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Enhancing Climate Resilience and Food Security in Greece Through Agricultural Biodiversity

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Abstract: This study examined how agricultural biodiversity can build climate change resilience and food security in Greece. The aims of this study were to identify and examine the role of genetic, species, ecosystem, and functional diversity in enhancing agricultural resilience against climate volatility. Data were collected from 384 agricultural specialists in Greece using a quantitative, cross-sectional survey technique. The self-administered questionnaire elicited information on the perceived effectiveness of different types of biodiversity in sustaining yield stability for crops, pest and disease control, soil conservation, and nutrient cycling. The hypotheses of this study were tested using descriptive statistics and multiple regression analysis. The findings revealed that genetic diversity decreases crop yield risks, species diversity lowers pest and disease vulnerability, ecosystem diversity impacts to soil and water conservation, and functional diversity can optimize nutrient cycling and ecosystem services. The regression analysis was able to explain 62.1% of the variability in agricultural resilience, underlining the importance of the conservation of biological diversity in the provision of food. This study points to the need for biodiversity management in agriculture to address the impacts of climate change and support productivity in food production.



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1. Introduction

Crop and livestock genetic resources are essential for sustainable agriculture, particularly in the context of climate change. Thus, crop, livestock, genetic, and ecosystem diversity can enhance the resilience of agricultural systems [1–3]. This resilience is helpful in maintaining food security and reducing the impact of climate variability [4,5]. However, in recent decades, the application of agricultural biodiversity has been an issue for the countries that are the most vulnerable to climate change, as is the case for Greece. Greece is one of the Mediterranean countries most likely to be impacted by the effects of climate change, including high temperatures, changes in precipitation patterns, and an increased frequency of extreme weather events [6,7]. These effects are known to have negative impacts on crop yields and food availability [8]. In this regard, agricultural biodiversity could help to increase the stability of agricultural systems [9]. Crop genetic diversity is essential for coping with climate change. It allows for the selection of varieties that could be bred to be more adapted to drought, heat, and other forms of stress [10–12]. This could have a

strong impact on food security, as genetic variation in crops has been found to improve yield stability under climate change [13]. For example, Georgopoulou et al. [14] reported that agricultural diversification in Greece increased crop yields, especially during climatic shocks [15]. Monoculture practices often result in a low soil nutrient status and higher susceptibility to pests and diseases, while polyculture and agroforestry practices involve high levels of ecosystem connectivity [16]. The heterogeneity of ecosystems in agricultural landscapes means a heterogeneity of soil and water functions. Some ecosystem services include nutrient cycling, soil formation, and water purification, which are important for sustaining agriculture [17–19].

Species diversity, or the number or types of species in agricultural systems, also helps to reduce vulnerability to pests and diseases by altering the life cycles of pests and pathogens and limiting their impact on crops [20,21]. Maintaining a diversity of ecosystems in agricultural areas for soil conservation and water management is a critical component of sustainable agriculture. Diverse ecosystems provide multiple services, including nutrient cycling, soil formation, and water purification [22]. They are useful for the long-term maintenance and development of agricultural production systems. This is because agricultural land and forests, wetlands, and agroforestry systems improve the structure and fertility of soils and, thus, crop productivity. In Greece, such management has been associated with improved soil health and better protection of water resources in various ecosystems [23]. Similarly, the importance of ecosystem diversity is consistent with the ecosystem services theory, which links diversity to ecosystem properties that are useful for agricultural food production [24]. Having a diverse ecosystem is helpful in mitigating environmental stresses, thus providing the support needed to improve soil and water sustainability. This resilience is particularly important in countries such as Greece, where water and soil scarcity is expected to worsen due to climate change [25,26]. In the agricultural systems in Greece, the intercropping of crops with trees and shrubs has been found to improve the soil's ability to retain water and prevent soil erosion, thus improving crop production even during the dry season [27]. These practices are in line with the United Nations Sustainable Development Goals (UN SDGs) for agriculture and climate-smart agriculture.

Kalogiannidis et al. [28] found that the sustainability of different cropping systems, forests, and wetlands in Greece depends on the soil health and available water sources. Functional diversity, which refers to the number of tasks performed by the species in a given ecosystem, determines the effectiveness of ecosystem services [9,29]. This diversity allows the ecosystem to maintain important ecosystem processes, such as nutrient cycling, pollination, and pest control, even when the environment changes [30]. Kozicka et al. [31] postulated that, given the functional diversity in Greek agricultural systems, nutrient cycling is promoted when ecosystem services are promoted, thereby improving the sustainability of agriculture. Such practices have been shown to be crucial in maintaining a defense against climate change and food insecurity [4,32,33]. This is in line with climate-smart agriculture, which aims to increase productivity, incomes, and food production while achieving climate resilience and reducing greenhouse gas emissions [34,35]. In Greece, various policy instruments and measures on sustainable agriculture support the practice of sustainable options to support biodiversity [6,36]. According to Mijatovi et al. [9], Greek farmers have adapted to environmental changes by using different crop and livestock species and other traditional practices. These practices have not only improved food production but also the management of genetic resources and ecosystem services [37]. Some of the more recent practices introduced in Greece include organic farming, silviculture, and the conservation of regional varieties [38–40]. These practices are supported by national legislation and global policies such as the EU CAP and the UN SDGs. One of the strategies

is the Farm to Fork strategy, which aims to build a competitive and sustainable food system for the EU [41]. This strategy also highlights the role of biodiversity, sustainable practices, food security, and resilience. This strategy has been applied in Greece through measures promoting biodiversity conservation, reductions in chemical use, and sustainable land management [6,36].

