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Review

Impact of Climate Change on Agroecosystems and Potential Adaptation Strategies

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Abstract: Agriculture is currently one of the leading economic sectors most impacted by climate change. Due to its great field of application and its susceptibility to meteorological variability, the effects of climate change on agriculture have significant social and economic consequences for human well-being. Moreover, the increasing need for land spaces for population growth has produced strong competition between food and urbanization, leading to a loss of the agroecosystem that supports food security. This review aims to understand the main risks generated by climate change in agricultural production and the potential strategies that can be applied to increase agriculture's resilience. Agricultural risk can be linked to the decrease in the productivity of foods, weed overgrowth at the crops expense, increase in parasites, water availability, soil alteration, negative impact on production costs and consequent change in the adopted cultivars, reduction in the pollination process, intense fires, and alteration of product quality. Thus, climate change can impact the provisioning of ecosystem services, reducing food security in terms of quantity and quality for future generations. Finally, in this review, we report the main adaptation strategies to increase agroecosystem resilience in adverse environments generated by climate change. Mainly, we highlight new technologies, such as new breeding technologies and agrivoltaic and smart agricultural applications, which, combined with agroecosystems, can reduce the agricultural risks following climate change (for example, drought events and low availability of water). We suggest that the combination of natural capital and technologies can be defined as an "innovation-based solution" able to support and increase ecosystem service flow in agroecosystems.

Keywords: climate change; agricultural resilience; adaptation strategies; provisioning ecosystem services; natural capital

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1. Introduction

Since the last century, there has been awareness that human life is directly and indirectly dependent on the capacity of the ecosystem to support goods and services, overall defined as ecosystem services [1,2]. Indeed, 50% of global Gross Domestic Product (GDP) is dependent on nature [3].

Natural capital can be defined as a flow of ecosystem services provided by the world's stock of natural resources, including biodiversity, soil, water, and air [4–6]. In addition, it is characterized by ecological processes and structures that are the basis for ecosystem services, and new knowledge in combination with new technologies can influence the capacity of humans to achieve new goods and services from nature, increasing ecosystem service provisioning [2,7].

The agroecosystem can be defined as the part of natural capital managed directly by human activities with a simplification and selection of biodiversity to support ecosystem function by providing food, feed, timber, fibers, and other products for market sale [8,9]. Therefore, agroecosystems are socio-ecological systems characterized by three interacting components: the managed fields, characterized by agricultural activities; the semi-natural or natural habitats, derived from a residual ecosystem of the heritage landscape; and the human-derived capital, characterized by knowledge, cultural traditions, technologies, settlements, and infrastructures [8,10–12].

The capacity of agroecosystems to support ecosystem services is strongly compromised by climate change, which is the main driver of ecosystem functionality damages [13–16]. For example, high temperatures associated with water shortages can increase plant evapotranspiration and reduce primary production, which is a basic supporting service for life on the Earth, because it guarantees the flux from solar to chemical energy [17–20]. This change can have a strong negative impact on the agroecosystem's capacity to support agricultural productivity in terms of human benefits derived from provisioning services. An example of the potential effects of climate change on food security was experienced during the El Niño Southern Oscillation from 2015 to 2016, which produced rising temperatures in 51 affected countries, with an estimated 5.9 million children becoming underweight [21].

Therefore, if economic activity drives climate change, climate change can reduce the capacity of the natural capital to support the economy, with negative effects also on food security, which is important for human life [22–24]. Mainly, food security refers to the possibility of ensuring equal access to food for the world population and sufficient food for a good life in time. "Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" [25].

However, the economy pushes towards the use of natural resources to fulfill human needs, with the subsequent reduction in agroecosystems, degradation of natural capital, and loss of regulation services that are important for reducing climate change [26–29].

The effects of climate change on agroecosystem production will be an important issue considering that it has been estimated that by 2050, the world's human population will increase by 70% [30].

Therefore, the combination of climate change and human population growth could decrease the capacity of agroecosystems to guarantee human subsistence. Thus, it is important to find a way to ensure food for a population that continues to grow, especially in developing countries; on the other hand, it is necessary to guarantee the quality and safety of the food produced and distributed [31,32]. Malnutrition does not only affect developing countries; it is becoming a global problem. For example, in the United States, many people lack regular access to healthy food [33], whereas in Europe and Central Asia, there is a serious problem with the quality of diets generated by the deficiency of nutrients important for human health in food products [21].

