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Review

Effects of Climate Change on Greek Forests: A Review

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Abstract: This study reviews the impacts of climate change on Greek forests, analysing factors such as climate trends, forest management, biodiversity, genetics, insects, and wildfires, using data from the Scopus and Mendeley databases and official reports. By utilising our current understanding and allocating necessary efforts and resources, we actively address climate change consequences on forests. This study focuses on climate change and extreme weather outcomes on forests. Greek mountain forests at 520–1310 m experience decreasing annual mean and minimum temperatures (−0.015 and −0.027 °C yr^{-1}) but increasing maximum temperatures (+0.014 °C yr^{-1}), especially in Southern Greece (+0.047 °C yr^{-1}). Recent findings reveal forests migrating to higher altitudes with favourable conditions, correlating with water availability, temperature, and tree growth, necessitating further research on forest productivity. A decline in fir tree-ring growth (Average Tree Ring Width Index < 0.6) is observed in mainland Greece, indicating temperature's effect on growth. Effective forest tree conservation requires prioritising biodiversity monitoring, considering climate change impacts on phenology and addressing the absence of strategies to protect and enhance genetic diversity. Climate change influenced 70 forestry pests' ranges, notably among Greek insect pests. Annual burned areas from forest fires data indicate a consistent long-term increasing trend, underscoring fire prevention prioritization and exploring fire risk, behaviour, and climate change. The study highlights two to four significant knowledge gaps, and one to three key challenges pertaining to the six research areas. Finally, it promotes partnerships for informed decision-making and better outcomes by integrating Indigenous knowledge, scientific understanding, and collaboration among research, policy, and local management.

Keywords: climate; Greek forests; forest management; biodiversity; forest genetics; forest fires; insects; Mediterranean zone

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1. Introduction

Mediterranean regions are particularly vulnerable to tree species loss due to the increased frequency and intensity of droughts [1,2]. Southern European forests have been subject to direct abiotic disturbances such as droughts and other climatic factors [3,4]. Forests in Greece cover a significant portion of the total area in this region, with a coverage of 65.5% (8.4 million hectares). According to the results of the First National Forest Inventory conducted in 1992, 49.3% of the land is covered with forests, of which 25.4% are highly productive forests and 23.9% are low-forested lands primarily used for grazing and soil protection. In recent years, many natural areas have been designated as "protected" to safeguard wild and vulnerable species of flora and fauna. There are 320 such sites (covering 2.7 million hectares) listed in the European Network Natura 2000 and special protected areas. These designations aim to preserve the natural habitats of these species and prevent their extinction [5].

Water scarcity is likely the primary climatic constraint in limiting forest growth in Greece. Studies have demonstrated a strong correlation between water availability and tree-ring width, tree growth, and different tree species in Mediterranean forests [6–9]. Mediterranean forests provide invaluable natural capital, yet they are facing threats due to climate change, population growth, and other causes of forest deterioration. To ensure sustainable forest management and to balance economic, social, and environmental factors, countries in the Mediterranean region are working to implement and enforce long-term policies [10].

As expected, Greek forests are affected by the changing climate conditions in various ways. The Mediterranean climate prevailing in Greece is characterized by hot and dry summers and mild and wet winters. The combination of hot and dry conditions, and the increase in the frequency and severity of wildfires, coupled with human activities such as burning agricultural wastes, has led to a sharp rise in forest fires, particularly in the summer months. Scientists frequently discuss the long-term ecological implications of climate change, such as changes to soil quality, water cycles, and biodiversity. Furthermore, changes in precipitation patterns and snowmelt timing affect water availability, increasing the risk of drought and creating challenges for the management and conservation of water resources. Sustainable forest management, restoration, and reforestation actions are valuable tools to mitigate all these effects.

Changing climate in Greece is affecting national forests in numerous ways, with far-reaching ecological and environmental consequences. To ensure the long-term health and sustainability of Greek forests, there is a need for comprehensive and integrated strategies to address the impacts of climate change on forests and the associated ecosystem services. By leveraging existing knowledge and providing more efforts and resources where needed, we can proactively address the implications of climate change on our forests.

This review aims to provide a comprehensive review of the current state of research on the impact of climate change on forests at the national level. It examines important achievements, as well as areas where progress is lacking, focusing on key issues such as climate trends, forest management, forest genetics, plant biodiversity, insect infestations, and forest fires. Finally, the authors draw attention to specific challenges in each thematic area, based on their viewpoint and the existing literature. This process could benefit the public dialogue, inform public decision-making, foster collaboration among stakeholders, and finally identify potential solutions to address challenges related to climate change and forest resource management.

2. Materials and Methods

This study is based on a comprehensive review and document analysis of literature on climate change impacts on Greek forests and concerning trends in climate parameters, forest management, forest biodiversity, forest fires, insects and forest genetics identified in the Scopus and Mendelay databases, only focusing on papers and important scientific official reports published over ther last three decades. Document analysis is a systematic procedure for reviewing or evaluating documents—both printed and electronic material—which requires that data are examined and interpreted to elicit meaning, gain understanding, and develop empirical knowledge [11,12].

We applied specific criteria to determine the relevance of the bibliography. These criteria included focusing on recently published studies and specifically targeting those that directly addressed the key objectives of our study. After manual search, we ensured that the selected studies covered our various thematic categories related to climate, allowing for a comprehensive analysis of the topic.

Once the relevant literature was identified, it was typically analyzed and synthesized to identify key themes, trends, and findings related to the main topic of the paper. The final product of this comprehensive review is typically a comprehensive and critical analysis of the existing literature, with a focus on identifying gaps in knowledge and key challenges/recommendations for future research.

3. Synthesis of Research Review

3.1. Climate Trends in Greece

Temperature, precipitation and their related attributes highly affect the growth, phenology and spatial expansion of forest species mainly due to the reduced water availability in the soil in association with the increased water demand for evapotranspiration [13,14].

Around the globe, temperature and precipitation patterns present high spatial and temporal variability. Their changes are associated with latitudinal and altitudinal gradients [15] and also by season, forming several topo-environments with different characteristics. The changes of the long-term climatic normals of temperature and precipitation occur both by natural and anthropogenic causes, attributed mainly to the increase in minor gasses in the atmosphere, including CO_2, but also to the dynamic effect of water vapor to determine heat flux exchanges [16]. The climatic changes appear to vary among different areas of the world. Indicatively, Lindzen [17] mentioned a relatively stable climate near the equator and major climate changes near the poles, compared to the past century. The paleoclimatic analysis conducted by Moriz et al. [18] indicates higher surface temperatures in the Arctic during the 20th century than during the preceding few centuries. Alizadeh and Babaei [19] identified significant warming trends with strong seasonal variability for the period of 1979–2020 over Southwest Asia, whereas in the mountainous areas, the temperature increase occurs much faster, especially in winter and spring. Certain mountain ranges, however, such as the southern part of the Tibetan Plateau, seem to exhibit resistance to global forcing, with warming occurring at a later stage [20]. For precipitation, Alizadeh and Babaei [19] detected high spatial and temporal variability with significant decreasing trends in winter in southwestern and eastern Iran, in southwestern Pakistan and over the Oman Seas, no significant changes were found in spring in Caucasus, but significant increases during autumn in Saudi Arabia and over the Persian Gulf were found.

In the Mediterranean, which is characterized by complex topographic patterns with high variations in altitudes, aspects and soil types, in continental and island areas, a large variety of local microclimates is formed, producing several types of forests with distinct characteristics [21]. Also considering the climate as a dynamically and constantly changing system, the Mediterranean is fairly characterized as a hotspot for both climate change [22,23] and biodiversity [24,25]. The inter-and intra-annual variability of the Mediterranean climate has fostered a lot of research interest during recent decades and influences national and local policies to ensure the sustainability of local economies, especially in the agricultural and forest sectors which are highly vulnerable. Especially, in the East Mediterranean basin, the local communities struggle to confront with the impacts of the changing climate in order to conserve and protect the natural heritage from a variety of risks including wildfires, droughts, floods, storms, heatwaves, decreased water availability, etc. For a proper climate assessment, including the detection and quantification of climate trends, the study of several meteorological and climatic attributes is required, in association with biotic factors, including the agricultural and forest ecosystems' responses (growth, phenology, production, etc.) [13,14,26].

On a global level, air temperature has increased by 0.84 °C since 1960, and the warming rate has maximized during the last three decades [27]. Especially for the summer months (June, July and August), future scenarios foresee a temperature increase by 0.6–1.8 °C for the period 2016–2035, with the greatest warming to occur at the continental part of the Mediterranean [27]. Feidas [28] identified a general cooling in the Mediterranean for the period 1955–1975 and a warming trend thereafter, underlining, a high spatiotemporal variability. Specifically, in the central and west part of the basin, the author identified distinct warming trends, but in the east part, the temperature trends are rather vague. Tanarhte et al. [29] conducted an analysis of recent climate trends in the Mediterranean and Middle East regions and found that temperature had increased in all areas examined, with, however, a high degree of spatial variability of the warming rates. The highest rate of temperature increase was observed in the East Mediterranean, ranging from +0.2 to +0.4 °C per decade after 1970. However, in the central and eastern parts of the basin, the rate of change was much smaller or not significant after 1990.