While there is a theoretical argument that high biodiversity is beneficial in terms of increasing resourcefulness and productivity, there is insufficient evidence [42,43]. Coping capacity is another rather general term referring to the ability of agricultural systems to withstand and manage different levels of stress, shocks, and transformation towards improved forms of sustainability [44,45]. Agricultural biodiversity can address all of these issues by helping to offset the effects of environmental variability, supporting sustainable agricultural practices, and promoting innovation in agricultural systems to increase sustainability [2,46,47]. There is also growing awareness and recognition of the potential of agrobiodiversity to mitigate climate change. The Global Food System Resilience framework examines the impact of increasing food system resilience through better management and use of biodiversity [48,49]. In Greece, this has been achieved through activities, climate-smart agriculture, and biodiversity considerations in the management of agricultural land, as detailed below [50–52]. However, several issues need to be discussed in order to address the use of agricultural biodiversity. These include the lack of awareness of AGF among farmers and policymakers, the increasing reliance on traditional knowledge and research, and the development of appropriate policies and incentives for AGF [53,54]. To overcome these challenges, consideration should be given to farmers, researchers, policymakers, and civil society organizations (CSOs) [2]. Therefore, this study aimed to contribute to the existing body of knowledge by providing empirical evidence on the crucial factors (namely, genetic, species, ecosystem, and functional diversity) underlying the vulnerability of Greek agricultural systems to climate change.

The primary aim of this study was to examine how agricultural biodiversity enhances resilience against climate change and improves food security in Greece. In order to achieve this, this study explored the relationship between genetic diversity and yield stability under climate variability, assessed the role of species diversity in reducing susceptibility to pest and disease outbreaks, analyzed the contribution of ecosystem diversity to maintaining soil health and water resources, and investigated the impact of functional diversity on nutrient cycling and other key ecosystem services. This study was guided by the following hypotheses: (1) higher genetic diversity in crops leads to greater yield stability under climate variability; (2) increased species diversity in agricultural systems reduces the incidence and severity of pest and disease outbreaks; (3) greater ecosystem diversity contributes to improved soil health and food security; (4) enhanced functional diversity can increase the efficiency of nutrient cycling and other vital ecosystem services. By addressing these aspects, this study seeks to highlight the importance of biodiversity in sustainable agricultural practices and inform policy measures that support resilient farming systems in Greece.

2. Literature Review

This study was informed by the ecosystem services theory. As postulated by this theory, the elements of biodiversity ensure the sustainable provision of ecosystem goods that support human existence and survival, the food and water supply, and climate stability [55–58]. According to this theory, different ecosystems are better able to cope with change and risk, which is useful for maintaining crop productivity and ecosystem integrity [2]. This resilience is due to the tolerance of the many species involved in important ecological processes. In terms of agriculture, the theory outlines the role of diversity in maintaining

the provision of ecosystem services required for crop production, pest control, and nutrient availability [4,59,60]. It has been widely used to explain how achieving agricultural biodiversity can lead to greater stability in farming systems. For example, in crops, genetic variation allows for the selection of varieties that perform well under stressful conditions, which is particularly important when environmental changes occur [61,62]. Similarly, crop species diversity helps to control pests and diseases by disrupting their life cycle [63,64]. Ecosystems such as forests, wetlands, and agroforestry systems support the soil and water supply and water security for sustainable management of agricultural soils [65–67]. The outcomes of traditional farming practices with high biodiversity in Greece support the ecosystem services theory. These practices have historically contributed to agricultural productivity through the conservation of germplasm and ecosystem services [68]. Other activities that have been recently implemented in Greece include sustainable agriculture practices that support and promote agricultural productivity in the face of climatic volatility in order to support agricultural production. This is in line with climate-smart agriculture, which aims to increase production, resilience to climate change, and the rate of greenhouse gas emissions [34,35]. The ecosystem services theory has been supported by research conducted in Greece and other parts of the world. For example, various analyses have shown that diverse agricultural systems are more resilient to environmental pressures or are able to sustain higher levels of agricultural productivity [2,41,69]. However, there is a paucity of studies that provide evidence to support such claims and generate conclusions about the potential of agricultural biodiversity [70]. Filling this knowledge gap is important for the development of climate change and sustainable agriculture policies and strategies [71].

Crop diversification is beneficial for increasing production and reducing the risks associated with climate change. Genetic variation also makes crops less vulnerable to stresses such as drought, heat, and pests, which are increasing due to climate change [11,72]. Therefore, it can be concluded that increased genetic variation promotes yields in the context of climate change, providing food security [4]. For example, changes in agro-diversity in Greece have been associated with improved climate resilience in terms of reduced yield volatility [6]. The literature has found that genetic variation is desirable when it comes to developing crop types that are well suited to certain conditions, such as drought or pest infestation [73]. This is especially true in countries like Greece, where the weather changes can be quite dramatic. In this way, farmers are able to build up the genetic stock and grow plants that are better suited to today's climate in order to increase yields [61,74].

Previous research has provided an empirical basis for increasing genetic variability as a means of increasing the stability of crop productivity. Mijatovi et al. [9] argued that crops with high genetic diversity are able to withstand adverse environmental conditions and produce higher yields than crops with low genetic diversity. Greek farmers have always adopted crop diversification techniques in order to overcome challenges that may be caused by environmental factors, and this has been facilitated by the traditional breeding practices used by Greek farmers [75,76]. These practices not only help to achieve yield stability but also preserve germplasm, which is central to future breeding. However, some concerns remain about the conservation and use of genetic resources. Most modern agricultural practices produce relatively high-yielding but genetically identical crops, which appear to be more vulnerable to environmental perturbations [77–79]. Therefore, there is a need to increase awareness and support for the conservation of genetic resources and the development of climate-smart crop varieties [80].

Biodiversity in agricultural production systems plays an important role in minimizing pest and disease risks. Different types of agro-ecosystems can help manage pests and diseases as they can alter the life cycles of pests and pathogens [20,81,82]. Lenné and Wood [83] found that species-rich agricultural landscapes are more resilient to pests and

diseases due to the presence of natural enemies and a more diverse physical environment. Similarly, Farooq et al. [84] claimed that higher species richness in agricultural systems improves the population of predators and parasitoids of pests. These natural enemies live in different ecological conditions that provide them with different prey and breeding grounds, meaning that they will always reproduce even when pests are scarce. This is important for sustainable pest control, reducing the use of chemicals that have negative impacts on the environment and human health [85,86]. While monoculture systems are extremely susceptible to pests and diseases because all the plants in a given area are of the same species, polyculture systems take advantage of their species heterogeneity to create more stable agricultural environments. Balyan et al. [87] found that polyculture agriculture in Greece, where different crop species are grown in the same field, significantly minimizes pests and diseases. Not only do they affect the life cycles of pests, but they also support the healthy development of crops as the ecosystem becomes more stable and balanced. Many studies have shown that crop diversification minimizes the risks and consequences of pests and diseases in different farming systems [88–90]. Thus, the interactions between diverse species form a network, increasing crop resistance to ‘biotic risks’. This is also evident in the research on functional diversity and the importance of different species playing different roles in an ecosystem [9]. This functional diversity enables ecosystems to be resilient and continue to provide services such as pest control in a dynamic environment [91]. Functional diversity has been estimated to be high in Greek agricultural systems, meaning that there is a better provision of ecosystem services such as pest and disease control [6].