It is currently difficult to have a complete vision of the consequences of climate change on food production and, consequently, of the effectiveness of the different adaptation strategies to reduce negative impacts. In this regard, scientific dissemination is an important point for sharing results and identifying best practices [21,34,35]. The aim of the present review is to describe the main impact of climate change on agroecosystems, with a global view on suitable strategies to increase the resilience of agricultural production to ensure food security, supporting dissemination with a transdisciplinary approach covering different aspects of the same problem from different points of view.

2. Materials and Methods

The review has been carried out using PRISMA methodology [36] (Figure 1).

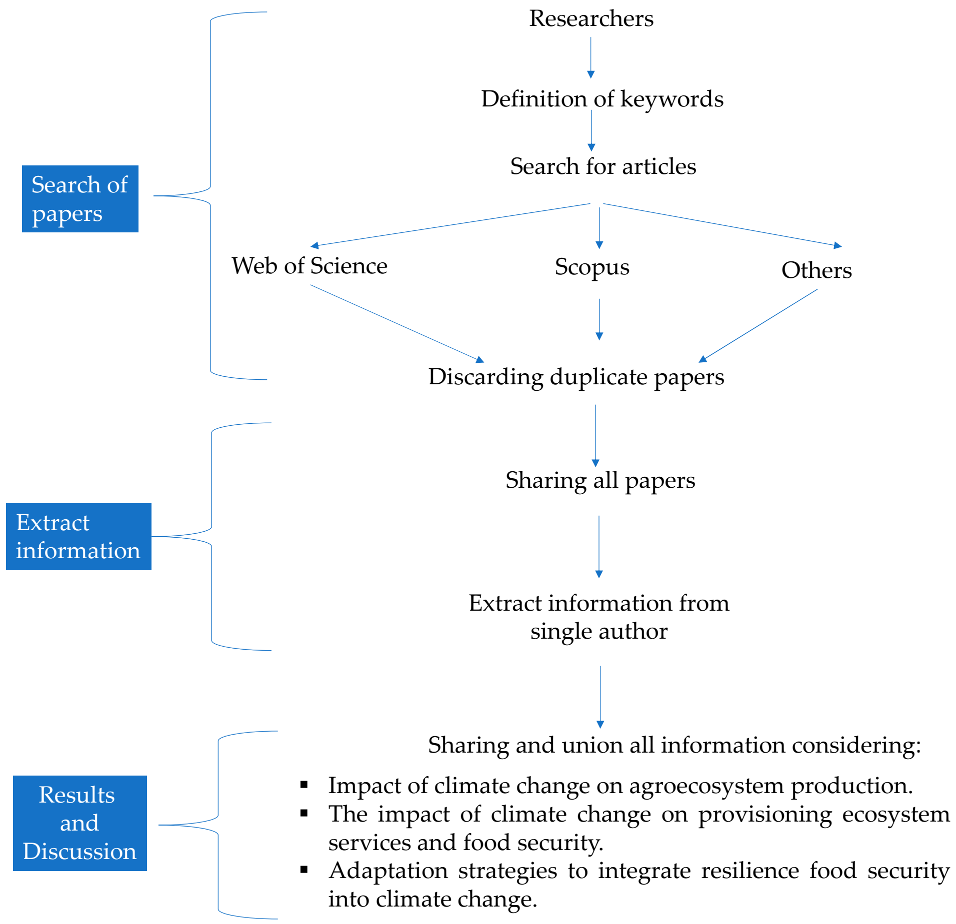

Figure 1. Framework applied for developing the review analysis.

We defined the criteria for inclusion or exclusion of publications used for this review. Mainly, we considered reviews, case study analyses and applications giving direct information on climate change effects on agriculture, potential mitigation strategies, reports of projects, and publications with simulation analysis. We considered only publications written in English and indexed in international journals under peer review processes to guarantee the quality of the reported information. Moreover, we also used some reports from officially recognized international agencies, such as the FAO, the UN, the UE, and others.

We did not include studies published before 2000 (with some exceptions) to have more recent information and knowledge about climate change. We did not consider conference proceedings and book chapters either.

