh et al., 2019). For instance, an earlier arrival of spring could result in flowers blooming before pollinating insects hatch from their eggs. Conversely, as the year’s progress and the demand for agricultural products increases, efforts to increase crop capacity are gaining momentum (Ozlu et al., 2022b). This largely depends on maintaining healthy soil and sustainably managing agricultural land (Ozlu et al., 2022b). At the same time, demand for biofuels and other plant-based products has increased due to the urgent need to replace fossil fuels and prevent greenhouse gas emissions (Battaglia et al., 2021). This, in turn, sustains the increasing demand for quality and quantity of crops.

The European Environment Agency's (EEA) report on the impacts and vulnerabilities of climate change addresses the effects of climate change on soil, including accelerated erosion caused by extreme weather events such as heavy rainfall, droughts, heatwaves and storms. In addition to causing land loss, rising sea levels can alter the composition of soil in coastal areas and cause pollution from sea salt. Depending on land use, climate change could make some agricultural areas, particularly in southern regions, unusable or less productive. In forestry, the value of forest land in Europe could decrease by between 14% and 50% by 2100 if the decline in the quality of economically valuable tree species continues. The same report indicates that there could be a significant loss of agricultural yield, of up to 16%, by 2050. However, the greatest climate-related soil concern is the release of carbon dioxide and methane gases stored in permafrost ecosystems in boreal regions, particularly in Siberia. As global temperatures rise, permafrost melts. This thawing process causes the organic matter trapped in the frozen soil to decompose. This can lead to large amounts of greenhouse gases being released into the atmosphere, accelerating global warming beyond human control (Anonymous, 2016).

Soil Systems as a Key Lever in Combating Climate Change

When it comes to tackling the climate crisis, soil — one of the most important carbon sinks — should not just be seen as a medium for plant growth. Soils have significant potential to regulate the climate; they must be recognized as a dynamic and critical component of the Earth system. This is because they constitute the largest terrestrial carbon reservoir, storing more carbon than the atmosphere and vegetation combined, and therefore plays a crucial role in reducing greenhouse gas emissions through carbon sequestration. Sustainable soil management practices such as conservation tillage, afforestation, cover crop cultivation, terracing, stabilization with woven fences and organic fertilization increase SOC stocks while simultaneously improving soil structure, water-holding capacity and microbial activity (Babur et al., 2021a; 2024). Furthermore, protecting soils against processes such as erosion, salinization and desertification is essential in preserving their carbon storage capacity and ecosystem services (Zdruli, 2014; Telo da Gama, 2023). In the face of increasing climate change, preserving soil biodiversity and functionality emerges as a cost-effective, nature-based solution. Therefore, it is essential to integrate soil conservation into climate policy frameworks and land-use planning to achieve long-term environmental sustainability and resilience.

Terrestrial ecosystems store approximately 75 billion tons of organic carbon. It has been noted that forest soils, and especially wet organic soils such as peat, have a greater capacity to store carbon. However, continuous changes in the organic carbon stock due to unsustainable land use and soil degradation complicate matters. A report by the Intergovernmental Panel on Climate Change (IPCC, 2019) therefore argues that, to keep global warming below 2 ^{o}C, greenhouse gas emissions must be reduced across all sectors, including soil and food. Despite the uncertainties, restoring ecosystems and improving soil quality can be a very cost-effective measure against climate change. First, according to the FAO, restoring currently degraded soils could store up to 63 billion tons of carbon, offsetting a significant portion of global greenhouse gas emissions. Second, healthy soils hold carbon underground. Third, many natural and semi-natural areas serve as a strong defense against the effects of climate change.

In fact, the most effective method of storing and sequestering atmospheric carbon dioxide is to ensure that soils are continuously covered with vegetation, thereby avoiding leaving land bare and uncultivated (Ozlu et al., 2021; Babur, 2024). The capacity of carbon sinks can be increased through afforestation, cultivating arable land or planting alfalfa between harvest and planting to improve soil fertility and prevent erosion (Ozlu et al., 2021; Babur et al., 2025b). Healthier soils and ecosystems can capture and store greater amounts of carbon dioxide from the atmosphere (Figure 12). Increasing green spaces is a significant step in activating many ecological functions. Conversely, changes in land use, such as draining peatlands, burning marsh peat for heating purposes or ploughing pastures or meadows, or failing to classify land according to its capabilities, mean releasing previously stored carbon back into the atmosphere. While soil alone is insufficient to mitigate and regulate climate change, it plays a vital role in storing atmospheric carbon.