Similarly, Storkey et al. [63] found that diversified cropping systems are not affected by catastrophic pest and disease outbreaks because different species disrupt the progress of pests and diseases. This resilience is particularly useful in the case of pest challenges, which are expected to be exacerbated by climate change [92]. Therefore, while low-diversity systems require chemical agents, in diverse systems, pests are managed through other approaches. These include ecological approaches, which are in line with sustainable agriculture and climate-smart agriculture [93]. These systems may also be less damaging to the environment and ecosystem as the use of chemical pesticides is reduced to a minimal level. Taken together, these studies show that biodiversity is an important factor in sustainable agriculture. More ecological practices such as polyculture and agroforestry should be practiced in Greece for long-term sustainable pest and disease management [6]. By building populations of many species in agricultural systems, farmers can improve the ability of crops to withstand stress, limit problems associated with pests and diseases, and begin to establish a framework for a sustainable agricultural system [94].

Studies have also shown that ecosystem diversity can reduce the negative impacts of climate change on agriculture by increasing soil fertility and water availability [33,95]. Plant diversity leads to soil nutrient availability and promotes the growth of microbes that are essential for soil sustainability. In addition, diverse ecosystems support pollinators and natural enemies of pests, which are important for crop production and protection [96]. Taken together, these studies point to the need to maintain and promote ecosystem heterogeneity in agro-ecosystems. Measures such as organic farming or nature conservation are crucial to supporting sustainable agricultural systems [97]. Integrating ecosystem diversity into agriculture thus strengthens the well-being of the soil and water, among other environmental and socio-economic benefits [2].

The functional roles or spaces of species in the ecosystem are very important for ecosystem services and production [9]. This diversity enables ecosystems to maintain important services and processes, such as nutrient cycling, pollination, and pest control, regardless of the circumstances [33]. In this context, functional diversity allows many

species to provide the same ecosystem services; therefore, if some species are lost, the ecosystem processes and functions are still maintained [2].

Kozicka et al. [31] pointed out that higher functional diversification in agricultural systems enhances nutrient cycling and is essential for soil fertility and crop yields. In Greece, there are questions about functional differentiation in agricultural mosaics and its impact on nutrient cycling and ecosystem services [6]. The different plant species used in agroforestry practices can improve nutrient uptake from the soil and increase the rate of decomposition of organic matter to improve soil quality [98]. Similarly, according to the ecosystem services theory, functional diversity is required to maintain ecosystem structures that are critical for human well-being. Thus, highly diverse agricultural systems are efficient in addressing and mitigating environmental threats and pressures. Unlike monoculture systems, which are highly selective in terms of fertilization and pest control, diversified systems are able to maintain soil fertility and health without assistance [99]. Studies have indicated that functional differentiation is a very useful strategy for increasing the sustainability of agri-food systems. In Greek agriculture, there are practices that increase functional diversity and improve nutrient cycling, such as crop rotation and the use of cover crops [37,100]. These practices improve soil fertility, which, together with other biotic factors such as pest management and pollination, is crucial in agriculture. However, the benefits of functional diversity are not limited to nutrient cycling, but also to other aspects of ecosystems [22,101]. Different plant species promote the development of beneficial insects and microorganisms that help control pests and enrich the soil quality [101]. Functional diversity has also been found to provide several ecosystem services that benefit agriculture and food security in Greece. Studies in Greece and other regions suggest that it is beneficial for agricultural environments to have a variety of functional plots. These findings highlight the need for functional diversity policies and practices in the context of creating stewardship-oriented agricultural systems [102].

Climate-smart agriculture also embraces agricultural biodiversity as one of the approaches to enhancing on-farm systems [103]. This approach helps to increase long-term productive capacities, combat climate change, and reduce greenhouse gas emissions. Some of the climate-smart practices implemented in agriculture in Greece to enhance biodiversity and resilience include organic farming, agroforestry, and conservation agriculture [50]. These practices are in line with the sustainable development goals of international bodies and contribute to combating the effects of climate change. Similarly, Vernoooy [104] pointed out that the implementation of vegetation diversification in production landscapes decreases the vulnerability of agricultural production systems to climate variability and change. In Greece, climate-smart measures have improved food production, soil health, and water management [105]. In contrast to conventional farming practices that use synthetic fertilizers and pesticides, climate-smart practices use natural production cycles and crop heterogeneity to support the agricultural process [106]. For example, organic farming does not use synthetic chemicals to increase yields and instead uses organic manure to increase soil productivity. Planting trees and shrubs alongside crops benefits plant and animal biodiversity by absorbing CO₂, combating soil erosion, and providing shelter for animals and birds [66].

In the context of Greek agricultural systems, these practices have been demonstrated to enhance sustainability and productivity. Common agriculture, which encompasses techniques such as minimum tillage and the utilization of cover crops, has been shown to promote soil health, augment water infiltration rates, and mitigate soil erosion [107]. It can also improve the ability of agricultural systems to withstand climatic shocks and stresses, making them more resilient [2]. Climate-smart agriculture is supported by several policies in Greece, such as the EU CAP and the Farm to Fork strategy. According to

Meuwissen et al. [69], policy frameworks increase the resilience of the food system by protecting the natural environment. Similarly, Frison et al. [2] support policies that aim to increase agrobiodiversity and agricultural production. These policies have been actively implemented in Greece, which have helped to promote sustainable policies that support biodiversity and human well-being [6]. Unlike many other regions where there is a lack of policy support for biodiversity, in Greece, the authorities have developed a clear policy that includes biodiversity as a factor in agricultural development plans [108]. These policies have been effective in supporting practices such as organic farming, agroforestry, and conservation agriculture, which are beneficial for ecosystems [109]. Organic farming in Greece has benefited from subsidies to farmers and technical assistance in adopting practices that support soil conservation and enhance ecological diversity [2,110].