Datasets such as Google Scholar, Scopus, and Web of Science were used to look for publications by searching with keywords such as "climate change, climate change's impact on agriculture, food security, climate change mitigation in agriculture, agricultural adaptation, climate change resilience, and agricultural mitigations".

In the present study, the decision to evaluate each publication was based on independent reading by each author. Following the search by keywords, the first check for selecting the manuscript was the title, keywords, abstract, and conclusions. All found publications were shared, and each author read the manuscripts, deciding to include or exclude them based on the reported information. If all the authors agreed on the exclusion, the publication was discarded. In the case of different views about a publication, the authors decided together if they should include it by considering the relevance of the given information for the study.

The analysis of each publication was then structured considering three points: (1) the main consequences of climate change and its effects on agroecosystems; (2) a deeper analysis of climate change's effects on vegetation adaptations that influence the quantity and quality of food security; and (3) potential strategies to improve the adaptability and resilience of agricultural production during climate change.

3. Results and Discussion

A total of 199 publications were collected and used for this review. However, 51 publications were used to gather information useful to define the general impacts of climate change on agroecosystems (point 1), 63 publications were used to implement a deeper analysis of climate change effects on food security (point 2), and 62 publications were used to define mitigation strategies (point 3) (Figure 2). There was some overlap among the three points because, in some cases, certain information pertaining to different points was reported in the same publication. An additional 35 publications were used to structure the introduction and conclusion.

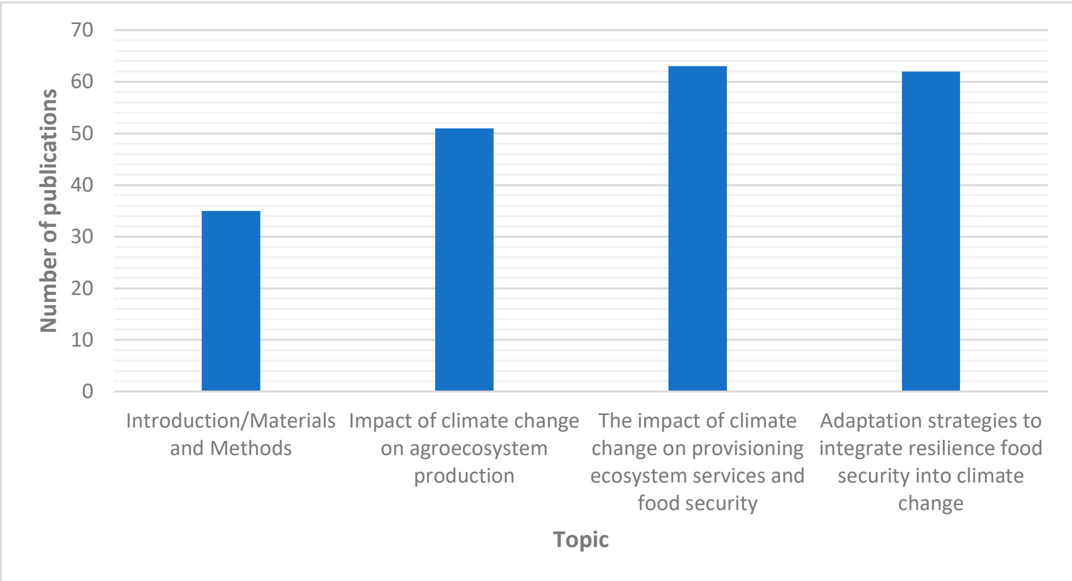

Figure 2. Distribution of used publications.

The majority of publications referred to on climate change effects and climate strategies analyzed are located in countries in Asia, Africa, and South America, where the agricultural sector is an important livelihood for the population. In fact, poor countries can suffer more from climate change effects on food supply than other regions [35,37].

In the following Section 3.1, we report our view of the main climate change effects on agroecosystems; in Section 3.2, we describe climate change effects on food security linked to the alteration of provisioning services; and in Section 3.3, we summarize the main strategies to improve the resilience of agricultural production from different analyzed publications.