In Greece, Feidas [28] analyzed data from 20 stations distributed within the Greek peninsula for the period 1955–2013 and satellite data for the period 1979–2013, and detected increasing average (annual and seasonal) temperature trends. The annual temperatures from ground measurments and satellite observations showed a rate of change of +0.038 °C yr^{-1}, with seasonal variations ranging from +0.019 °C yr^{-1} in winter to +0.064 °C yr^{-1} in summer from the ground data, and from +0.024 °C yr^{-1} in autumn to +0.045 °C yr^{-1} in spring from the satellite data.

The warming effect appears to have also affected high-altitude mountainous areas. Proutsos et al. [30,31] investigated the trends of minimum, maximum and mean temperature attributes in nine mountainous Greek forests of *Abies borisii-regis*, *Abies cefalonica*, *Pinus nigra*, *Querqus frainetto* and *Fagus sylvatica* at altitudes ranging from 520 to 1.310 m, for the period 1960–2006 and identified significant decreases of annual mean and minimum temperatures with average rates of −0.015 and −0.027 °C yr^{-1}, respectively, whereas the maximum temperature was detected to have increased, compared to the past, with an average rate of +0.014 °C yr^{-1}, which is higher (+0.047 °C yr^{-1}) in S. Greece. In the island of Crete, (S. Greece) Proutsos et al. [32,33] studied the temperature changes in Herakleion for the period 1955–2017 and reported warming trends for all (mean, maximum and minimum) temperature attributes (with annual rates +0.008 °C yr^{-1}, +0.010 °C yr^{-1} and +0.016 °C yr^{-1}, respectively). The authors also identified that temperatures were cooling up to the mid-1980s, but changed to rapidly warming thereafter until today. Similar changes were also found for the number of cold days, which had significantly decreased during the recent climatic period.

Precipitation varies greatly, both in magnitude and trend, on a global scale [34]. In general, precipitation trends in N. Europe indicate wetter conditions compared to the past, whereas the Mediterranean basin has become drier [27]. The future conditions are expected to be even more unfavourable, especially for the East Mediterranean countries, due to the anticipated precipitation reduction during the wet period of the year [27]. Specifically in Greece, the precipitation trends are in general negative, suggesting drier conditions compared to the past, especially for the island areas [9,35]. In continental regions, the trends are less clear, though in recent years, some areas of Northern Greece have seen increasing trends [36]. In coastal regions, the average changing rates show about a 5% decrease, whereas the most rapidly decreasing precipitation was detected in 1960–1990 and changed to increasing rates thereafter [37–41]. Proutsos et al. [42] investigated the precipitation trends in 32 rural and forest areas at varying altitudes (1–1.310 m) and latitudes across Greece for the period 1951–2006 and found decreasing precipitation trends, particularly in lower altitudes and at northern latitudes. At the low altitudinal areas, the local forests grow under highly variable climatic conditions. The precipitation trends of Nestos river basin (N. Greece) for the last 50 years confirm the rapid and significant decrease in precipitation at the river's delta but also indicate increasing precipitation and thus higher water availability for the local vegetation at the higher altitudes of the river's basin [43,44].

The combined effect of precipitation and temperature, expressed through drought and aridity indices, is critical in assessing the effect of climate change on vegetation, especially for rain-fed agricultural and forest ecosystems. According to UNEP's [45] aridity classification system, the Greek climate is in general humid or sub-humid, whereas many parts of the Greek peninsula are already arid or sub-arid, especially in central Greece and the central Aegean islands [46]. Tsiros et al. [47] investigated the changes of aridity and related factors during the last century (1900–1997) by employing long-term series of 91 ground station data and found that most regions of the Greek Peninsula are facing more arid conditions during the recent climatic period (1960–1997), with lower water surpluses in the wet period and stronger water deficits in the dry period of the year, compared to the past. It appears that even high-altitude ecosystems are being impacted by aridity. Indicatively, in Metsovo (alt. 1310 m, N. Greece), during the last 50 years, the effective precipitation has significantly decreased and evapotranspiration has significantly increased, both presenting, however, high seasonal variability [48]. Similarly, in the urban and peri-urban area of Attica (central Greece), the local climate has changed to more arid conditions with less available water for vegetation, negligible water surpluses and increased water deficits during the recent decade compared to the past, and these climatic changes are more severe and rapidly occurring in the urban area compared to the peri-urban forests [49].

The assessment of weather attributes also confirms that the high pressures for the Greek forests are not only imposed by the long term effect of a gradually changing climate to more adverse conditions but also due to rapid short-term meteorological changes on daily, monthly, seasonal or annual timesteps and, additionally, due to extreme weather events [26]. A drought assessment in the riparian forest ecosystem of Nestos (S. Greece) for the last 50 years, conducted by employing different drought indices, revealed that drought is more intensively occurring at the altitudinal lower parts of the River's Delta (and parts close to the sea) and is less sound at the higher altitudes [50]. In S. Greece (Herakleion-Crete), the drought assessment for the period 1955–2022 indicated more frequent and severe drought in recent years compared to the past, which is expected to be more intense in the future, impacting local urban green infrastructures [51].

The findings from the studies in Greece suggest that the pressures imposed by the changing climate and extreme weather events are expected to force the local forests to either remove their boundaries to higher altitudinal zones or migrate to northern regions, where more favorable conditions persist. It should be also noted that human-induced stress factors, in conjunction with the pressures of the changing climate, could result in significant changes in forests expansion, growth and phytosociological characteristics. Overgrazing and illegal logging can seriously affect forests' dynamics and ecological status (expansion, regeneration rates, seed production, etc.), especially in highly protected habitats [52]. Extremely important is the adoption of measures for the conservantion of habitats or species surviving at the tops of the mountains or in areas where the vegetation adaptation/migration rates are slower compared to the pace of climate change. In such cases, the local flora is highly threatened and the danger for species or habitat extinction is likely to occur in the near future.

3.2. Climate Change and Forest Management

Given the numerous management objectives involved in Mediterranean forestry, it is difficult to evaluate these objectives at the forest-stand level. The risk and uncertainty associated with decision-making in this context are among the most pressing challenges. Unfortunately, climate fluctuations will likely remain a source of uncertainty concerning forest dynamics, increasing the risk of forest fires, droughts, and the emergence of new diseases and plagues [53]. Conversely, it is predicted that a change in temperature and/or precipitation in Mediterranean countries may lead to a decrease in productivity [54]. Nevertheless, the concept of sustainable forest management is designed to promote the long-term use of natural resources, as well as to safeguard forest ecosystems.

Almost the half of Greece is made up of forests and other woodlands. A majority of these forests consist of sub-selection and selection stands, with the rest being even-aged stands. Coppice forests, which are mostly even-aged stands, account for a large portion of the forests. Unfortunately, their quality and quantity of growing stock is not ideal, mainly due to human activities such as fires, grazing, land clearings, illegal fallings, and the lack of silvicultural treatments [5]. It has been reported that forest management typically focuses on wood production (including boat building), non-wood production (such as resin, honey, livestock, mushrooms, and pharmaceutical wild-plants), as well as social uses (including wildlife, recreation, and hunting) [5].

Greece's forests serve multiple purposes, such as generating wood and other products, preserving the soil from destruction, controlling water flow, supplying food and shelter for wild animals, providing grazing land for livestock, offering recreational activities, and providing wildlife habitats. Koulelis [55] reported that the majority of forests in Greece are located in areas with steep mountains and slopes, which make harvesting difficult. This, in turn, decreases both the production and quality of wood due to managerial and ecological factors (e.g., the abundance of knots).

Koulelis [56] also classified Greece as having lower timber productivity than other EU countries. The forests in Greece mainly generate logs for sawn wood, used mainly by the state power company or telecommunications companies or for mining timber, and wood chips for particleboard, MDF, paper, and pellet production. Greek fir trees, together with oak, beech, pine, and spruce, play a significant role in the Greek economy; so, some studies have focused on them. Data from the forest inventory reveals the importance of this species, which is one of the most economically important tree species in Greece. Greek fir forests consist of 43.133.020 m^3 of tradeable industrial round wood, making up 30.23% of the total production [57]. The most recent Greek Forest Strategy [58] aims to secure sustainable timber production at a nationwide level. It is necessary to recognize the growth rates of the commercial species in order to balance harvesting and regrowth. Variations in climate factors can have repercussions on the productivity and/or forest-site productivity of forests [59]. For instance, elevated temperatures and prolonged periods of drought can impede the growth rates of trees, restrict the development of new wood, and consequently diminish the overall yield of timber. It is worth noting that the existing literature at the national level does not adequately address this particular concern.

Research shows that forest growth not only describes the volume production potential of forests and the dimension and quality of the produced wood, but it is also a useful base for understanding the relationship between trees and their environment. Water scarcity is one of the principle climatic limitations to forest growth in Greece. Multiple studies have established a strong association between the amount of water available and tree-ring width, and growth for various Mediterranean forests and varieties of trees (e.g., [7–9,26]). In this way, tree-ring analysis can be helpful in cost-efficient forest management.