In Greece, sustainable agriculture policies have improved measures of soil status, water use and management, and productivity. These policies demonstrate the need for a coordinated approach involving government departments, research institutes, and farmers' associations [2]. In addition, other international frameworks such as the United Nations Sustainable Development Goals (UN SDGs) and the Convention on Biological Diversity (CBD) provide a global framework for agricultural biomass-based diesel (BBD). These frameworks help countries integrate improving biodiversity into agricultural practices and policies, as they support sustainable consumption and global production of food [111,112]. In Greece, the endorsement of these global goals has only strengthened the appreciation of the principles of biodiversity conservation and organic agriculture [113].

3. Materials and Methods

This study used a cross-sectional survey and a quantitative research design. This allowed for the collection of data on the current agricultural biodiversity status and its impact on resilience and food security. This is important because quantitative research allows for the evaluation of variables and/or the rejection or validation of hypotheses through statistical analysis [114,115]. In a cross-sectional study, the data are collected at one point in time; using this approach allowed us to analyze the current status and relationship between agricultural biodiversity and resilience in Greece [15,28]. The participants of this study were agricultural experts working in Greece, who had knowledge about agricultural biodiversity and its relationship with food security and climate adaptability. The participant group consisted of farmers and researchers involved in agricultural practices, policymakers, and university administrators. Greece (Figure 1) was chosen as the case study because of its diverse agro-ecological systems that are sensitive to the impacts of climate change [6,116].

In order to obtain a random sample that would be reasonably representative of the population of agricultural professionals, a technique known as stratified random sampling was employed. The sampling was stratified in two dimensions: the occupational roles of the participants, such as farmers, researchers, policymakers, and agricultural extension agents, and the geographical area, covering different agro-ecological zones in Greece. These dimensions were considered because they are core drivers of opinions regarding agricultural biodiversity and food security. Simple random sampling was conducted for each of the dimensions to ensure that each sub-sector was well represented. This procedure increases the external validity and reliability of this study's conclusions [117]. The sample size was estimated based on Yamane's [118] formula to represent a large population at a 5% level of significance. This led to a sample of 384 agricultural specialists (Equation (1)).

$$n = \frac{N}{1 + Ne^2} \quad (1)$$

where n is the sample size, N is the population, e is the significance level, and 1 is a constant. Using a 5% (0.05) significance level, we obtain the following:

$$n = \frac{10,000}{1 + 10,000 (0.0025)^2} = 384$$

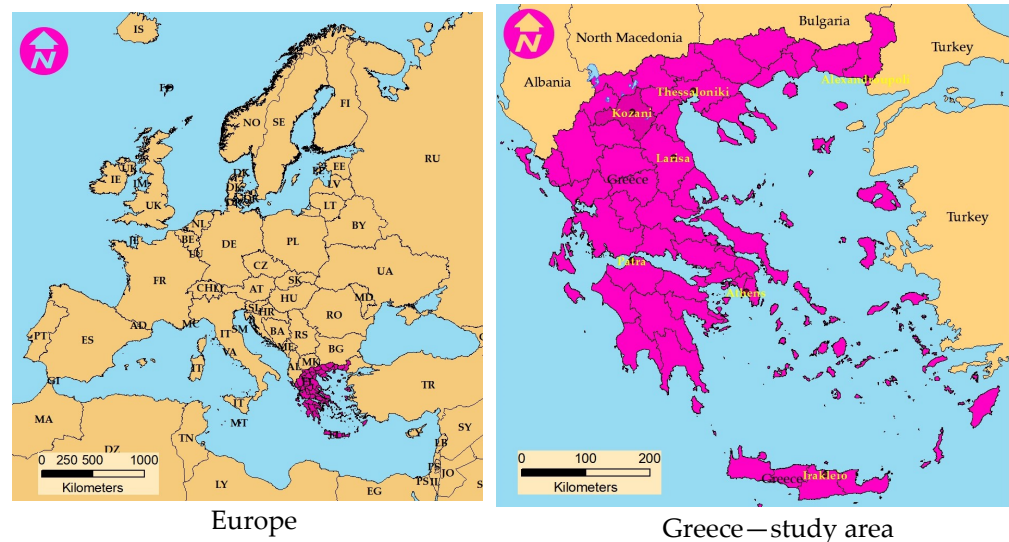


Figure 1. Maps of Europe and Greece.

Invitations were sent to specialists via e-mails or through social media accounts used by members of the agricultural community operating in Greece. The online survey method may have resulted in a pool of respondents who are more educated and inclined towards technology, thus increasing the chances of internet use and sample bias. The current study took this into consideration, and we recommend that other research studies should survey less technologically savvy people to obtain more generalizable findings [119,120].

To collect data for the analysis, an online survey was administered to the selected agricultural professionals. In the questionnaire (see Appendix A), one set of questions was about the significance of agricultural biodiversity in relation to aspects such as yield stability, pests and diseases, soil conservation, nutrient replenishment, and food security. Despite not directly discussing food security, the concept was inferred through questions relating to the respondents' understanding of how climate change affects agricultural production and the maintenance of food security [121,122]. Regarding food availability and access, the questionnaire contained questions on yield stability, the ability to withstand unfavorable conditions, and sustainable agriculture practices. While no special emphasis was placed on food security in the questionnaire, the questions were designed to ask the respondents whether they thought that agricultural biodiversity contributed to decreasing vulnerability in food systems. However, for a more detailed analysis related to food security, future research could include a separate section dedicated to the three dimensions of food security: accessibility, availability, and utilization. The survey employed a Likert scale to score the items, which had the respondents indicate to what extent they agreed or disagreed with each statement, with the options ranging from strongly disagree to strongly agree. These questions were grounded in the broader literature on agricultural biodiversity and its effects on resilience and food security. A pilot survey was administered with a sample of 10 agricultural professionals in order to simplify the survey instrument and minimize ambiguity. The wording and structure of the questions in the pre-test were changed based on the feedback to improve the survey's reliability and validity.

