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The impact of climate change on hazelnut cultivation

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ABSTRACT

Hazelnut (*Corylus avellana* L.) cultivation faces substantial challenges in the wake of climate change. This review synthesizes findings from various studies to examine the impacts of climate change on hazelnut cultivation, strategies for mitigating these impacts, and the potential role of hazelnut orchards as carbon sinks. I discuss the physiological responses of hazelnut trees to changing climatic conditions, explore management strategies to enhance resilience and productivity, and evaluate the carbon sequestration potential of hazelnut orchards. Additionally, I assess the role of fertilization, irrigation, and other agricultural practices in shaping hazelnut growth and yield under shifting climate scenarios. By integrating sustainable agricultural practices and leveraging precision agriculture technologies, hazelnut growers can improve environmental sustainability and economic viability. This review provides comprehensive insights and practical recommendations for sustaining hazelnut production in the face of climate change.

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1. Introduction

Hazelnut (*Corylus avellana* L.) cultivation stands at the intersection of agricultural productivity and environmental sustainability, facing significant challenges posed by climate change. As one of the most important perennial fruit crops, hazelnuts play a vital role in global food security and economic prosperity, particularly in regions with temperate climates. However, the increasing frequency and intensity of extreme weather events, shifts in precipitation patterns, rising temperatures, and elevated atmospheric CO_2 levels threaten the stability and productivity of hazelnut orchards worldwide.

Climate change poses multifaceted challenges to hazelnut cultivation, impacting various stages of growth and development, from floral differentiation and blossom to pollination and nut setting. The sensitivity of hazelnut trees to environmental conditions, particularly their reliance on chilling requirements, makes them highly susceptible to the effects of warming temperatures. Additionally, the projected increase in global temperatures is expected to alter the geographical distribution of suitable growing regions, potentially displacing hazelnut cultivation to new areas with more favorable climate conditions on long term (Cabo, 2020). In the face of these challenges, there is an urgent need to develop and implement strategies to mitigate the impacts of climate change on hazelnut production while ensuring the long-term sustainability of orchards. This necessitates a comprehensive understanding of the physiological responses of hazelnut trees to changing climatic conditions, as well as the development of adaptive management practices to enhance resilience and productivity.

Furthermore, hazelnut orchards have the potential to serve as important carbon sinks, sequestering atmospheric carbon dioxide through the process of photosynthesis and storing it in tree biomass and soil organic matter. Harnessing this carbon sequestration potential can contribute to climate change mitigation efforts while providing additional economic and environmental benefits to hazelnut growers (Granata et al., 2020).

In this context, this review aims to synthesize existing knowledge on the impacts of climate change on hazelnut cultivation, explore management strategies for climate resilience and productivity enhancement, and evaluate the carbon sequestration potential of hazelnut orchards. By examining the interplay between hazelnut cultivation, climate change, and sustainable agricultural practices, this review seeks to provide insights and recommendations for the future of hazelnut production in a changing climate landscape.

2. Physiological responses of hazelnut trees to climate change

Hazelnut trees exhibit complex physiological responses to changing climatic conditions, with temperature, precipitation, and atmospheric CO_2 levels playing key roles in shaping growth, development, and yield (Table 1). Understanding these responses is important for predicting the impact of climate change on hazelnut cultivation and developing adaptive strategies to mitigate its effects.

Table 1. Physiological responses of hazelnut trees to climate change

Climate factor	Response	Impact on growth/Yield	Source/Reference
Rising Temperatures	Disruption in chilling requirement, earlier phenology, a reduction in the duration of the flowering period, increasing degree of dichogamy	Reduced yield, smaller nut size, decreased kernel weight	Črepinšek et al., 2012; Asseng et al., 2015; Škvareninová, 2016; Cabo, 2020; Balık and Arif, 2023
Changes in Precipitation	Increased water stress	Reduced nut set, lower kernel quality, root health issues	Milosevic and Miosevi, 2012; Asseng et al., 2015; Tonkaz and Bostan, 2019
Elevated CO_2 Levels	Enhanced photosynthesis and growth	Potentially increased yield under optimal conditions	An et al., 2020
Extreme Cold Events	Frost damage, reduced pollination success	Significant yield losses, tree damage	Beyhan et al., 2007; Balik and Kayalak Balık, 2015; Anonymous, 2021