Koulelis et al. [6] utilized the Standardized Precipitation Index (SPI) [60] and tree-ring analysis to explore the connections between climatic elements and tree growth (*Abies cephalonica*) on the mountain Giona over a period of 55 years. It was found that negative or positive changes in growth were caused by these events, while milder events, as indicated by the SPI, had a lesser effect on the measurable tree-ring growth. The SPI of the previous year's growing season (March to August) was seen to be an important factor in extreme drought event analysis, as it pointed to the potential of the current year to cause fluctuations in tree-ring growth. There was a decline in growth observed at both elevations after 1998, which was unrelated to SPI, but seemed to be linked to the European fir budworm (EFB) defoliations that had been observed.

Sarris et al. [9] provided evidence that the eastern Mediterranean has been experiencing a drying trend since the late 1970s, as seen in both weather records and tree-ring data. Analysis of plots in Samos, an island in the eastern Aegean Sea, demonstrated that tree-ring width and annual radial stem increments have declined, which indicates that trees are adapting to the dry conditions by adjusting their growth responses to precipitation. In 2000, a vast amount of low altitude pines perished, demonstrating the drastic effects of this trend. This evidence corroborates the Intergovernmental Panel on Climate Change's forecast that the eastern Mediterranean will become increasingly arid as temperatures rise.

Papadopoulos [8] investigated the tree-ring patterns and climate responses of three fir populations along a latitudinal gradient in Central Greece, where the common endemic species *Abies cephalonica* and *Abies borisii-regis* have experienced problems such as forest fires and fir decline exacerbated by climate change. An examination of tree-ring widths showed that 59% could be attributed to commonly occurring tree-ring patterns and 25% to variations between the south and north. Tree-ring widths were positively affected by late spring and summer precipitation, October and April temperatures, and June drought.

All dendrochronological statistics and tree-ring patterns showed a south-to-north trend following climatic and phenotypic variation.

On the other hand, Koutavas [61] found an unprecedented and sustained increase in ring-width variations from eight Greek fir trees (*Abies cephalonica*) growing on Mt. Ainos on the island of Cephalonia since 1990, with no relationship to regional temperature or precipitation. It is hypothesized that this growth reflects a fertilization effect due to rising CO_2 in the atmosphere, and that the growth may be age dependent. He concluded that further sampling is needed to confirm this hypothesis.

A recent study by Koulelis and Petrakis [62] examined the relationship between tree-ring growth, climate, and insect infestations of *Abies cephalonica* stands across Central Greece and Giona Mountain. Results show that extreme drought and wet events had a negative or positive effect on tree growth, respectively. April's precipitation had a positive correlation with growth, and the average maximum temperature of the growing season and the maximum temperatures of April, July, and August were also linked to growth. Evapotranspiration during the growing season was seen to be inversely proportional to the growth. A significant decreasing tendency in growth was observed in recent years, likely due to temperature, which suggests that more research into tree rings and their relationship with climate is necessary for successful and sustainable forest management in the future.

Koulelis et al. [7] examined how regional climatic conditions can impact tree growth in *Quercus frainetto* Ten., *Fagus sylvatica* L., and *Abies borissi-regis* Matt f., as observed in three long-term intensive monitoring plots in Greece over the period 1996–2009. By analyzing the relative basal area and volume increments, the authors have observed a reduction in growth following periods of high temperatures and aridity. This decline has been statistically validated in oak and beech plots, offering a solid foundation for future monitoring programs and forest management strategies to address potential climate implications.

More analysis for broadleave trees was made by Xystrakis [63]. He studied the drought–tolerance threshold of *Fagus sylvatica* on calcareous soils at Mt. Olympus in NC Greece. Data from 108 plots showed a gradient from dry pine-related plots to more moisture-favorable beech-related plots. Results indicated that actual evapotranspiration and moisture deficit are the driving factors of the vegetation pattern. More specifically, beech-related vegetation units were predicted to dominate on sites with actual evapotranspiration rates > 276.5 mm while pine-related vegetation units were predicted to dominate on sites with actual evapotranspiration rates < 276.5 mm and moisture deficit > 312.5 mm during the three drier months.

In addition to studying the effects of climate on tree rings and production, there are also studies that focus on vegetation and vegetation dynamics through forest management techniques. Spanos et al. [64] provide an overview of forests, forest management and biodiversity in Greece, summarizing the distribution of the main forest species and their ecosystems, their functions and uses, management type/regime, risks and threats, and conservation measures. The paper concludes with a discussion of the new Rural Development Program (2014–2020) and highlights the future management and conservation of forests. The authors also propose several common and well-known actions to deal with climate change in forests, such as enhancing mixture with broadleaves (e.g., oak, beech), removing dead trees, maintaining viable populations in isolated areas, preserving intra- and inter-population genetic diversity, preserving natural habitats, and controlling grazing according to the tree species.

Along similar lines, Tzedakis et al. [65] provided an interesting look into the correlation between climate variability and vegetation changes in northeast Greece over the last 450.000 years. Their analysis presented a good overview of the various elements that influence the vegetation changes, such as orbital and suborbital frequencies, North Atlantic ice-rafting events, changes in atmospheric CO_2 levels, and high-latitude insolation.

Fyllas et al. [66] described the development of a model, GREFOS, to simulate the dynamics of Mediterranean forest ecosystems including areas in Northwestern Greece and *Pinus nigra* species. GREFOS is adapted to the bioclimatic conditions and species traits of the northeastern part of the Mediterranean Basin. It follows the structure of the ForClim model, and incorporates a life history strategy parameter and a simplified fire submodel. Simulation exercises and scenarios of changes in fire frequency were explored, which suggested that pioneer pine species would be able to increase their abundance at the upper and lower limits of Mediterranean and temperate vegetation.

Chrysopolitou et al. [67] explored the effects of climate change on forest management in Greece through a LIFE project called AdaptFor. They discovered that remote sensing and time series of temperature and precipitation can be used to identify correlations between climate change and the death of certain tree species. Surprisingly, however, there seemed to be no connection between the presence of conifer species in broadleaved forests and climatic parameters, which needs further exploration. Additionally, inadequate management was found to aggravate the problem.

In the same topic, Beloiu et al. [68] conducted research on the treeline dynamic in semi-arid Crete, Greece, from 1945 to 2015 and found that, despite an increase in temperature over the past 70 years, there was no shift in the treeline. Strong correlations were found between the treeline elevation and topographic exposure to wind, suggesting that the temporal lag in treeline response to warming could be explained by a combination of topographic and microclimatic factors. This pointed out that the lack of climate-mediated migration at the treeline should raise concerns about the threats posed by warming, such as drought and wildfire, especially in the Mediterranean region.

Fyllas et al. [69] explored the potential shifts in vegetation and fire regime in some dominant forest types in the northeastern part of the Mediterranean basin under climate change. It was conducted in two altitudinal gradients in the continental part of Greece, using a forest gap dynamics simulator and two climatic change scenarios. Results showed that fire was found to be significant in low-altitude sites, and its significance increased with the severity of the climate change scenario. The study concluded that mountainous Mediterranean drier areas are more vulnerable to compositional alteration and flammability trends due to changes in drought stress and fire frequency.

More focused on land desertification and land management, Tzamtzis et al. [70] examined the current GHG balance in Greek forests and the effect land use and land-use changes have had on this balance in recent decades. They used data from the 1st National Forest Inventory, a great number of forest-management plans, and data on land-use changes to analyze the effect of forest management practices and deforestation on GHG emissions. They found that forest land acts as a net carbon sink, with its capacity increasing from ca −1.1 Mt CO_2 eq in 1990 to −2.1 Mt CO_2 eq in 2016, mainly due to forest management practices. Additionally, net emissions from deforestation in the period 2008–2016 amounted to 0.5 Mt CO_2 eq.

In the same line, Kairis et al. [71] looked into how land management techniques influence soil erosion and land degradation in an agro-forest landscape in Crete, Greece that is particularly susceptible to desertification. Results demonstrated that sustainable grazing produced less water runoff, sediment loss, and soil temperature compared to overgrazing, and that plant cover was more effective in reducing water erosion from the 'sustainable grazing' area than from the 'overgrazing' area. The findings of this study suggest that overgrazing is a major factor in land degradation in southern Europe and that the appropriate management of pastoral landscapes may help reduce desertification risks.

3.3. Climate Change and Biodiversity

The natural environment in Greece has received pressure over the centuries, both in intensity and duration. However, this environment still impresses both by the virtue of its naturalness and by its rich biodiversity. The latter encompasses the variety of living organisms of all origins (species level), their genes (genetic level), and the ecosystems they inhabit (ecological status) [72]. It includes how we perceive and appreciate the diversity among different levels of life organization. Additionally, biodiversity reflects the quantity, diversity, and variability of living organisms and the systems they form [73].

Greece is renowned for its abundant natural wealth, boasting a remarkable array of terrestrial, wetland, and marine ecosystems with an array of diverse species and high density. Its vibrant and fascinating flora further adds to its value. Greece's vascular flora is made up of 5927 species and 2008 subspecies (native and naturalized), totalling 6811 taxa from 1089 different genera and 184 families [74,75].