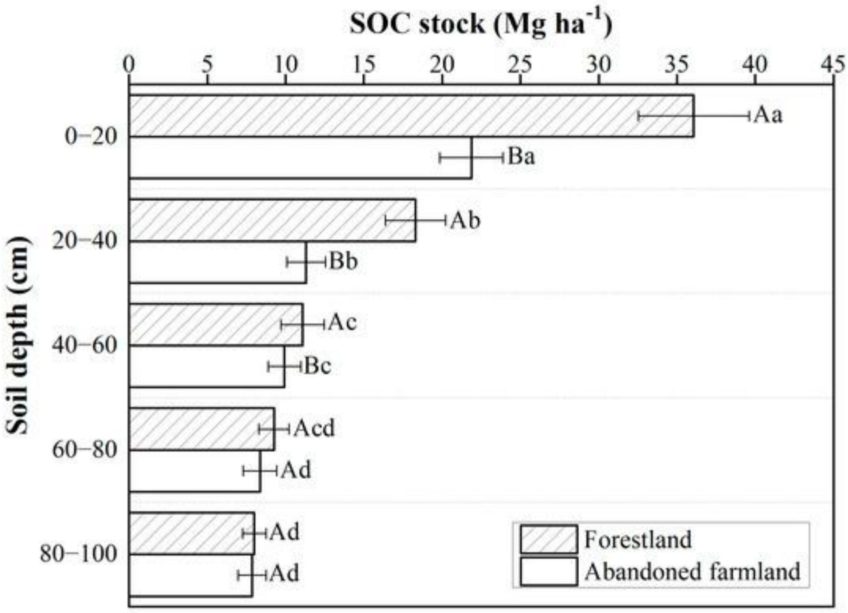

Figure 12. Variation in SOC stock in forested and abandoned farmland at different depths. Values indicated by different lowercase and uppercase letters show significant differences within each treatment and at each depth, respectively ($p < 0.05$) (Wu et al., 2025).

Land use, soil and climate change

Land use, soil dynamics, and climate change represent complex, interacting drivers that significantly impact global ecosystems and one another. Changes in land use, such as deforestation, the opening up of new agricultural areas and urbanization, directly alter soil properties, organic matter content and biochemical processes (Babur et al., 2021a; 2025a). Such changes often result in soil degradation, reduced productivity, and diminished carbon sequestration capacity, which can lead to increased greenhouse gas concentrations in the atmosphere. Conversely, practices such as afforestation, conservation agriculture and sustainable land management can increase soil organic carbon stocks, improve soil health and fertility, and mitigate the effects of global warming.

Soils play a central role in climate regulation by functioning as sinks for carbon and other greenhouse gases (Battaglia et al., 2022; Ozlu et al., 2021). The EU's thematic strategy and implementation report on soil conservation emphasizes the importance of healthy soil in both mitigating and adapting to climate change. However, soil system degradation triggered by abiotic stress factors, such as improper land use or drought caused by extreme temperatures, can accelerate the decomposition of soil organic matter. This increases emissions of greenhouse gases, primarily carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Werku et al., 2025). Furthermore, changes in climate elements can alter soil processes by affecting soil moisture content, microbial populations and their activity, and nutrient cycling. Therefore, integrating land-use planning with soil conservation strategies is essential for achieving climate-resilient ecosystems. Approaches that priorities soil stabilization and conservation, minimize land degradation, and enhance ecosystem functionality are considered the most effective nature-based solutions (Babur et al., 2021b). In this context, conserving soil biodiversity, improving land management practices and restoring degraded land are essential for mitigating climate change and ensuring the long-term sustainability of terrestrial ecosystems and their associated services.

In this context, EU Member States anticipate that new regulations relating to land use, land use change and forestry will fully offset greenhouse gas emissions between 2021 and 2030 at the very least. The EEA will support the reporting and monitoring of these regulations.