2.1. Effects of temperature, precipitation, and CO_2 levels on hazelnut growth and yield

The findings indicate that temperature is the most influential climatic factor affecting hazelnut cultivation (Ustaoğlu, 2009). The impact of rising temperatures on yields can vary depending on the different characteristics. However, in general, a significant increase in temperature could lead to water scarcity. This scenario suggests a negative correlation between rising temperatures and agricultural productivity. Increased precipitation might improve soil moisture in semi-arid areas, yet exacerbate issues in regions already facing water surplus especially flat areas. Conversely, a decrease in rainfall could yield opposite effects. In irrigated areas, the adverse effects of altered precipitation and higher temperatures are mitigated by access to irrigation water, rendering yields more resilient to climate fluctuations (Agovino et al., 2019). Even in the Black Sea Region, where hazelnut cultivation is most intense in Türkiye, some years there may be yield and quality losses due to insufficient and irregular rainfall (Anonymus, 2024).

The adverse effects of extreme cold temperatures on hazelnut orchards in spring, exacerbated by climate change, were notably exemplified in events from 2004, 2014 and 2021 in Türkiye, the world's main hazelnut producer. Following temperatures above seasonal norms in December and January of that year, a cold wave swept through the region, affecting hazelnut orchards (Figure 1). Subsequently, the region witnessed a frost damage, in Eastern Black Sea Region, due to effective snowfall in February and March. Detailed assessments conducted by producer associations revealed significant damage ranging from 30 to 90 percent in hazelnut orchards situated between altitudes of 200 and 600 meters (Balık and Kayalak Balık, 2015; Anonymus, 2021).

Figure 1. Impact of extreme cold temperatures on hazelnut orchards in Ordu, Türkiye (Anonymous, 2024)

Temperature exerts a significant influence on hazelnut growth and development, with both mean temperatures and temperature extremes affecting various physiological processes (An et al., 2020). The hazelnut trees have chilling requirements, which can affect critical phases of floral differentiation, blossom, and fruit nut setting. (Cabo, 2020). Changes in climatic conditions, especially temperatures, influence the initiation and progression of the phenological growth stages (Kasprzyk et al., 2004). Previous studies (Črepinšek et al., 2012; Škvareninová, 2016) conducted in Slovenia and Slovakia have demonstrated that rising temperatures lead to an earlier onset of phenological growth stages in hazelnuts and a reduction in the duration of the flowering period. In addition, higher temperatures may extend growing seasons and promote increased photosynthetic activity, potentially enhancing yield under certain conditions. Changes in precipitation patterns, including alterations in the frequency and intensity of rainfall events, also impact hazelnut growth and yield. Hazelnut trees require regular annual precipitation for efficient nut development, and drought conditions during critical growth stages lead to reduced yields and lower nut quality. Conversely, excessive precipitation can increase the risk of waterlogging and nutrient leaching, negatively affecting root health and overall tree vigor. In contrast to water stress, which can be alleviated through irrigation, the adverse impacts of rising temperatures on chill hours and leaf scorching are not easily remedied. Likewise, elevated temperatures can accelerate vegetative growth, shortening the time available for kernel development and decreasing kernel weight (Asseng et al., 2015).

A repercussion of climate alteration manifests as heightened occurrence and severity of hailstorms. Hailstorms represent a significant peril to hazelnut producers particularly in regions characterized by temperate climates, where hazelnut cultivation predominates and where the incidence of hail is notably elevated. Projections (Botzen et al., 2010) based on climate change models forecast a substantial rise in both the frequency and severity of hailstorms, thereby amplifying the economic challenges faced by the agriculture.

While floods may not exert as substantial an impact on hazelnut cultivation as they do on certain other crops, their occurrence remains a notable concern deserving careful consideration. Azerbaijan ranks among the principal global producers of hazelnuts, with its primary production hub located in the Zagatala district. In recent years, the incidence of hazelnut orchard inundations in this region has escalated, attributed to the impacts of climate change (Figure 2).

Figure 2. Flooding in hazelnut orchards in Zagatala District, Azerbaijan (Anonymous, 2022)

Similarly, in July 2023 (Anonymous, 2023), a flood disaster struck Duzce, Türkiye, inflicting significant damage on hazelnut orchards and underscoring the vulnerability of hazelnut cultivation to extreme weather events. With hazelnuts cultivated across 632 thousand decares, the inundation of floodwaters wreaked havoc on agricultural lands (Figure 3). The heavy rains not only submerged crops in gardens but also triggered landslides and strong winds in cultivated areas on slopes, leading to premature crop loss. The overarching assessment points to a considerable threat looming over agricultural productivity. With an estimated 430 thousand square kilometers of flood-prone cropland facing a doubling in flood frequency by 2050 under certain climate scenarios, the potential impact on crop yields and food security is profound (Arnell and Gosling, 2016).