The higher species richness of vascular plants can be attributed to a combination of several factors. Firstly, the country's diverse geography, including vast valleys, mountains, numerous islands, islets, rocky islands, and peninsulas, along with its complex landscapes and morphology, create a favorable environment for plant growth and diversification. Secondly, the geological structure of the country showcases a wide range of rocks and rock formations, further contributing to the variety of habitats available for different plant species. Additionally, the country's flora is enriched by the presence of Central European species that sought refuge in the region during the glacial period, as well as species from the Black Sea and Eastern regions. Finally, the long history of human presence, dating back to prehistoric times, may have also influenced the diversity and distribution of plant species [76].

The native Greek flora is abundant and diverse, flourishing in a wide range of terrestrial habitats, whether they are natural or man-made. Within forest ecosystems, the flora is predominantly composed of a diverse assemblage of plant communities that collectively shape the varied vegetation found in these habitats. This vegetation displays a multitude of physiognomic characteristics, which in turn enhance the overall richness and intricacy of the forest flora [77].

The preservation and protection of biodiversity ensure the development of sustainable populations and ecosystems. Approaching biodiversity in an anthropocentric way, it is important to mention the direct benefits arising from its exploitation. The exploitation of high biodiversity and ecosystems provides food, energy, medicine, timber, fibre, and other raw materials, operational practices, experience, and knowledge yielding valuable capital in the global economy. At the same time, this vast "warehouse" of life forms and ecosystems generally provides free recycling services and environmental sanitation [78,79].

In recent years, there has been a loss and degradation of ecosystems as well as a loss of Greek species of flora/fauna and natural habitats, creating multidimensional negative effects and, consequently, degradation of ecosystems and the services they provide [73]. The main possible causes leading to the loss of biodiversity are the following: (a) intensification of agriculture, (b) changes in land use, (c) direct exploitation of organisms, (d) climate change, (e) pollution, (f) alien species, and (h) overexploitation of natural resources [80].

The phenomenon of climate change is one of the main causes of biodiversity loss and changes in ecosystem services worldwide. In the fourth report of the Intergovernmental Panel on Climate Change [1], it is stated that if the scenarios considered are come to pass, climate change is likely to have significant effects on components of biodiversity such as species, ecosystems, genetic diversity within species and ecological interactions. In addition, the sixth assessment report [81] underlines that the global biodiversity loss is increasing due to rising extinction risks for numerous plant and animal species, driven by local extinctions, sub-species declines, climate change-related global species extinctions, and projected impacts on taxa surpassing natural rates, with some taxa facing potential extinctions of over 50% of their species. The effects of climate change on biodiversity could be multifaceted. Specifically, biodiversity can be affected by a combination of factors including the direct effects on organisms (e.g., temperature affects survival rates, reproductive success, dispersal, and behaviour patterns), the impacts through biotic interactions (e.g., conferring a competitive advantage), and the impacts through changes in abiotic factors (e.g., inundation with water, changes in ocean currents) [1].

Based on IPCC estimates, climate conditions in Greece may change, which could have consequences for forest ecosystems. It is estimated that if the IPCC predictions are confirmed, the forest ecosystems of higher altitudes may be replaced by shrublands, i.e., generally degraded ecosystems [82]. Plant species on Greek mountains will come under competitive pressure from species of lower altitudes that are migrating to higher altitudes as a result of increasing air temperature [83]. Furthermore, any change in the flora and fauna diversity of a forest due to climate change will lead to a decrease in their population or even to their disappearance if the rate of occurrence of climate phenomena does not allow their migration. For example, in Greece, due to reduced rainfall and snowfall, there is a weakening of the individuals of *Abies cephalonica* and of the *Viscum album*, which is a plant that uses the fir as a host, with the consequence that it is stressed too [84]. Also, based on the climate scenario IPCC A2, the population of the following species will be reduced significantly in Greece. More specifically, the *Quercus ithaburensis* sub *macrolepis* will be reduced by 56% and the *Matricaria chamomilla* by 88% [1].

3.3.1. Changes in Vegetation Patterns

Climate change is predicted to reduce habitat at different rates [85]. Plant communities would be affected by habitat loss [86] and seed production [87] caused by climate change. Extreme cold events [88] and drought [89] can also affect fauna. The most susceptible vegetation zones in the Mediterranean extend to the region's southern limits. In addition, there would be severe impacts on plant populations due to changes in atmospheric CO_2 concentration (reaching 600 ppm by the end of this century [90]), which would affect both plant productivity and water-use efficiency [91,92]. Climate change adaptation strategies of vegetation would also lead to habitat migration to regions with more favourable climate conditions. However, many plant species cannot adapt to the requirements for the transition or establish new plant communities in new environments [93]. Species would take about 250–1000 years to complete a 100 km migration transition if climate change occurs more rapidly (as predicted by the A1B scenario, temperature increase velocity is 42 km per 100 years and can reach 100–1000 km per 100 years in many regions) [94].

Warmer winters in the Mediterranean region are predicted to reduce frost damage to plants [95] and increase winter photosynthesis [96]. This could result in a shift in the competitive advantage of species, leading to an alteration of the forest structure and population dynamics that could convert forests to shrublands [97]. Greek mountains are particularly vulnerable to climate change because they have higher air temperatures and decreased precipitation compared to other mountains in the region [98]. This could potentially trigger a transition in the composition of vegetation, wherein xerophilous plant species become dominant in low mountain areas, while there is a decline in the prevalence of vegetation that exhibits moderate tolerance to water availability [99]. It could also lead to an expansion of semi-arid forests and a reduction in the range of cold gymnosperm forests [25].

3.3.2. Changes in Plant-Species Phenology

Climate change affects phenology and changes are expected in the season of flowering, leaf development and seed maturation of forest trees in Greece [100]. Physiological functions of the trees will be affected and changes in the rate of photosynthesis and transpiration will occur. Drought will reduce productivity in sensitive species. Such conditions are expected to affect the regeneration potential and forest composition. The distribution of species will change and bioclimatic envelopes (conditions in which a species grows best) will move north or to higher altitudes. Due to the change in temperatures, the decrease in soil moisture and the increase in CO_2, the competition between species is expected to change and result in a decrease in biodiversity in Mediterranean ecosystems. Changing the competitive dynamics of species will significantly affect mixed stands and natural ecosystems. In the coming years, the natural ranges of forest species will be affected, as their warmer and drier ranges change (specific climatic conditions characterized by higher temperatures and reduced moisture levels). In the future, species migration is expected [83].

3.3.3. Mitigating the Impacts of Climate Change on Biodiversity

Forest conservation offers opportunities to protect biodiversity and limit climate change. The EU proposed measures to deal with the effects of climate change for the protection and sustainable use of biodiversity [101]. These measures are considered "low-cost co-benefit" options as they provide multiple benefits simultaneously. Some of these options include preserving and restoring degraded land, forests, peatlands, and wetlands. Additionally, reducing the conversion of pastureland, minimizing slash and burn practices, and improving grassland management are also part of these measures (ibid.). In addition, they should enhance ecosystem resilience, maintain healthy and productive forests and enhance carbon storage. Other measures that should be taken into account include the following: a) management strategies need to be adjusted, and immediate measures must be implemented; b) knowledge and research around the sensitivity of species and ecosystems should be further developed in order to create a clear picture of their actual resistance limits; and c) to carry out systematic monitoring of forest ecosystems, with the aim of early observation of any changes [102–104].

According to Solomou [105], there is a significant lack of scientific data pertaining to the various components of biodiversity and their characteristic trends. This dearth of information hinders our ability to make well-informed decisions crucial for effective conservation strategies, as highlighted by the study conducted by Dimopoulos et al. [106]. To address this issue, it is essential to gather more monitoring data in order to accurately assess biodiversity changes, as emphasized by Solomou and Sfougaris [107]. The Greek Ministry of Energy, Environment and Climate Change [108] has further highlighted the partial or inadequate implementation of existing institutional frameworks, which have so far failed to prevent illegal activities such as poaching, overfishing, and arson.

Additionally, there are other obstacles still harming biodiversity at the national level: (a) failure to integrate sustainability principles into productive functions like activities related to industries, agriculture, manufacturing, or any other sectors that contribute to economic output and productivity; and (b) A lack of stable funding, leading to understaffing of protected areas, insufficient management structures, and a lack of specialized, appropriately staffed services (both central and regional) [107,108]. Hence, Greece ratified the convention in 1994 (Law 2204/1994), yet it took 20 years for the National Strategy for Biodiversity to be completed by Joint Ministerial Decision number 40332/2014, facing many of the above issues.

The adoption of the first Greek Biodiversity Strategy is a milestone in national biodiversity conservation policy. This outcome is a direct consequence of the strategy's emphasis on key objectives, including halting biodiversity loss and ecosystem degradation by 2026, restoring them where feasible, promoting biodiversity as a national asset, and strengthening Greece's global efforts to combat biodiversity loss [109,110].