The survey was conducted online using e-mail and internet tools popular among Greek agricultural professionals. Self-administered questionnaires were used because they are cost-effective and allow for a large, random sample across wide geographic distances. The questionnaires were administered over a period of three weeks and follow-up emails were sent to those who did not complete their questionnaires after one week. A total of 384 participants completed the survey [121,122].

The collected data were then analyzed using the Statistical Package for the Social Sciences (SPSS ver. 23) software. Frequencies and percentages were calculated to analyze the demographic characteristics of the respondents and their responses to the survey questions. This provided a general overview of the sample and the general trends in the data. The hypotheses of this study were tested using multiple regression analysis. The regression analysis allowed for the assessment of the relationship between the dependent (climate change resilience and food security) and independent (agricultural biodiversity) variables [123]. The multiple regression model used in this study is expressed as shown in Equation (2):

$$Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4 + \dots \varepsilon \quad (2)$$

where Y is the dependent variable; β_0 is the intercept; β_1 , β_2 , β_3 , and β_4 are the coefficients for the independent variables X_1 , X_2 , X_3 , and X_4 (genetic, species, ecosystem, and functional diversity, respectively); ε is the error term. The significance of each coefficient was tested at a significance level of 0.05.

The hypotheses were assessed based on the regression results, specifically the *p*-values and standardized coefficients (beta weights). $p < 0.05$ means that the independent variable has a significant relationship with the dependent variable [124]. The R-squared and adjusted R-squared values were also provided to show the amount of variance in the dependent variable that can be accounted for by the independent variable.

Consent was obtained from the participants to take part in this study, and they all understood the purpose of this study, their right to withdraw from this study, and the steps that would be taken to ensure their anonymity and confidentiality [125,126]. The data were kept secure and were only used by the research team; the identifiers were removed to ensure the anonymity of the participants [127]. In addition, in this study, we ensured that we adhered to the guidelines for the use of human subjects in research by obtaining permission from the relevant ethics committee. This helped to avoid any bias in the research process and to protect the rights of the participants.

4. Results

4.1. Demographic Characteristics of the Respondents

The demographic information of the respondents is presented in Table 1.

As demonstrated in Table 1, the gender distribution of the respondents revealed that 57.3% of the participants identified as male, while 42.7% identified as female, thereby indicating a slight predominance of males within the sample. With respect to the age distribution, the largest proportion of respondents was in the 40–49 age range (34.9%), with the 30–39 age group comprising 26.6% of the sample. The age groups < 29 years and >60 years were the smallest, with 11.7% and 8.3% of the respondents falling into these categories, respectively. This suggests that the study population was primarily composed of middle-aged individuals. With respect to educational attainment, a significant proportion of the respondents had attained postgraduate levels of education, indicating a high level of educational attainment within the study population. The predominant proportion of the respondents held a master's degree (45.8%), followed by a bachelor's degree (37.8%), with a mere 16.4% possessing a doctorate. This high educational attainment indicates a high level of specialization among the respondents in their respective domains. In terms of

occupation, a significant proportion of the respondents were farmers, constituting 39.8% of the study population. Other professions included researchers and policymakers, which accounted for 27.3% and 22.4% of the study population, respectively. The ‘Other’ category accounted for 10.4% of all the respondents, indicating a diverse range of occupations within the sample. This occupational distribution highlights the roles of various stakeholders, particularly those engaged in farming practices and the formulation of agricultural policies.

Table 1. Demographic characteristics of the respondents.

Characteristic		Frequency	Percentage (%)
Gender	Male	220	57.3
	Female	164	42.7
Age (years)	<29	45	11.7
	30–39	102	26.6
	40–49	134	34.9
	50–59	71	18.5
	>60	32	8.3
Education Level	Bachelor’s Degree	145	37.8
	Master’s Degree	176	45.8
	Doctorate	63	16.4
Occupation	Farmer	153	39.8
	Researcher	105	27.3
	Policymaker	86	22.4
	Other	40	10.4

4.2. Effects of Genetic Variation on Crop Yield Resilience

The respondents were invited to rate the importance of the effects of genetic diversity on crop yield stability under climate variability.

As demonstrated in Table 2, a significant proportion of the respondents concurred that genetic diversity exerts a favorable influence on yield stability in the context of climate variability. Delving deeper, it is noteworthy that 68.5% of the respondents selected ‘agree’ or ‘strongly agree’ as their response to the inquiry supporting the hypothesis that a higher level of genetic differentiation in crops is associated with greater yield variability. This substantial proportion lends credence to the notion that genetic diversification provides a degree of resilience to environmental stresses, thereby ensuring more stable productivity in a changing climate. However, a relatively small proportion of respondents expressed disagreement (12.5%) or neutrality (19.0) regarding the impact of genetic diversity on yield stability. These respondents may require further evidence or may have had experiences indicating that other factors, such as soil type or water accessibility, contribute more to crop yield consistency. The high level of agreement reflects a consensus among agricultural specialists that genetically diverse crops are better able to cope with the sometimes unpredictable and worsening climate conditions due to climate change. These benefits could include better drought tolerance, pest resistance, or temperature tolerance, which are essential for production when climate change is factored in.

Table 2. Public perception on whether genetic variation increases crop yield resilience.

Response	Frequency	Percentage (%)
Strongly Disagree	19	4.9
Disagree	29	7.6
Neutral	73	19.0
Agree	154	40.1
Strongly Agree	109	28.4

4.3. Role of Species Diversity in Mitigating Pest and Disease Vulnerability

The importance of species diversity in reducing the vulnerability to pests and diseases was also assessed and the results are shown in Table 3.

Table 3. Perception of whether species diversity reduces pest and disease vulnerability.