Forest and climate change

Forests cover approximately 30% of the Earth's land surface. Healthy forests are terrestrial ecosystems that provide clean drinking and usable water resources as well as store high amounts of carbon (Altun et al., 2016; Adamczyk, 2021). Forests absorb carbon dioxide (CO_2) through photosynthesis, balancing CO_2 levels in the atmosphere. Land use, soil dynamics, and climate change represent complex, interacting drivers that significantly impact global ecosystems and one another (Ahrends et al., 2017). It is estimated that forests have stored an average of 2 billion tons of carbon from the atmosphere each year since 2000 (Harris et al., 2021). Old-growth and well-managed forests store large, long-term carbon stocks. Additionally, Forests play a key role in regulating the climate at regional and local scales. Through evapotranspiration and canopy cover, they influence temperature, humidity, and precipitation patterns. Lejeune et al. (2018) reported that deforestation leads to more intense heat waves in North America and Eurasia because trees release moisture that cools the air around them. By maintaining the hydrological cycle, forests can mitigate the effects of drought, stabilize rainfall patterns, and prevent extreme temperature fluctuations. However, climate change is increasingly impacting forest ecosystems through rising temperatures, changing rainfall patterns, and more frequent extreme events such as drought, wildfires, and pest outbreaks. These stressors can reduce forest productivity, alter species distributions, and in severe cases, cause carbon losses from forests. At the same time, deforestation and forest degradation significantly contribute to greenhouse gas emissions, further accelerating climate change. Similarly, burning organic compounds as fuel leads to an increase in CO_2 concentration in the atmosphere. The continuation of ecosystems and life is only possible by achieving a balance between carbon emissions and sequestration. Therefore, sustainable forest management, afforestation, reforestation, and the protection of existing forest ecosystems should become a fundamental strategy to help combat climate change, increase climate resilience, and maintain the vital ecological functions provided by forests.

Overall, forests are an effective solution to climate change. They capture and store carbon, regulate climate systems and strengthen the resilience of ecosystems. This makes them an indispensable part of global climate strategies.

The importance and necessity of sustainable forest management.

The United Nations General Assembly defines sustainable forest management as a dynamic and evolving concept aimed at maintaining and enhancing the economic, social, and environmental values of all types of forests for the benefit of present and future generations (United Nations General Assembly, 2007). The resolution recognizes seven thematic elements of sustainable forest management:

1) Maintaining forest resources;
2) Forest biodiversity;
3) Forest health;
(4) The productive functions of forest resources;
5) Protective functions;
6) Socio-economic benefits;
7) Strong legal and policy frameworks.

Taking action to mitigate and adapt to climate change in the field requires a comprehensive approach supported by robust policies and appropriate legal and governance frameworks. Sustainable forest management is a universally accepted concept that informs forest policies and practices around the world, establishing an inclusive approach to forest management. At the national or sub-national level, implementing sustainable forest management requires effective policies, laws, and institutions. This involves implementing sound management practices in the field based on scientific and traditional knowledge. This approach can be applied to all types of forest, regardless of management objectives (e.g. production, conservation, protection or multiple uses).

In 2007, the United Nations General Assembly adopted a resolution that defined and set out the concept of sustainable forest management. This includes a wealth of knowledge, experience and guidance on the best practices, tools and mechanisms that can support the overcoming of the challenges posed by climate change, as well as information on collaborative efforts. Adopting sustainable forest management as a general framework helps ensure that adaptation and mitigation measures are implemented synergistically alongside other forest management objectives, while taking into account the economic, social and environmental value of forests.

Need for Adaptation

The rate of climate change varies depending on the geographical location and size of ecosystems. Generally, the extent of change increases with distance from the equator. Locally, rates and directions of climate change are influenced by topography and proximity to large bodies of water. Forest species differ in their resilience to, and ability to adapt to, the severity of climate change. In order to cope with climate change, species must either adapt to changing conditions or migrate to areas that are more suitable for survival. Their ability to do so will depend on their dispersal capacity and the availability of physical connections to suitable habitats. The risk of species loss and ecosystem degradation in forests can vary geographically and over time. Neither climate nor species responds linearly to changing conditions; both tend to react abruptly when certain thresholds are reached. Communities respond differently depending on their vulnerability to climate change. The most vulnerable communities are those already struggling with poverty, with limited options for finding work or generating income, and who are directly dependent on rain-fed agriculture or forests for their livelihoods. Adaptation in the forest sector involves changes to management practices that are intended to reduce the vulnerability of forests and forest communities to climate change. Forests and climate change adaptation are linked in two main ways (Locatelli et al., 2010). Firstly, forests contribute to climate change adaptation by providing ecosystem services that reduce the vulnerability of local communities and wider societies. For instance, the supply of forest products tends to be more resilient to climate change than that of conventional agricultural products. During periods of famine or major disaster-related food supply failure, forests can act as a safety net, providing food and income to affected communities. Forests also provide essential ecosystem services for livelihoods, food security, environmental sustainability and national development. However, climate change endangers the provision of these goods and services. The second way in which forests are linked to climate change adaptation relates to the measures required to mitigate the negative impacts of climate change on forests and maintain forest ecosystem functions. The adaptation measures chosen for a particular forest depend on the anticipated impacts of climate change, management objectives (which may change in light of climate change) and other factors. All management actions aimed at adapting a forest to climate change must be consistent with sustainable forest management. Policies, laws and governance frameworks must be flexible enough to facilitate and support these actions.