3.4. Impacts of Climate Change on Forest Genetics

The Mediterranean basis is considered a hotspot of biodiversity for plants harbouring evolutionary footprints of plant taxa [24,111]. Genetic diversity permits high adaptability of forest ecosystems and is the key force for allowing evolution of all living organisms [112]. It is the basic element of biodiversity at all levels (species, ecosystem, landscape) and knowledge of the adaptive potential of forest genetic resources is a pre-requisite for successful forest management [113]. Forest managers must consider the role of genetic diversity in mitigation and adaptation practices in the face of the ongoing climatic changes [114].

Situated in the southeastern region of Europe, Greece's unique genetic pools are a product of its geographical location, which acts as a marginal distribution frontier for numerous plant species. Being a Mediterranean country, Greece stands out as one of the most biodiverse regions, with an impressive array of over 7000 native plant taxa.

Greece has a unique genetic pool compared to the European continent for various forest species [115–117]. Moreover, recent studies have further revealed the unique epigenetic role played by forest tree species in their adaptation. This highlights how epigenetics serve as a direct response of plants to climatic changes, allowing them to fully adapt to new environments [118–120].

Forests in Greece face threats due to ongoing climatic changes, pest and insect attacks, fires [121,122], drought periods [26,46,47], invasive alien species [123], and biodiversity loss [110]. Consequently, the genetic diversity of forest species is actively lost [124]. Projecting future forest conditions has become (and will become even more) complex. In general terms, the conservation and protection measures for forest genetic recourses must be enhanced and incorporated into forest management practices in order to successfully conserve the future adaptability of our natural environment [125].

3.4.1. Developing Strategies to Protect and Enhance Genetic Diversity

In situ conservation is usually the preferred approach for maintaining the genetic diversity of forest species, even though these forest species are also conserved ex situ in seed banks, clone collections, provenance trials, planted conservation stands and botanical gardens, especially when population size is extremely low in nature [126]. Therefore, ex situ conservation is defined as the conservation of genetic diversity outside the natural environment (ibid.).

Ex situ conservation is static by maintaining the genetic diversity of the sampling, in contrast to in situ conservation which is dynamic and allows temporal and spatial changes in genetic diversity. Furthermore, conserved ex situ is costly and more challenging to implement, enabling only a limited number of trees/populations to be preserved, compared to in situ conservation. Additionally, trees in ex situ conservation are not subject to evolutionary processes, as they do not interact with their surroundings and do not compete with individuals of the same or other species" However, no single technique can preserve the entire range of genetic diversity of a target species. Both techniques (ex situ and in situ) should be used in a complementary manner to ensure the greatest conservation of genetic diversity.

Greece joined the European Information System on Forest Genetic Resources (EUFGIS) network which was created as an information system with the aim of creating Gene Conservation Units throughout Europe. In addition, in 2018, 15 Gene Conservation Units were established for *Pinus halepensis*, *Pinus brutia*, *Pinus nigra*, *Abies cephalonica* and *Abies borisii regis* [127]. Moreover, 443 areas of the European network Natura 2000 have been established in Greece, which are divided among 202 special areas of conservation and 241 sites of community importance. Their total area covers ca. 4.300.000 hectares. In situ conservation efforts have also been made by nationally or internationally founded programs implemented by universities [115], forestry research institutes [128–133] and international collaborations. In general, it is well known in Greece that more effort should be put forth to conserve and preserve the country's unique genetic diversity.

In terms of ex situ conservation, the first time that Greece implemented a relevant program was due to a project funded by the United Nations Development Program entitled UNSF/FAO/GRE: 20/230, which was aimed at strengthening forest resources. Under this project, an afforestation program was initiated in which pilot provenances trial areas were established in 11 areas across the country. The main species that were planted in those areas were *Pinus radiata*, *Pinus pinaster* and *Pinus brutia*. In the second project funded by the UNDP entitled "Forest Development—Afforestation", three pilot areas were established for afforestation and the main species that were used were *Pinus pinaster*, *Pinus nigra* and *Pinus brutia*. The Food and Agriculture Organization (FAO) has established, in Greece, a network of provenance trials for *Pinus halepensis* and *Pinus brutia* to investigate the levels of existing variation for adaptive traits. In 1970, organized breeding programs were initiated, with the selection and collection of material on a provenance and mother-tree basis [131]. Apart from these efforts, the country should enhance the preservation of these ex situ trials and establish more in order to be prepared for future problems which will be associated with the climatic changes which are already happening.

3.4.2. Forest Genetic Monitoring

Genetic management of forest trees requires long-term commitment, planning and action. Each forest unit should have a specified status as a genetic conservation area, recognized by the competent authorities, to ensure its long-term management for this purpose. The management plan should be updated on the basis of genetic conservation [113]. The size of conservation populations is determined based on the likelihood of increasing the capture of the existing diversity of alleles (sampling perspective) and reducing the risk of losing genetic diversity during evolution (dynamic perspective) [134]. Species can be grown in pure or mixed stands with one or more stands of different age classes [135,136].

Forest genetic monitoring (FGM) is a crucial method because it monitors the temporal changes that occur in the genetic variation and structure of target tree populations. FGM can verify how well genetic diversity is maintained over time. Forest genetic monitoring includes three indicators (natural selection, genetic drift and gene-flow-mating system) and their assessment is based on demographic (age and size class distribution, reproductive fitness and regeneration abundance) and genetic (effective population size, allelic richness, latent genetic potential and outcrossing/actual inbreeding rate) verifiers [137].

In the context of the LIFE13 ENV/SI/000148 program "Life for European Forest Genetic Monitoring System" (LIFEGENMON), one coniferous (*Abies borisii regis*) and a broadleaf (*Fagus sylvatica*) were monitored. The results showed that both species are currently adapting well to climate change by maintaining their genetic diversity. In addition, within the framework of this project and based on the results obtained, a manual for forest genetic monitoring was created which is freely available online.

In the context of climatic changes, a HORIZON 2020 program was also implemented in Greece named "GenTree: Optimizing the management and sustainable use of forest genetic resources in Europe" and contains phenotypic and environmental data from 4.959 trees from 12 ecologically and economically important European forest tree species. For Greece, eight main species were investigated: *Fagus sylvatica* L., *Picea abies* (L.) H. Karst, *Pinus halepensis* Mill., *Pinus nigra* Arnold, *Pinus sylvestris* L., *Populus nigra* L. *Abies alba* Mill. and *Taxus baccata* L. [138]. Simultaneously, tree-ring collection was also implemented for seven key species in Europe and also in Greece [139], and the potential use of those data will be highly valuable for assessing ecological and evolutionary responses to environmental conditions, as well as for model development and parameterization, to predict adaptability under climate change scenarios.

3.4.3. Conservation and Management of Forest Genetic Resources

Although in Greece there are "in situ" conservation units of forest species, further development and protection is needed to protect and preserve the genetic pool. In addition, the lack of financial resources needed to preserve and protect the FGR is important. There is external funding from Europe, through several calls (LIFE, H2020) submitted by Universities and Research Institutes, but there is no National program to preserve and protect the forest's genetic resources. The Central Forestry Seed Warehouse also faces difficulties in maintenance due to financial reasons. An important step would be the creation of a National Forest Gene Bank where seeds from all important forest species would be stored and preserved for future use.

Although the management of the forest's genetic resources is important for conservation and protection, in Greece, where so many endemic forest species grow, little attention is paid to this subject. It is well known that there is a strong demand that forest management practices should take into account the protection of genetic diversity, including genetic monitoring and the creation of in situ plots for key tree species [113].

3.5. Insects and Climate Change

A recent account of invasive and alien species of Greece indicated that a number of insects (~300 species) [123] arrived in Greece from their country of origin, mainly as a result of geographical range expansion. For example, insects inhabiting Far East ecosystems expanded their geographical range towards western palearctic territories (e.g., *Xylotrechus chinensis*, Coleoptera, Cerambycidae). So far, what is known for range expansion is that it cannot be discriminated from forced expansion because of international trade. Range expansion is not known in several cases (Table 1). Climate change has affected the ranges of 70 forestry and agricultural pests apart from expansion due to international trade [140]. There is a significant disparity in the number of native insect species compared to those that have extended their geographic ranges through international trade, particularly evident in the case of Greek insect pests. [123].

Table 1. Forestry pests, hosts, and range expansion in Europe with descriptive references. The first six lines show species with a known mechanism of range expansion and the following four species with an unknown mechanism.