Figure 3. Flooding in hazelnut orchards in Duzce, Türkiye (Anonymous, 2023)

These findings underscored the susceptibility of hazelnut cultivation to extreme weather events induced by climate change, highlighting the urgency for implementing adaptive strategies to ensure the resilience and sustainability of hazelnut production in affected regions.

Atmospheric CO_2 levels play a dual role in influencing hazelnut physiology, acting as both a substrate for photosynthesis and a driver of climate change. Since the onset of the Industrial Revolution, atmospheric CO_2 levels have surged from 280 parts per million (ppm) to surpassing 410 ppm (Ciais et al., 2013). Initially, a rise in soil CO_2 benefits plants by curbing evapotranspiration through biomass conversion fueled by water stored in leaves. Elevated CO_2 concentrations have the potential to stimulate photosynthetic rates and increase biomass production in hazelnut trees, leading to enhanced growth and potentially higher yields. Yet, as air temperatures climb, this early advantage may diminish (An et al., 2020). Heightened CO_2 levels are anticipated to boost leaf photosynthetic rates. However, the extent to which this enhancement will manifest remains uncertain, as CO_2-induced stimulation of photosynthesis hinges on factors such as leaf temperature, as well as the availability of water and nutrients (Chaves and Pereira, 1992; Leakey et al., 2009; Zhu et al., 2017).

2.2. Phenological shifts and implications for pollination, flowering, and nut development

Climate change is driving phenological shifts in hazelnut trees, altering the timing of critical developmental stages such as pollination, anthesis, fertilization, nut set and harvest time. Increased temperatures and altered precipitation patterns might result in the advancement or delay of phenological events (Table 2). Hazelnut pollens wind-pollinated. Successful pollination requires the synchrony of pollen release and female flower receptivity. However, dichogamy is common in most of the cultivars. Protandry is often seen. Phenological shifts can disrupt this synchrony, reducing pollination efficiency. For instance, asynchronous pollen release and female flower receptivity, or adverse weather conditions (e.g., heavy rainfall, lack of pollinizer) during the pollination period, can significantly diminish the likelihood of successful pollination.

Table 2. The key impacts of phenological shifts on hazelnut flowering, pollination, and nut development

Phenological phase	Impact of climate change	Implications
Pollination- Flowering	Disrupted timing of pollen release, flower receptivity and degree of dichogamy	Reduced pollination efficiency
Nut Development	Accelerated ripening due to higher temperatures, flower bud development (produce the next year's crop)	Smaller, lower quality nuts, kernels, yield deficiency
Overall Impact	Shift in growing season length and temperature patterns	Variable yield and quality, increased management costs

The research conducted on the Iberian Peninsula has documented notable phenological changes in early spring species, including *Corylus* L. (hazelnut trees), over the years. Specifically, an earlier onset of flowering was observed at most of the studied locations. Additionally, earlier nut ripening was recorded at all sampling sites, and earlier nut harvesting was noted at the majority of these locations (Hidalgo-Galvez et al., 2018).

3. Management strategies for climate resilience and productivity

As climate conditions evolve, there is the potential for changes in the suitability of certain regions for hazelnut cultivation over the long term. While immediate shifts may not be imminent, the gradual impact of changing temperatures, precipitation patterns, and environmental factors could eventually alter the landscape of hazelnut production. This dynamic underscores the importance of ongoing assessment and adaptation in hazelnut farming practices to ensure resilience in the face of future climate scenarios.

Mitigating the impacts of climate change on hazelnut cultivation requires the implementation of effective management strategies to enhance resilience and productivity. Research findings suggest several approaches to address climate challenges and optimize hazelnut orchard management.