Response	Frequency	Percentage (%)
Strongly Disagree	13	3.4
Disagree	23	6.0
Neutral	69	18.2
Agree	163	42.4
Strongly Agree	116	30.0

The findings presented in Table 3 offer insight into the respondents' perspective on the role of species diversity in reducing the vulnerability of agricultural systems to pests and diseases. A significant proportion of the respondents expressed their agreement with the notion that an increase in species diversity can help mitigate pest and disease occurrences and severity. Specifically, 72.4% of the respondents selected either 'Agree' (42.4%) or 'Strongly Agree' (30.0%) when asked whether increased species diversity can reduce pest and disease occurrences and severity. This substantial consensus suggests a prevailing understanding that diverse ecosystems possess greater resilience, likely attributable to the abundance of species that can assist in controlling the propagation of specific pests and diseases.

This notion is further substantiated by ecological studies, which demonstrated that crops with limited biodiversity or those cultivated from a select variety of species are susceptible to pest and disease infestations, resulting in substantial economic losses.

The level of disagreement with the statement among the respondents was relatively low. A mere 3.4% of the respondents strongly disagreed, while 6.0% disagreed, amounting to a combined 9.4%. This minority may be questioning the efficacy of species diversity in pest and disease management or may hold divergent perceptions or knowledge about farming practices. However, 18.2% maintained a neutral stance on this topic. This may be indicative of a lack of understanding about the topic, confusion about the impact of species diversity, or the belief that other factors, not species diversity, are more influential in pest and disease management.

4.4. Effects of Ecosystem Diversity on Soil Health and Water Supply

The results pertaining to the role played by ecosystem diversity in soil health and water availability are presented in Table 4.

The results presented in Table 4 demonstrate that the majority of the respondents (75.3%) expressed agreement (44.5%) or strong agreement (30.8%) with the statement that greater ecosystem diversity is important for enhancing soil health and effective water management. This finding suggests that a substantial consensus exists regarding the significance of biodiversity in supporting essential ecosystem processes, such as nutrient

cycling in soils and water purification and storage. Conversely, a relatively small proportion of the respondents expressed divergent views, with only 2.6% strongly disagreeing and 4.7% disagreeing. This suggests that a minority of the individuals may lack a firm grasp on the relationship between ecosystem diversity and environmental health, or may be unacquainted with the biological principles underpinning this association. The neutral responses (17.4%) may indicate that there are many people who have not formed a definitive opinion about the concept or who do not care about it, which may be due to inadequate information or experience with regard to the effects of biodiversity on soil and water quality.

Table 4. Subjective perception of whether ecosystem diversity improves soil health and the water supply.

Response	Frequency	Percentage (%)
Strongly Disagree	10	2.6
Disagree	18	4.7
Neutral	67	17.4
Agree	171	44.5
Strongly Agree	118	30.8

4.5. Effects of Functional Diversity on Nutrient Cycling and Ecosystem Services

The participants were also asked about the impact of functional diversity on nutrient cycling efficiency and other ecosystem services, and the findings are presented in Table 5.

Table 5. Perception of whether functional diversity positively impacts nutrient cycling and ecosystem services.

Response	Frequency	Percentage (%)
Strongly Disagree	14	3.6
Disagree	27	7.0
Neutral	74	19.3
Agree	159	41.4
Strongly Agree	110	28.7

As illustrated in Table 5, the majority of the participants (70.1%) perceived high functional diversity to be beneficial for nutrient cycling and other ecosystem services. Notably, 41.4% of the participants expressed strong agreement, while 28.7% indicated moderate agreement, collectively signifying a substantial degree of consensus regarding the beneficial role of functional diversity in ecological systems. In contrast, a smaller proportion of the participants expressed skepticism or held no opinion on the role of functional diversity. Specifically, only 10.6% of the participants (3.6% who strongly disagreed and 7.0% who disagreed) disagreed that functional diversity enhances ecosystem efficiency. Conversely, 19.3% of the respondents gave a neutral response, indicating uncertainty regarding the impact on nutrient cycles and ecosystem services.

4.6. Regression Analysis

To test this study's hypotheses concerning the role of genetic, species, ecosystem, and functional diversity in agricultural resilience and food security, a multiple regression analysis was conducted. The results are presented in Table 6.

The regression results indicate that all four forms of diversity—genetic, species, ecosystem, and functional—were perceived to have a statistically significant impact on agricultural resilience and food security ($p < 0.05$). The model had an adjusted R-squared value of 0.621, indicating that 62.1% of the variance in the dependent variable, defined as resilience, was attributable to the independent variable of biodiversity.

Table 6. Regression analysis results.

Independent Variable	Unstandardized Coefficient	Standardized Coefficient	t	Sig.	R-Squared	Adjusted R-Squared	F	Sig. (F)
	B	Std. Error	Beta					
(Constant)	41.07	4.67		8.79	0.621	0.614	31.85	0.000
Genetic Diversity	0.54	0.152	0.046	3.55	0.000			
Species Diversity	0.621	0.038	0.550	16.34	0.000			
Ecosystem Diversity	0.111	0.028	0.202	3.96	0.001			
Functional Diversity	0.421	0.028	0.550	15.04	0.000			

The positive and statistically significant unstandardized coefficient ($B = 0.54$) and t -value (3.55 , $p < 0.001$) support Hypothesis 1, implying that increasing genetic heterogeneity in crops is crucial in minimizing the impact of climate change on agricultural productivity. The second hypothesis was supported by a large standardized coefficient ($Beta = 0.550$) and the highest t -value (16.34 , $p < 0.001$) among all the independent variables, affirming the capacity of polyculture to slow the spread of pests and diseases, thereby leading to healthier crop systems. The third hypothesis, which proposed that ecosystem diversity enhances soil health and water management, was supported by a positive and statistically significant result ($B = 0.111$; $t = 3.96$, $p = 0.001$). This finding suggests that diverse habitats in agricultural environments contribute to improved natural resources and, consequently, sustainable food production. Functional diversity was also perceived to have an impact on efficient nutrient cycling and ecosystem services, supporting Hypothesis 4 ($Beta = 0.550$, $t = 15.04$, $p < 0.001$). This means that organisms with multiple functional traits are effective in maintaining the ecological processes that are crucial for agriculture.