Species	Host	Type of Expansion	References
Epirrita autumnata	Broadleaves	Elevation, Latitude	[141,142]
Operophtera brumata	Broadleaves	Elevation, Latitude	*ibid*
Thaumetopoea pityocampa	*Pinus*, *Cedrus*	Elevation, Latitude	[143]
Cameraria ohridella	*Aesculus*	Latitude, Longitude	[144]
Dryocosmus kuriphilus	*Castanea*	Latitude, Longitude	[145]
Phyllonoricter platani	*Platanus*	Latitude, Longitude	[144]
Matsucoccus feytaudi	*Pinus*	Longitude	[140,146]
Neodiprion sertifer	*Pinus*	Latitude	[147]
Thaumetopoea processionea	*Quercus*	Latitude	[148]
Zeiraphera diniana	*Larix*, *Picea*	Elevation	[149]

However, range expansion may not be the underlining distribution pattern of many insect species and what we observe now may be the result of population cycles [148,150] and our ignorance about these cycles forces the strict view of range expansion. This expansion is mainly caused from the increased trade and people exchange between Greece and the country of origin, which are usually Far East territories. The historical presence of population cycles in studied insect–plant systems amplifies this argument and offers evidence for it. Alpine insects have been found to exhibit population oscillations, which could be attributed to climate change. These oscillations and their associated consequences, irrespective of the underlying mechanism (e.g., trophic interactions, maternal effects), have been documented. However, due to the complexity of ecological processes, establishing definitive proof of the direct relationship between these oscillations and climate change remains challenging [149]. An example is the system of *Zeiraphera diniana* and its host tree *Larix decidua* (larch–budmoth system) which exhibits population oscillations peaking every 9.3 years. Such oscillations are not seen in Greece but may exist in other systems such as the European fir bud moth (Chor [6,151] or the pine processionary moth *Thaumetopoea pityocampa*) [152]. The latter insect is the flag insect species for all studies associated with the impact of climate change on insects [148,152]. Almost all authors agree that even in this case, the population recolonizes areas rather than expanding its range.

Historically, insect species inhabiting high-latitude environments have exhibited a notable sensitivity to temperature increases, which is a characteristic shared by ectothermic animals [153]. Several life history traits, such as survival, growth rate and voltinism (the number of generations or broods that occur within a specific time period, usually a year), are likely to change in warmer environments. In northern Europe, hemipteran *M. fairmairei* is univoltine while in western and central Europe, it has two generations. In southern Europe, *M. fairmairei* is probably polyvoltine (i.e., has many generations). This demonstrates that, as the voltinism of a species increases with the warming climate, the populations of that insect species may increase, or even result in population outbreaks [154]. This same idea applies to any other biological organisms (e.g., arthropods other than insects) that are ecologically associated, which can obscure the impact of climate change. Climate change is usually associated with local extinctions of insect species. For instance, *Muellerianella* species are not found in the tropics, which means that their voltinism approached a ceiling above which there is no time for proper development.

Another case is associated with monophagous insect species and the local migration of their host to higher altitudes [155,156]. These studies revealed that almost 20% of the plants migrated to higher latitudes in the multi-summit mountain range of Lefka Ori (Crete) as a result of the warming of the climate. However, the majority of insects cannot be monophagous on Cretan endemic plants and, as a result, this restricted (i.e., 20%) migration did not result in a simultaneous insect migration. Migration of shrubs or trees is not observed in mainland Greece, except for the pseudo-alpine area of mountains generated by browsing and/or forest fires. For this, no insects were transferred attitudinally to cooler areas. Usually, the migration of insect species to cooler areas is geographically greater than the boundaries of one small country such as Greece. On a local scale, insects usually die off due to the warming of the climate rather than migrating to cooler areas. In central Greece (Schinias, Marathon), the population densities of heteropterans and hemipterans inhabiting the coastal pinewood are greatly reduced from an initial number of 150 species to a mere 10 species. Again, it is unclear if this is a result of climate change or the destruction of insect biotopes.

To all these events, the Epstein–Laferty controversy should be added [157]. Epstein, in a comment on the argument presented by Laferty, stated that the assertion "... *that while climate has affected and will continue to affect the habitat suitability for infectious diseases (many of them are transferred by insects), climate change seems more likely to shift rather than expand (their) geographic ranges* ... " has serious shortcomings. The shift of infectious diseases reflects a shift rather than an expansion of insect geographical ranges. Moreover, the latter argument, faces several challenges, including the definition of climate change, the non-uniformity of global warming in space and time, and the broad range of concerns involved. Climate change encompasses not only changes in global temperature but also shifts in weather patterns. These weather changes impact the timing, intensity, and location of disease outbreaks. Additionally, as warming occurs, there are more extreme weather events, both hot and cold, wet and dry, and the emergence of unprecedented occurrences like hurricanes in atypical regions. The distribution of these events no longer follows a Gaussian bell-shaped curve but appears to be trending towards a bimodal distribution with increased extremes at both ends. This controversy highlights the complex and ongoing debates within the scientific community regarding the precise impacts of climate change on disease vectors and the need for further research to better understand these dynamics. Another controversy is stated in a book about climate change in Mediterranean regions [3,158,159]. More precisely, the authors in this edited book agree that there is confusion on the distinction between 'climate change' and 'weather change' and this confusion is widespread. Nevertheless, there is a connection between the two that further complicates the situation. The existence of several Mediterranean cyclones is presented as an example of this together with the anomalies in the incidence of rainfalls. Specifically, the cyclones in the EMNEA region (East Mediterranean and Northeastern Africa) during the wet season 2019–2020 (October-May) were studied and it was concluded that they are rare events. They incorporate heavy rain (>900 million m^3) and gusty winds (>120 Km/h), which are considered a sign of climate change [159].

3.6. Climate Change and Forest Fires

The link between weather and forest fires is well known. Stronger winds, lower relative humidity, higher temperatures, drought, and unstable atmospheric profiles can act together to make fire behaviour more intense and increase the difficulty of suppression. All these parameters are expected to be affected by climate change. Thus, it can influence many aspects of wildfire behaviour and risk [160]. Trying to understand the link between forest fires and climate change, and to predict the future, researchers look at the available fire statistics and try to reveal links between forest fire trends and weather pattern modifications that can be attributed to climate change. They also use fire weather predictions based on climate projections and fire behaviour and risk models to predict future fire characteristics and regimes. The two approaches are often combined, identifying correlations and learning from the past and then trying to make projections in the future. Globally, there is a wealth of such studies because there is a lot of anxiety in the scientific community, since every year we stand witness to catastrophic fire seasons around the world.

The Mediterranean region is a climate change hot spot, so there is great concern about the effects of climate change on forest fires. Greece is one of the Mediterranean countries that have been heavily affected by forest fires in the last few years. Greece has experienced its worst fire season ever in 2007, undergoing a wildland–urban interface fire with 102 fatalities in East Attica, 25 km from Athens, in 2018, and suffered one more disastrous fire season in 2021. Climate change may have contributed to these calamities, and its role has been discussed in a number of studies and publications. The rising threat of forest fires has been linked to shifting climate conditions, characterised by higher minimum temperatures (approximately 1.3 °C) and a decrease in winter precipitation by an average of 15% [161]. In Greece, during the 2007 fire season, the combination of elevated temperatures and prolonged periods of drought led to the previously mentioned devastating forest fires [162]. These fires even affected ecosystems that are not typically prone to fires, suggesting a deviation from the recent burning patterns observed in history [163].

Long-term forest fire statistics allow for the identification of trends and the exploration of causality. Forest fire statistics in Greece are generally not accurate and dependable, especially in the post-1998 period [164]. This is especially true regarding fire ignitions because the way fires start are recorded and changed after the transfer of responsibility of forest fire suppression from the Forest Service to the Fire Service in 1998. For example, in the four years preceding the change (1994–1997), the average annual number of forest fires was 2.078. In the 4 years after the change in responsibility (1998–2001), it climbed to 12.461 fires. This change precludes a meaningful long-term analysis of fire occurrence. On the other hand, the data on annually burned area, although they also suffer from inaccuracies [164], are more dependable and establish a long-term increasing trend (Figure 1).

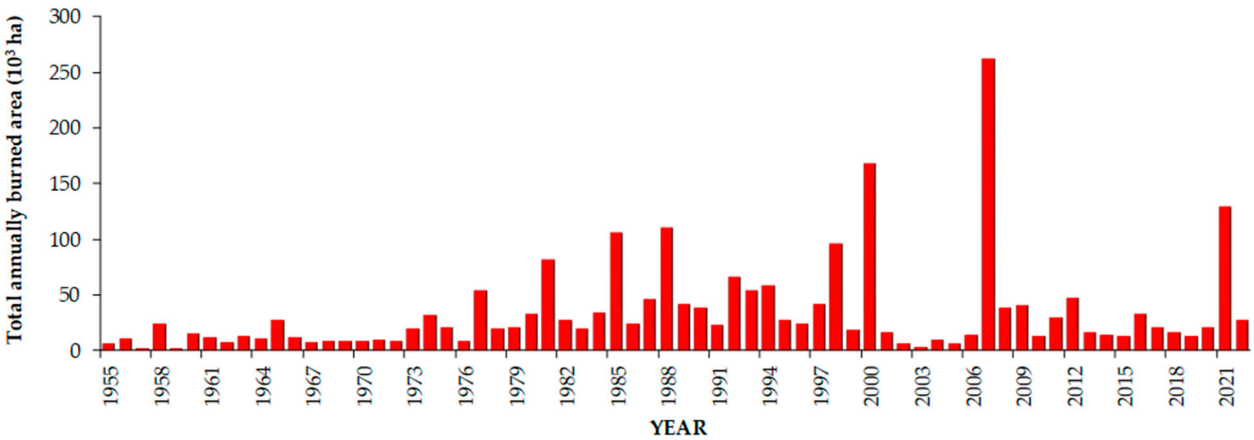

Figure 1. Evolution of the annually burned area in Greece (1955–2022) based on Forest Service and Fire Service data.