Knowledge Gaps and Future research agenda

In globally, studies need about;

- Tropical forests remain poorly investigated.
- Long-term experiments are scarce.
- Belowground biodiversity is underrepresented.
- Microbial functional genes are rarely evaluated.
- Multi-factor climate experiments are limited.
- Carbon–nitrogen–phosphorus interactions remain unclear.
- Most studies focus only on temperature.
- Mediterranean ecosystems are underrepresented.

Table 1 describes the conceptual summary of the major pathways through which climate change affects forest soil ecosystems. The table highlights the primary climate drivers (warming, drought, elevated atmospheric CO_2, and wildfires), their effects on soil properties, subsequent microbial responses, ecosystem-level consequences, and the principal knowledge gaps requiring future investigation (Zdruli, 2014). Overall, warming and drought predominantly reduce soil moisture, microbial biomass, enzymatic activity, and nutrient availability, thereby accelerating SOC losses and reducing ecosystem productivity. Elevated atmospheric CO_2 generally enhances carbon inputs through increased plant productivity but also alters microbial functional composition, leading to uncertain long-term effects on soil carbon sequestration. Wildfires cause rapid losses of the organic layer, restructure soil microbial communities, and substantially increase carbon emissions. The identified research gaps emphasize the need for long-term ecological monitoring, increased research in Mediterranean forests, multi-omics approaches to investigate microbial functions, and improved understanding of post-fire ecosystem recovery trajectories.

Table 1. Summary of major climate change drivers, soil and microbial responses, ecosystem consequences, and key research gaps.

Climate Driver	**Soil Response**	**Microbial Response**	**Ecosystem Consequence**	**Research Gap**
Warming	Soil moisture	Biomass	SOC loss	Long-term studies
Drought	Enzyme activity	Diversity	Nutrient limitation	Mediterranean forests
Elevated CO_2	Carbon input	Functional shifts	Carbon storage	Multi-omics
Wildfire	Organic layer loss	Community restructuring	Carbon emissions	Recovery trajectories

Figure 13 presents an integrated framework outlining seven strategic research priorities for improving the understanding, conservation, and sustainable management of forest and soil ecosystems under climate change. Long-term monitoring (Priority 1) is essential for detecting ecological trends, thresholds, and ecosystem responses over time. Microbial functional genomics (Priority 2) emphasizes the application of multi-omics approaches to reveal the functional roles of soil microorganisms in carbon and nutrient cycling. Machine learning prediction (Priority 3) highlights the integration of artificial intelligence with climate, soil, and remote-sensing data to improve ecosystem forecasting and decision support. Forest restoration (Priority 4) focuses on recovering degraded forests and soils while enhancing biodiversity and ecosystem functioning. Climate-smart forest management (Priority 5) promotes adaptive silvicultural practices that increase forest resistance to climate-related disturbances. Carbon neutrality (Priority 6) underlines the importance of maximizing carbon sequestration and supporting net-zero emission strategies. Forest resilience (Priority 7) aims to strengthen the adaptive capacity of forest ecosystems against future environmental stressors. The figure also emphasizes that these priorities should be supported by cross-cutting enablers, including interdisciplinary collaboration, open data sharing, capacity building, science-based policy, and stakeholder engagement, to achieve resilient, productive, and climate-smart forest ecosystems.