5. Discussion

This study examined the role of agricultural biodiversity in improving resilience towards climate change and food security in Greece. The outcomes confirmed that genetic diversity in crops improves yield resilience to climate change, thereby agreeing with previous research that found that genetic variation helps crop varieties perform well under different forms of environmental stress [4,104,128]. The contribution of agricultural biodiversity in improving the ability to adapt to climate change has been confirmed in numerous previous analyses. The findings of this study strengthen the evidence that increased genetic variation in crop plants enhances yield robustness due to the ability to withstand factors compromising crop productivity like drought, heat, and pest attacks. These findings are in agreement with those of earlier studies that showed that genetic diversity makes crop varieties more resilient against poor climatic conditions, which also holds true in Greece, which is climatically volatile [4,104,128]. Utilizing such diverse genetic reserves for future breeding endeavors could enhance the long-term adaptability of agricultural management in the context of climate fluctuations [6]. This serves to underscore the need to conserve different types of germplasm to protect agricultural production systems against volatile weather conditions.

A higher species diversity in agricultural systems was found to contribute to lower pest and disease pressures in this study and is also supported by the literature change [72,129]. Indeed, it can be argued that species-rich agroecosystems have higher levels of ecological complexity, enabling biological control through predation and parasitism. These findings are especially relevant for Greece: previous polyculture systems, where two or more crops are cultivated simultaneously, resulted in a decrease in pest occurrences. This approach can reduce the use of chemical pesticides and, in the process, foster the adoption of environmentally sustainable practices [63,130,131]. The results of the present study support such claims and underscore the importance of applying multiple paddock systems

with close-row planting of several crop species to suppress pests and increase the stability of agricultural systems.

The results show that species diversity has a positive impact on managing pests, but the assessments could benefit from more precise analyses. Potential confounding factors include the management practices on the farms, the economic conditions in the particular region, and the current policies that govern such practices. For instance, effective farming techniques, such as the use of synthetic pesticides or fertilizers, could affect the efficacy of biodiversity in pest control. In addition, the costs and access to grants, subsidies, and incentives for farmers may determine the ability or readiness of farmers to implement biodiversity improvement measures. European policies, such as the CAP and the recently proposed Farm to Fork strategy, have assisted in the promotion of sustainable farming methods in Greece [6]. Nonetheless, variations in policy implementation and regional economic conditions may have influenced the results of this study. A more comprehensive analysis of these factors could enrich the results by examining the overall context in which agricultural biodiversity is applied. Another factor to keep in mind is the impact of ecosystems on soil and water conservation. This study revealed that diverse ecosystems indeed provide critical biophysical services such as nutrient cycling, soil development, and water treatment [132,133]. This is in agreement with other research findings, which found that farms with diverse species are better able to perform such processes, improving the sustainability of agroecosystem practices. The ability of diverse ecosystems to maintain these essential functions is likely to become more important given the increasing global environmental pressure from climate change. The incorporation of such ecosystems in agricultural systems could sustain future production and ecological permanency, which is an aspect of climate-smart agriculture [134]. However, future studies could build on our findings by explaining how different types of ecosystem services are interlinked and how these interrelationships affect general agricultural production and sustainability. For instance, although there is evidence of the benefits of ecosystem diversity, a qualitative analysis should be performed considering the potential risks associated with trade-offs in ecosystem services. For instance, when one of the ecological functions improves, say, soil fertility, it might have negative effects on water conservation or the proliferation of pests. Understanding these interactions could help in further improving the effects of agricultural biodiversity.

This study also examined how functional diversity affects nutrient cycling and ecosystem service provision. For example, crop rotation and the inclusion of cover crops can lead to improved nutrient cycling and the minimal use of chemical fertilizers [135], cutting costs and preserving the environment. The impact of functional diversity in nutrient cycling is in line with the rationale for climate-smart approaches that improve productivity while reducing the impacts on the environment [136]. However, functional diversity comes with an economic trade-off. For farmers, higher costs may be incurred to realize these benefits. It is a complex challenge for different policy designs to consider incorporating biodiversity into agricultural policies.

However, as pointed out above, some of the findings of this study remain inconclusive and require further research to determine the specific pathways between biodiversity, agricultural resilience, and food security. Since agriculture affects global food security, especially in the face of climate change, future studies should examine how various policy tools at both the national and international levels can help promote the inclusion of biodiversity in agricultural systems. The current study was conducted with an online survey and using a selected pool of respondents, predominantly with higher education; therefore, further studies should compare the results obtained from farmers with various educational backgrounds and use other research methods to reduce biases. Another limitation of

this study is that the use of an online questionnaire meant that the respondents may not be fully representative of the general farming population as they may be more technologically literate or have higher education levels than the general population of farmers. One possible source of bias could be that the highly educated farmers and agricultural administrators in this study could be more aware of issues on biodiversity and climate change than their counterparts with less education, thereby skewing the results. A larger, more diverse sample of farmers—especially those who are less tech-savvy or come from a less privileged socio-economic background—could provide a more realistic view of the general perception of agricultural biodiversity. In addition, the cross-sectional research design employed in this study means that the data collection was conducted at one time point and does not capture dynamic processes inherent in agriculture systems and biotic diversity. Well-designed studies that follow the evolution of Best Agricultural Practices (BAP) or their impacts on resilience and food security over time would offer much more convincing evidence of the long-term advantages of agricultural biodiversity.

6. Conclusions

This study underscores the pivotal role of agricultural biodiversity in bolstering climate resilience and ensuring food security within Greek agricultural systems. The empirical analysis reveals that genetic, species, ecosystem, and functional diversity collectively enhance yield stability, strengthen pest and disease resistance, improve soil structure and fertility, and support efficient nutrient cycling—core elements of sustainable agriculture.

A key insight from this study is the widespread consensus among agricultural specialists regarding the ecological and economic value of maintaining high levels of biodiversity within agricultural landscapes. Increased genetic variation was shown to improve crop adaptability to climatic stressors, while species diversity mitigates pest and disease outbreaks by promoting ecological balance. Similarly, ecosystem diversity contributes to the preservation of soil and water quality, and functional diversity enhances ecosystem service provision, particularly in relation to nutrient retention and productivity.