3.6.1. Fire Risk and Climate Change

Drought is one of the important climate characteristics related to climate change. Although drought is complex to define and investigate, there is a general consensus on a decrease in Mediterranean precipitation in future scenarios [165]. In Greece, Dimitrakopoulos et al. [166] examined the impact of drought on fire occurrence and burned area in the 1961–1997 period using the Standardized Precipitation Index (SPI) [60]. They found a general worsening trend but the impact between the parts of the country was variable. However, they could not attribute a direct causal relationship to climate change, citing various factors such as changes in fire causes due to social, economic and land management changes, as well as fuel accumulation due to the abandonment of the countryside [166–168] as potential co-contributors. Forest fires are strongly influenced by weather, in addition to drought.

The interactions between wind, relative humidity, and temperature are highly intricate. In an effort to address this complexity and relate weather to fire risk and behaviour in a simple way, experts have resorted to the development of certain indices. One of the most broadly used ones is the Canadian Fire Weather Index (FWI) [169]. It is a numeric rating of fire intensity that ranges from 0 to 101 and is used as a general index of fire danger. Although originally developed for Canadian forests, it is currently used in many other places around the world, including Europe. The ability to capture the combined influence of weather parameters to fire risk in one non-dimensional index has made FWI a favoured tool for assessing the effect of climate change on forest fires, through the predicted influence of the latter on weather parameters.

In the Mediterranean, Good et al. [170] examined the meteorological conditions associated with extreme fire risk in Italy and Greece, using meteorological data from seven meteorological stations for calculating FWI, and statistics of the daily fire frequency and burned area of fires within a radius of ∼150 km around each meteorological station. Their work confirmed that FWI is able to predict fire occurrence in Greece and Italy. Additionally, they concluded that for climate model studies in the two countries, an FWI > 15 can be considered as a threshold for elevated fire risk, while an FWI > 45 can be used as a useful threshold of extreme fire risk [170]. The thresholds used in other countries such as Portugal are different [170], being affected by biophysical gradients [171]. In Greece, Karali et al. [172] established similar FWI thresholds to those of Good et al. [170] and calculated FWI using outputs from a regional climate model (RCM) for three time periods: 1961–1990 (using it as reference for comparison), 2021–2050 (near future projection) and 2071–2100 (distant future). Their results suggested a general increase in fire risk, with 10 to 20 additional days of critical fire risk days in Greece in the near future. In the distant future, up to 40 additional critical fire risk days were predicted. In a similar study, Rovithakis et al. [173] evaluated the FWI index as calculated from the output of three different regional climate model (RCM) simulations aiming to reduce the influence of potential model biases. Their results also showed a general trend of increasing FWI index values in response to global warming, with up to 40 additional high fire danger days for parts of Greece.

Varela et al. [174] also used climate model data to calculate FWI and two other indices of the Canadian Fire Weather Index system, the Initial Spread Index (ISI) and the Fire Severity Rating (FSR), for a past period as reference (2006–2015) and a near future period (2036–2045), producing maps of predicted changes at local or regional scales. They found that areas in Greece with a humid and cold climate should expect large changes in the number of extreme fire weather days, while those in the drier and hotter Mediterranean zone will experience smaller changes.

Politi et al. [175], who also calculated FWI and ISI estimates for the future under climate change, found that certain areas of the country will be more impacted than others regarding extreme fire risk days, as estimated by FWI. Also, ISI, which assesses the rate of fire spread, will increase across much of the country. In summary, all the studies that utilized FWI and predictions by various RCMs concluded that parts of Greece will face up to 40 more days of extreme fire danger within the current century.

3.6.2. Fire Behaviour and Climate Change

The effect on climate change on future forest fire behaviour was investigated by Mitsopoulos et al. [176] who assessed climate change impacts on fire growth, rate of spread and fireline intensity for the area of the Penteli mountain, a typical Mediterranean landscape near Athens. They developed a high-resolution mapping of the fuels and used the minimum travel time (MTT) algorithm that is embedded in the FlamMap 3.0 software [177] for fire growth simulation (USDA Forest Service, Missoula Fire Sciences

Laboratory, Missoula, Montana, USA). Weather data were obtained from an RCM, for both the present and the future period. The future period simulations of the model were based on the IPCC SRES A1B scenario. They found worsening trends in maximum fire rate of spread, fireline intensity and burned area. However, only rate of spread presented a statistically significant difference, and that was by the end of the century.

Kalabokidis et al. [160] introduced a different perspective in a study of potential fire regime modifications due to climate change in a particular prefecture of Greece, Messinia. Similar to [176], they used climate projections from RCM model, under the SRES A1B emission scenario. In addition to estimating FWI, they ran thousands of fire simulations using the command-line version of the MTT algorithm called Randig [178], starting from random fire ignition locations, without firefighting, which then were modelled with a random selection among several predefined weather scenarios. One of the Randig outputs they focused on was the conditional burn probability (CBP) grid of the area, representing the conditional likelihood that a cell will burn given a certain set of ignitions, fuel moistures and wind speeds/directions, similar to the historic fires. Using an FWI > 32 as the threshold for elevated fire risk, they predicted an increase in the number of high-risk days within this century and found a clear trend for more fires exceeding a size of 500 ha. Accordingly, the CBP was projected to increase on 93.5% of the landscape.

3.6.3. Current Trends in Forest Fire Management in Greece

Recent catastrophic fires, namely the fire of eastern Attica of 2018 [179] with 102 fatalities and the catastrophic fire season of 2021 with 130.000 ha burned across the country and serious damages to properties, led to forest fire management changes. This is in line with [180] who found that views on climate change, including risk perception, are connected to direct disaster experience. The changes are primarily in the direction of strengthening the fire suppression organization in the country and including establishment of a new “Ministry of Climate Crisis and Civil Protection”. The development is in line with the findings of a survey among foresters and forest scientists on climate change and fire management in European Mediterranean forests carried out by Raftoyannis et al. [181] that showed a preference for increasing firefighting efficiency and public awareness over fuel management actions. However, it ignores the weaknesses of the “war against fire” paradigm [182] and the scientifically supported assertion that a paradigm change is needed: policy effectiveness should not be primarily evaluated by the burned area (as is usually the case) but rather as a function of avoided socio-ecological damage and loss [183].

Fortunately, the new Ministry, acknowledging the predictions for long-term forest fire danger increase due to climate change, in addition to increasing emphasis on fire suppression, also started cooperation with the Ministry of Environment and Energy and the Forest Service on an extensive fuel management program that started in 2022 and is planned to continue for at least three years.

4. Understanding the Relationship between Greek Forests and Climate: Insights, Gaps, and Challenges

Table 2 presents various research areas related to climate change and its impact on Greek forests. It highlights the gaps in knowledge and identifies key challenges in each area.

Table 2. Knowledge, gaps and challenges in understanding Greek forest relationships with climate.

Research Area	What Questions Have Been Answered?	Gaps in Knowledge	Key Challenges
Climate Trends	a. Concerns about the trends in temperature and precipitation levels at both the Mediterranean and local scales. b. Growing apprehension over the rapid and abrupt meteorological shifts and extreme weather incidents occurring over short time frames. c. Spatial variability of warming and drought rates. d. Drought and aridity indices as important tools to answer questions. e. Established pressures to local communities.	a. More detailed research on the specific patterns and trends of these changes at the regional and local levels. b. More research about the effects of climate on the water cycle, including the availability of groundwater and surface-water resources.	a. How different adaptation and mitigation strategies can be applied in the context of Greece's unique climate and environmental conditions. b. Is it essential to integrate drought management measures into long-term strategies for droughts and land use, as well as overall development strategies? [184]
Forest Management	a. Water scarcity and temperature affect tree growth, primary production and the quality of wood. b. Necessary to recognize the growth rates of the commercial species in order to balance harvesting and regrowth. c. Drought indices and other climate parameters have been used to determine the connections between climatic elements and tree growth, mostly on *Abies cephalonica*, *Abies borissi-regis*, but to some commercial broadleaves as well (*Quercus frainetto Ten.*, *Fagus sylvatica* and others). d. Vegetation dynamics through forest management techniques but potential shifts in vegetation and tree lines as well. e. Proposing several common and well-known actions to deal with climate change in forests (e.g., enhancing mixture with broadleaves). f. How land-management techniques influence soil erosion and land degradation.	a. Further research is needed to explore the efficacy of diverse forest management strategies and practices in enhancing the resilience of Greek forests and addressing changes in national forest productivity. b. More research is needed on the impacts of forest management practices, such as logging and grazing and wildfires as well, on carbon sequestration and other ecosystem services. c. More research on the potential of sustainable forest management, restoration, and reforestation strategies. d. More research is needed to understand how different forest types respond to changing climate conditions, and what implications this has for biodiversity (forest-dependent species, insects and fungi) and ecosystem services.	a. How different stakeholders, such as forest owners, forest user groups, and government agencies, can work together to develop comprehensive and integrated strategies for the sustainable management of Greek forests in the context of climate change (as suggested by the literature for Mediterranean countries, e.g., [185]).