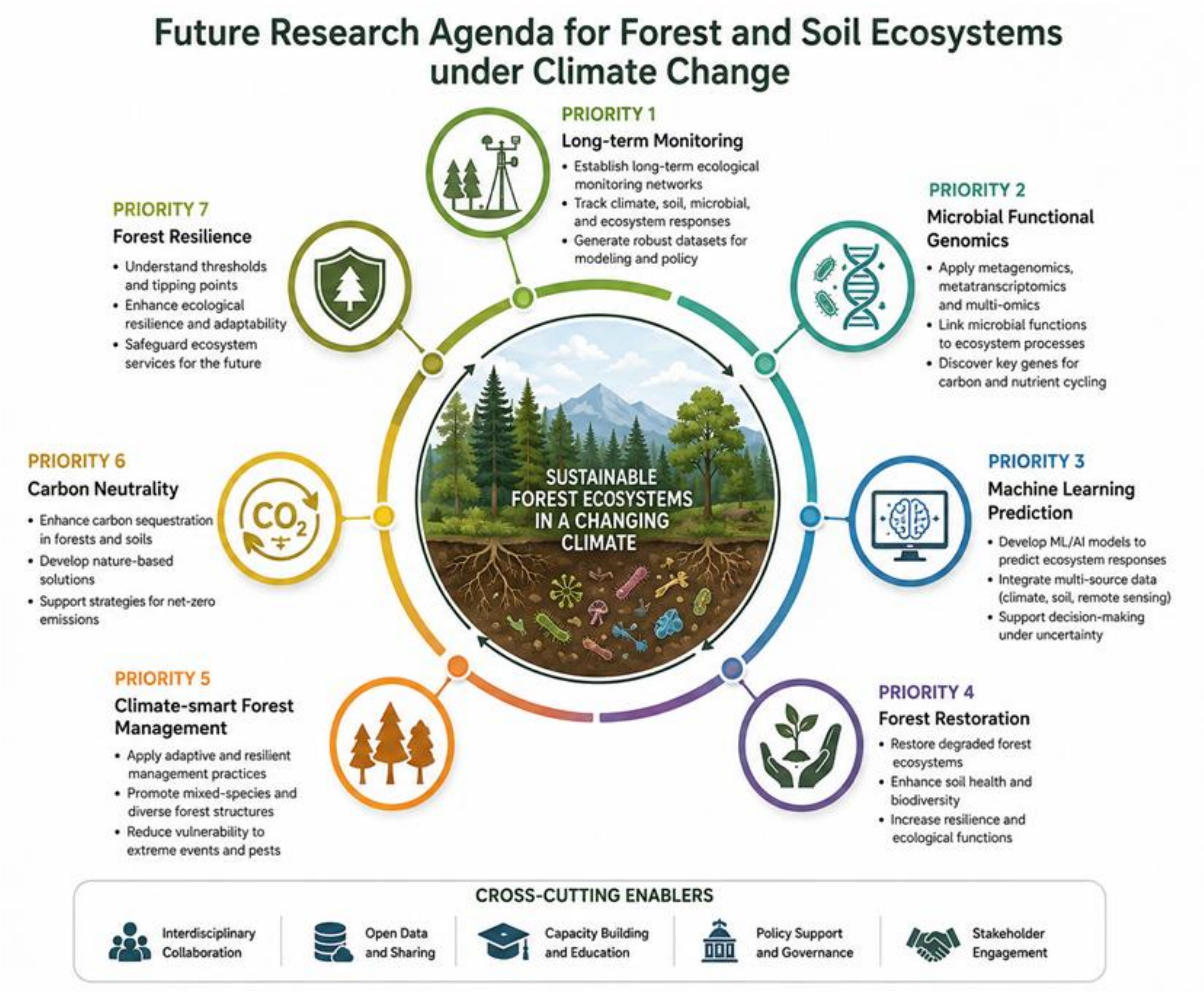

Figure 13. Future research agenda for forest and soil ecosystems under climate change.

CONCLUSION

This study highlights that forest conservation should be understood not merely as an environmental objective but as an integral component of climate mitigation, food security, sustainable land management, and long-term socioeconomic resilience. The interdependence among forests, agricultural production, and climate regulation shows that land-use decisions beyond forest boundaries can substantially affect the stability and functioning of forest ecosystems. Accordingly, achieving sustainable development requires a transition from fragmented sectoral interventions to integrated land-use strategies that jointly address forest conservation, agricultural productivity, ecosystem resilience, and rural development.

Although climate-smart agriculture, sustainable forest management, and precision-based land-use technologies offer technically viable pathways to reduce environmental pressures, large-scale implementation remains constrained by financial limitations, institutional fragmentation, insufficient technical capacity, and information asymmetries. Overcoming these barriers requires more than isolated policy instruments. National strategies should establish coherent investment frameworks that align climate, forestry, agriculture, and rural development objectives and enable effective coordination among governments, local communities, landowners, researchers, and the private sector.

Future policy frameworks should therefore prioritize integrated landscape governance, long-term financing mechanisms, knowledge transfer, and locally adaptable management strategies. Particular attention should be given to strengthening the link between scientific evidence and policy implementation, ensuring that climate and land-use strategies move beyond formal commitments toward measurable, context-specific actions. Ultimately, building resilient landscapes will depend on recognizing forests, agricultural systems, soils, water resources, and rural communities as interconnected components of a single socioecological system. Such an integrated perspective is essential for transforming existing climate and forestry commitments into effective, equitable, and durable pathways toward sustainable development.

AUTHOR CONTRIBUTIONS

Emre Babur: The process includes formulating the research topic, reviewing the literature, and writing the article.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

ETHICS COMMITTEE APPROVAL

Ethics committee approval is not required for this study.

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