These findings highlight the urgent need to mainstream biodiversity conservation into agricultural policy and practice. Integrating diverse biological systems into farming not only safeguards food production in the face of environmental volatility but also supports broader socio-economic and ecological sustainability goals. To this end, policy frameworks must be strengthened to incentivize diverse and resilient farming practices capable of meeting global nutritional demands while mitigating the impacts of climate change.

Nevertheless, this study is not without limitations. The cross-sectional design offers only a snapshot in time, limiting the capacity to assess long-term ecological dynamics. Additionally, reliance on self-reported data introduces the possibility of response bias. Future research should employ longitudinal methodologies and integrate quantitative biodiversity metrics to provide a more robust and comprehensive understanding. Expanding the geographic scope beyond Greece would also enhance the external validity and applicability of the findings across different agroecological contexts.

Implementation

This study highlights the vital role of agricultural biodiversity—genetic, species, ecosystem, and functional—in bolstering climate resilience and food security in Greece. Findings indicate that these dimensions of biodiversity enhance yield stability, improve pest and disease resistance, support soil and water health, and promote efficient nutrient cycling. These insights underscore the need to shift towards diversified, resilient agroecosystems.

To translate these findings into practice, we propose the following policy recommendations:

- Incentivize biodiversity-based practices such as polyculture, crop rotation, and agroforestry through subsidies and CAP-aligned programs.
- Integrate biodiversity metrics into national agricultural monitoring systems and resilience assessments.
- Support the conservation of local landraces and livestock breeds via seed banks and on-farm conservation schemes.
- Promote farmer education and training in biodiversity-enhancing practices, especially in climate-vulnerable regions.
- Foster multi-stakeholder platforms for policy co-creation involving researchers, farmers, and civil society to embed biodiversity in agri-food systems.

Strengthening biodiversity-focused policy frameworks—aligned with the EU Green Deal, the Farm to Fork Strategy, and the UN SDGs—can support both climate adaptation and sustainable development goals. While this study provides a strong empirical basis, its cross-sectional design limits insights into temporal changes. Future longitudinal and multi-country studies are recommended to validate these findings and inform broader applications.

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Abbreviations

The following abbreviations are used in this manuscript:

UN SDGs	United Nations Sustainable Development Goals
CSOs	Civil society organizations
EU CAP	European Union common agricultural policy
CBD	Convention on Biological Diversity
BBD	Biomass-based diesel

Appendix A

Agricultural Biodiversity and Climate Resilience Questionnaire

Purpose: This questionnaire is designed to gather insights from agricultural specialists regarding the role of biodiversity in enhancing climate resilience and ensuring food security. The questions reflect key findings in this study.

Demographic Information

1. Gender:

- ☐ Male
☐ Female

2. Age:

- ☐ Below 29
☐ 30–39
☐ 40–49
☐ 50–59
☐ Above 60

3. Highest Level of Education:

- ☐ Bachelor's Degree
☐ Master's Degree
☐ Doctorate
☐ Other (please specify) _____

4. Occupation:

- ☐ Farmer
☐ Researcher
☐ Policymaker
☐ Other (please specify) _____

Section A: Effects of genetic variation/Diversity on crop yield resilience

Please indicate your level of agreement with the following statements (1 = Strongly Disagree, 5 = Strongly Agree):

1. Genetic diversity in crops improves yield stability in response to climate variability.

- ☐ 1 (Strongly Disagree)
☐ 2 (Disagree)
☐ 3 (Neutral)
☐ 4 (Agree)
☐ 5 (Strongly Agree)

Section B: Species Diversity and Pest/Disease Management

Please indicate your level of agreement with the following statements:

1. Increasing species diversity in agricultural systems reduces the vulnerability to pest and disease outbreaks.

- ☐ 1 (Strongly Disagree)
☐ 2 (Disagree)
☐ 3 (Neutral)
☐ 4 (Agree)
☐ 5 (Strongly Agree)

2. Species diversity enhances natural pest control mechanisms through ecological interactions between species.

- ☐ 1 (Strongly Disagree)
☐ 2 (Disagree)
☐ 3 (Neutral)
☐ 4 (Agree)
☐ 5 (Strongly Agree)

Section C: Ecosystem Diversity and Environmental Health

Please indicate your level of agreement with the following statements:

1. Greater ecosystem diversity improves soil health by supporting nutrient cycling.
 - ☐ 1 (Strongly Disagree)
 - ☐ 2 (Disagree)
 - ☐ 3 (Neutral)
 - ☐ 4 (Agree)
 - ☐ 5 (Strongly Agree)
2. Ecosystem diversity contributes to better water management practices by enhancing water purification and storage.
 - ☐ 1 (Strongly Disagree)
 - ☐ 2 (Disagree)
 - ☐ 3 (Neutral)
 - ☐ 4 (Agree)
 - ☐ 5 (Strongly Agree)

Section D: Functional Diversity and Ecosystem Services

Please indicate your level of agreement with the following statements:

1. Functional diversity (such as crop rotation and cover cropping) enhances nutrient cycling and improves soil fertility.
 - ☐ 1 (Strongly Disagree)
 - ☐ 2 (Disagree)
 - ☐ 3 (Neutral)
 - ☐ 4 (Agree)
 - ☐ 5 (Strongly Agree)
2. Functional diversity in agricultural ecosystems ensures the availability of essential ecosystem services like pollination, pest control, and nutrient cycling.
 - ☐ 1 (Strongly Disagree)
 - ☐ 2 (Disagree)
 - ☐ 3 (Neutral)
 - ☐ 4 (Agree)
 - ☐ 5 (Strongly Agree)

Section E: Food Security and Resilience

Please indicate your level of agreement with the following statements:

1. Biodiversity contributes to food security by ensuring stable crop yields under varying climate conditions.
 - ☐ 1 (Strongly Disagree)
 - ☐ 2 (Disagree)
 - ☐ 3 (Neutral)
 - ☐ 4 (Agree)
 - ☐ 5 (Strongly Agree)
2. The adoption of biodiversity-friendly agricultural practices is critical for maintaining long-term food security.
 - ☐ 1 (Strongly Disagree)
 - ☐ 2 (Disagree)
 - ☐ 3 (Neutral)
 - ☐ 4 (Agree)
 - ☐ 5 (Strongly Agree)

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