Table 2. *Cont.*

Research Area	What Questions Have Been Answered?	Gaps in Knowledge	Key Challenges
Biodiversity	a. Questions about the higher species richness of vascular plants compared to other countries. b. Questions about the main possible causes leading to the loss of biodiversity at the national level. c. Questions about the greatest pressures on plant species on Greek mountains. d. Changes in vegetation patterns and plant productivity due to climate. e. Questions about changes in plant species phenology especially in sensitive species due to climate. f. Importance of monitoring aiming to make informed decisions crucial to implementing a conservation strategy. g. Other obstacles which are harming biodiversity and biodiversity strategies at the national level.	a. More research is needed on the impacts of climate change on the distribution and abundance of different forest plant species. b. More research is needed on the potential impacts of invasive species in the context of climate change. c. The potential impacts of climate change on the relationships between forest plants and other species, such as pollinators and herbivores, have not been fully comprehended yet.	a. What is the potential of conservation and management strategies, such as seed banking, habitat restoration, and assisted migration (or managed relocation), to help preserve the biodiversity? b. Is it wise to focus on scientifically studying and experimenting with conservation strategies and sustainable management (as suggested by the literature for Mediterranean countries, e.g., [186])?
Forest Genetics	a. Unique genetic pool, rich biodiversity, marginal distribution frontier for many plants, unique epigenetic role for adaptation of forest tree species. b. In situ and ex situ conservation, genetic monitoring as strategies to protect and enhance genetic diversity through many EU and national projects.	a. Identifying and managing areas of high genetic diversity. b. Genetic factors underlying resistance or susceptibility of forest tree species to pests and diseases. c. Default strategies to protect and enhance genetic diversity.	a. What are the potential impacts of changing climate conditions on the genetic diversity of forest plant species in Greece, including their potential for adaptation and evolution? b. The Mediterranean forest research community should play a prominent role in studying genetic diversity, mitigating threats from climate change and human activities, and utilizing local and landscape heterogeneity over the next 10 years [187].

Table 2. *Cont.*

Research Area	What Questions Have Been Answered?	Gaps in Knowledge	Key Challenges
Insects	a. Several forestry pests with a known or unknown mechanism of range expansion. b. Relationships between climate, rising temperatures voltinism and local migration to higher altitudes of some species. c. Some insect species involved in outbreaks in Greek forests.	a. Limited information on the taxonomy, distribution, and population dynamics. b. Incomplete knowledge of the ecological interactions between forest insects and their host trees. c. Lack of research on the effectiveness of different management strategies to control forest insect outbreaks and mitigate their impact on forest ecosystems.	a. How can we implement more comprehensive and long-term monitoring programs to assess changes in forest insect populations and their potential effects on forest health and productivity? b. Emphasizing four primary effects of climate: changes in distributional ranges, outbreak frequency and intensity, seasonality and voltinism, and trophic interactions [188]. c. The connections between climate change and the spatiotemporal population dynamics of forest insects are increasingly evident, revealing the emergence of certain general patterns [189].
Forest fires	a. Links between weather and forest fire behaviour and risk are well known and documented. b. Prediction of future fire characteristics and regimes based on climate projections and fire behaviour and risk models. c. Adequacy of long-term forest fire statistics (generally not accurate and dependable). d. Impact of drought on fire occurrence and burned area (nationally) e. Employment of global indices (most of them with Canadian Fire Weather Index (FWI)) to address the complexity and relate weather to fire risk and behaviour. f. Fire behaviour modification scenarios. g. Ambiguous ways the country manages forest fires.	a. More research is needed on the impact of human activity, including land-use changes and forest management practices, on forest fire risk. b. The effectiveness and efficiency of different forest fire prevention and management strategies, such as prescribed burning and early-detection systems, need to be better understood and evaluated. c. More research is needed on the long-term ecological impacts of forest fires in Greece, including on soil health, plant regeneration, and biodiversity.	a. Is there a need for improved coordination and communication among stakeholders involved in forest fire management, including the government, forest service, academics and local communities? b. There is a lot of discussion, at national, European and even global scales about the needed emphasis on fire prevention vs. suppression, and the corresponding balance of funding. However, there is relatively weak knowledge and availability of scientifically supported tools for the objective evaluation of the needs and determination of the funding levels. c. While there is consensus about the worsening fire problem as a result of climate change and build-up of fuels in forests and agricultural areas, there is an urgent need for knowledge on improved management practices that include local communities and can lead to fire-resilient landscapes.

In reference to climate trends, this review mentions concerns about temperature and precipitation trends, rapid meteorological shifts, warming and drought rates, and pressures on local communities.

However, more detailed research is needed on regional and local patterns and trends, as well as the effects of climate change on the water cycle and water resources. The challenges consist of determining suitable adaptation and mitigation strategies that align with Greece's distinctive climate and environmental conditions, and incorporating long-term strategies for managing drought, land use, and overall development.

In forest management research, water scarcity and temperature's effects on tree growth and wood quality are noted. It emphasizes the importance of balancing harvesting and regrowth, determining connections between climate elements and tree growth, and potential shifts in vegetation and tree lines due to forest-management techniques. The need for more research on the effectiveness of different forest-management strategies, their impact on biodiversity and ecosystem services, the changes in national forest productivity and collaboration among different stakeholders is also highlighted.

The research on forest biodiversity addresses species richness, causes of biodiversity loss, changes in vegetation patterns and productivity, and the importance of monitoring for conservation decision-making. However, there are gaps in knowledge about the impacts of climate change on forest plant species, invasive species, and relationships between forest plants and other species. The literature underlines the challenge of determining the conservation and management strategies to preserve biodiversity.

Forest genetics research emphasizes the need for conservation and genetic monitoring strategies, but gaps exist in identifying and managing areas of high genetic diversity, understanding genetic factors underlying resistance to pests and diseases, and developing strategies for protecting and enhancing genetic diversity. A key challenge is the proposed assessment of the impacts of changing climate conditions on the genetic diversity of forest plant species and their potential for adaptation.

Research on forest insects identifies forest pests and their relationship with climate change, but gaps remain in knowledge about taxonomy, distribution, population dynamics, and ecological interactions with host trees. Effective management strategies and long-term monitoring programs are lacking. Unique management strategies for Greek forests and comprehensive monitoring are needed. One major challenge lies in effectively implementing comprehensive and long-term monitoring programs to assess changes in forest insect populations, their impact on forest health, and recognizing the four primary effects of climate on forest insects, as well as describing the emerging patterns and connections between climate change and population dynamics.

Regarding forest fires, as it is a phenomenon strongly affected by weather, which is predicted to become more unfavourable with climate change, a large body of research in Greece and around the world predicts that they will become worse. In order to mitigate the phenomenon before it becomes critical, it is needed to foster improved coordination and communication among stakeholders in forest-fire management and to support them with the appropriate amount of funding, cleverly split between the various functions of prevention and suppression. Improved landscape resilience, including agriculture and forests, is becoming a main objective of current management practices.

As all the above are affected by context specificity as they include various ecosystems and involve stakeholders at various levels, it is necessary to cover knowledge gaps, develop decision support tools, and devise innovative methods for the involvement of the public to reduce fire hazard, make fires controllable, and ultimately reduce damages.

5. Concluding Remarks

Research at the national level is investigating various aspects of climate change impact on forests, including temperature and precipitation trends, extreme weather events, water scarcity and its effects on tree growth, forest-management strategies, biodiversity and genetic diversity loss and conservation, forest insects, forest fires, and the management of fire risk. Even though there are still significant gaps in knowledge and several key challenges that need to be addressed. The need for detailed regional climate trend analysis and water resource impact assessment, along with tailored adaptation and mitigation strategies for Greece's unique climate is underlined. Forest management requires further investigation into strategy effectiveness, forest productivity, and different stakeholder collaboration. Knowledge gaps exist regarding climate change's effects on forest species and relationships, hindering conservation efforts. Genetic diversity identification and management, resistance factors, and climate impact assessments are crucial in forest genetics. A better understanding of taxonomy, distribution, population dynamics, and ecological interactions is needed for forest insects, supported by comprehensive monitoring programs. Effective stakeholder coordination, funding allocation, and preventive measures are vital for addressing forest fires.

The present review could be useful for advancing knowledge, informing decision-making, promoting conservation and sustainability, facilitating stakeholder collaboration, and guiding policy development. It helps identify research gaps and could support evidence-based decision-making and the development of more effective policies and strategies. Nevertheless, the influence of research on policy-change processes is usually indirect. Research knowledge serves as one of several inputs in decision-making, and its impact on policy outcomes can be challenging to determine due to the complex and non-linear nature of policy decision processes. Research, however, plays a significant role in shaping conventional wisdom by driving change and providing a counterbalance to new ideas [181]. In addition, it should always underpin the most effective policy, and the best way to ensure this is to foster a collective awareness of upcoming issues among different organizations, forest proprietors, and interested parties.

In conclusion, the primary focus of the Mediterranean forest research community should be on providing support to policymakers and stakeholders in making well-informed decisions, implementing effective strategies, and allocating resources in a manner that effectively tackles the unique challenges presented by climate change, particularly in countries such as Greece that are highly susceptible to its impacts.

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