One key strategy involves the utilization of preharvest foliar spray treatments. Studies (Cabo, 2020; Cabo et al., 2020) have demonstrated that treatments with compounds such as kaolin, natural biostimulants, and salicylic acid can mitigate heat and drought stresses, improve water use efficiency, and enhance physiological performance in hazelnut trees. These treatments have been associated with increased nut and kernel sizes, higher vitamin E and antioxidant activity levels, and improved biometric parameters. In addition to foliar spray treatments, leveraging hazelnut by-products for bioactive compounds presents an opportunity for sustainable agricultural practices. Hazelnut husks, a by-product of hazelnut cultivation, contain phenolic compounds with antioxidant properties. Valorizing hazelnut husks through extraction and purification processes can contribute to the development of bioactive molecules for various applications, further enhancing the sustainability of hazelnut production. Transitioning to sustainable agricultural practices is another crucial aspect of climate resilience and productivity enhancement. Organic farming and good farming techniques, reduced fertilizer use, and efficient irrigation management can promote soil health, conserve water resources, and minimize environmental impacts in hazelnut orchards. Additionally, regular maintenance practices such as pruning, based on soil and leaf analysis fertilizing, pest control to yield increase and orchard sustainability. Promoting genetic diversity and breeding resilient cultivars are essential components of climate-resilient hazelnut cultivation. Research on hybrid hazelnut trees has shown their potential for low-input, high-productivity systems capable of sequestering carbon. Breeding programs focused on developing cultivars resilient to climate stressors can further enhance orchard resilience and productivity. Continuous monitoring and adaptive management are critical for effectively addressing climate challenges in hazelnut cultivation. Integrated pest and disease management, weather monitoring systems, and precision agriculture technologies can help optimize resource use, minimize risks, and ensure orchard productivity under changing environmental conditions.

Crop adaptation to climate change heavily relies on the practice of breeding (Araus and Kefauver, 2018). Breeding new cultivars of hazelnut trees adapted to climate change is pivotal for sustaining hazelnut production amidst evolving environmental challenges. By selecting varieties tolerant to heat, drought, and other climatic stresses and incorporating genetic diversity, breeders enhance hazelnuts' resilience. Moreover, breeding for pest and disease resistance reduces dependence on pesticides. Although breeding programs increasingly prioritize climate resilience, there is growing evidence indicating the obstacles and complexities involved in creating crops prepared for climate change (Xiong et al., 2022). Collaborative efforts among researchers, geneticists, agronomists, and farmers are crucial for advancing these objectives and securing the future of hazelnut production systems.

Soil carbon sequestration emerges as a promising strategy to mitigate climate change effects on hazelnut cultivation. By restoring depleted soil organic carbon (SOC) through innovative land management practices like cover cropping, reduced tillage, and nutrient recycling, carbon emissions can be slowed, and soil fertility and resilience can be improved (Nazir et al., 2024). No-tillage (NT) practices have emerged as a scientifically supported method for mitigating climate change by significantly reducing CO_2 emissions from soils. Research conducted over a six-year period has consistently demonstrated the efficacy of NT in comparison to conventional tillage (CT) methods. NT, particularly when combined with surface mulch, has shown to reduce CO_2 emissions by an average of 51% compared to CT practices. These findings underscore the potential of NT as a sustainable agricultural approach that aligns with global efforts to combat climate change (Mühlbachová et al., 2023).

Hazelnuts, like many other tree crops, typically don't require tilling (USDA Climate Hubs, n.d.). This characteristic offers promising implications for climate change mitigation. By minimizing tillage, hazelnut orchards contribute to preserving soil organic matter and enhancing carbon sequestration potential, thus aligning with efforts to mitigate greenhouse gas emissions. Therefore, expanding hazelnut orchards or adopting minimal tillage practices in hazelnut cultivation can serve as effective strategies for promoting sustainable agriculture and combating climate change.

4. Carbon sequestration potential of hazelnut orchards

Hazelnut trees exhibit considerable potential for carbon sequestration, often ranking among the leading fruit tree species in terms of carbon storage capacity. Research has elucidated the amount of carbon dioxide (CO_2) sequestered by hazelnut orchards, particularly in the Mediterranean region, where woody agriculture predominates. Studies have quantified the carbon sequestration capacity of hazelnut orchards under routine horticultural care, revealing substantial CO_2 uptake rates. Hazelnut orchards have been found to sequester an average of 58.8 ± 9.1 Mg CO_2 ha^{-1} $year^{-1}$, with peak sequestration occurring during the growing season (Granata et al., 2020). Notably, hazelnut cultivation areas are expanding, indicating the increasing significance of these orchards as carbon sinks. Pacchiarelli et al. (2022) demonstrated that the cultivation of European hazelnut (*Corylus avellana* L.) initially leads to a decline in soil organic carbon stock, with a reduction ranging from 23% to 58% during the first 3-5 years after planting. This decrease is attributed to land preparation, frequent tillage operations, and the transition from grassland to orchard. However, despite this initial decline, the study highlights the potential for soil carbon stock recovery and the exponential increase in hazelnut orchards with optimal fertilization and management practices. The distribution of carbon sequestration within hazelnut orchards varies over time, with carbon allocated to different tissues evolving as trees mature. While the exact mechanisms underlying carbon allocation patterns require further investigation, it is evident that hazelnut orchards contribute to soil carbon storage over time.

Furthermore, the impact of fertilization on carbon sequestration in hazelnut orchards has been examined. While fertilization primarily enhances woody biomass production, hazelnut cultivation has been characterized as a low-input crop with significant potential for carbon storage. Comparisons with conventional commodity crops underscore the carbon sequestration potential of hazelnut orchards. Despite yielding slightly lower in-shell nut production compared to certain crops like soybeans, hazelnut orchards exhibit substantial woody biomass accumulation. Hazelnut orchards had stored an estimated 12 tonnes/hectare of woody biomass, highlighting their role in long-term carbon storage (Fireman, 2019).

Hazelnut orchards employing a single trunk training system have garnered popularity in recent years. But, emerging research (Granata et al., 2021) suggests that bush-like training systems offer heightened efficacy in carbon sequestration, crucial for mitigating greenhouse gas emissions. A recent study conducted in Italy's Piedmont region, a prominent hub for hazelnut production, compared the carbon sequestration capabilities of two orchard management approaches: single trunk and bush-like. Results unveiled a notable advantage for the bush-like system, showcasing significantly higher rates of carbon dioxide (CO_2) sequestration per plant and per unit area. This disparity was attributed to the bush-like system's ability to foster a greater leaf area index, facilitating enhanced carbon assimilation. Despite inherent CO_2 emissions associated with orchard management practices, such as diesel fuel usage and machinery operation, both orchard types were found to function as net carbon sinks over the study period (Granata et al., 2021). While the single trunk system is gaining popularity, the majority of global hazelnut orchards still utilize bush-like systems. Based on the findings presented above, enhancing the efficiency of these bush-like systems holds significant potential to improve both carbon sequestration and overall productivity on a global scale.

Although challenges such as cost-effective harvest methods persist, small-scale hazelnut orchards demonstrate strong potential as low-input, high-productivity systems that sequester carbon effectively. Continued research and innovation in hazelnut cultivation hold promise for maximizing carbon sequestration while ensuring sustainable food production and environmental stewardship.

5. Conclusion and Future Directions

This review underscores the substantial challenges that climate change poses to hazelnut cultivation, highlighting the necessity for adaptive management strategies to ensure sustainability. Physiological responses of hazelnut trees to climate change, including temperature, precipitation, and CO_2 levels, have profound implications for growth and productivity. The practical implications of this research are multifaceted, encompassing the need for improved agricultural practices, such as the application of preharvest foliar sprays to enhance plant resilience and the development of climate-resilient hazelnut cultivars through advanced breeding programs. For stakeholders, including farmers, agricultural policymakers, and researchers, the findings emphasize the importance of adopting integrated approaches that combine sustainable agricultural practices with innovative mitigation techniques.

Management strategies for climate resilience and productivity play a crucial role in mitigating the adverse effects of climate variability on hazelnut production. One of the key recommendations is the implementation of soil and water management practices that optimize resource use and enhance plant health. Additionally, the carbon sequestration potential of hazelnut orchards presents an opportunity for mitigating greenhouse gas emissions and enhancing environmental sustainability. Continued research on carbon dynamics and ecosystem services of hazelnut agroforestry systems is needed to quantify their contribution to climate change mitigation. Interdisciplinary research that integrates agronomic, ecological, and socio-economic perspectives will be crucial in developing holistic solutions.

Given the regional variability in climate impacts, examining the adaptations of hazelnut varieties according to different regions is critical. Specific adaptations may include selecting varieties that are better suited to local climate conditions, such as drought-resistant cultivars for semi-arid regions or cold-hardy varieties for areas prone to late frosts. This regional approach ensures that adaptation strategies are tailored to the unique environmental conditions and challenges faced by hazelnut growers in diverse geographic areas.

By addressing practical and research-oriented recommendations, such as continued innovation and adoption of sustainable management practices, the hazelnut industry can better navigate the challenges posed by climate change. This comprehensive approach, coupled with scientific research and extension efforts, will ensure the sustainability of production and contribute to broader environmental conservation efforts. It will not only benefit hazelnut growers but also support global endeavors to combat climate change and promote sustainable agriculture. Overall, these concerted efforts will be critical for ensuring the resilience, productivity, and sustainability of hazelnut cultivation in the face of climate change and global environmental challenges.

Compliance with Ethical Standards

Conflict of Interest

The author declares no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Authors' Contributions

The author carried out the concepting, designing, supervision, data collection and/or processing, data analysis and/or interpretation, literature search, writing, critical review, submission and revision, project management, funding acquisition.

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