3.1. Impact of Climate Change on Agroecosystem Production

Farmers experience climate change largely as extreme events' frequency and severity change. In particular, such events can be represented by floods, abnormal heat waves, fires, droughts, hailstorms, storm surges, rising seas, floods caused by rivers overflowing, a saline intrusion into the groundwater, and soil degradation due to floods [38–42]. Table 1 reports a summary of the direct and indirect effects of climate change on agricultural production extracted from scientific publications.

The consequences of climate change on agroecosystems depend on the intensity and timing of extreme events and their combinations in space and time. For example, the effects of extreme high temperatures can be amplified by reduced water availability caused by precipitation reduction because rain-fed agriculture has an important role in food security, covering 80% of the world's cultivated area and supporting crop production for approximately 60% [43,44]. Moreover, the high frequency of flooding events can increase the incapacity of the fields to catch the rainwater and use it at a different time.

Climate change can influence the integrity of agroecosystems and health, with negative impacts on food security, by modifying the crop types used, weed invasion, and pests, and by altering the plant physiological and biochemical processes that sustain ecosystem service provisioning. Moreover, climate change due to habitat destruction (i.e., changing agricultural practices, deforestation, industrialization), global warming, and the uncontrolled spread of invasive species could lead to biodiversity loss, with a decline and deterioration of ecosystems, species, and genetic resources important for tolerance to biotic and abiotic stresses [45].

The effects of climate change can be influenced by the geographic area because their impact on agricultural production is different depending on the latitude and altitude of the area. Such an impact is high and produces a reduction in food production in hot countries, whereas it could be positive and lower in cold countries [23,44].

Nevertheless, crops present highly different sensitivity to climate variations and responses; e.g., a positive effect would be expected in terms of higher concentrations of CO_2 in relation to crop yields. For example, an increase of 200 ppm could favor yields in rice production [22,46]. However, plant production is related to multi-factors; therefore, extreme temperatures are an important limiting factor that has a general negative influence on the yield of crops. Moreover, the effect of CO_2 could produce more positive effects on C3 plants (e.g., wheat, rice, cotton, soy, and potato) than on C4 plants (e.g., corn, sorghum, sugar, and others) at first due to their physiological differences, but over the long term, this effect could change [22,47,48]. In any case, if the increase in CO_2 can be a good factor in improving the yield of certain crops, its high concentrations could reduce important nutrients in the food products, such as proteins in wheat [49].

Another important impact of climate change could be linked to higher ozone concentrations, which have direct negative effects on primary production in the agricultural system by reducing photosynthesis processes and altering reproductive functions [50,51].

The direct effects of agricultural production related to climate change can be linked to indirect effects caused by abiotic and biotic stresses that can alter natural capital and the human actions taken to try to keep the crop yield in time.

Impaired agricultural production due to unfavorable climate conditions could make foods and staple crops inaccessible to vulnerable populations, leading to a high risk of food insecurity and increasing malnutrition risk in many countries. In fact, while the quantity and quality of food could decrease, staple crops could be subjected to augmented costs, thus reducing the affordability of a safe and nutritious diet for all, and particularly for low-income populations [52].

Table 1. Climate change impacts on agricultural system productions.

ID	Impacts	Explanation	References
1	Decrease in crop production	Extreme temperatures change the rate of plant growth, decrease the photosynthetic process, and greatly affect plants' reproductive ability.	[21–23,53–62]
2	Increased weed prosperity that can reduce the growth of agricultural plants	Weeds compete with agricultural crops for water and nutrients. Climate change modifies the dynamics of competition between agricultural crops and weeds. High temperatures and water scarcity influence the effectiveness of herbicides because they modify their mode of action, favoring the growth of weeds. Wheat weeds, which are vital to global food security, could benefit from climate change.	[21,35,63]

Table 1. *Cont.*

ID	Impacts	Explanation	References
3	Increased pest propagation	Climate change will increase pest infestations in many crops because warmer, wetter conditions favor pest reproduction. A one-degree increase in temperature could increase losses from insect infestations by 10 to 25%. Furthermore, high temperatures can influence their behavior beyond the proliferation of parasites.	[21,58–60,64–71]
4	Water availability	It reduces the amount of water available for plant growth. The combined effect of water stress caused by heat waves and a drastic reduction in rainfall can accentuate the lack of water in plants, resulting in a reduction in productivity.	[21,72,73]
5	Soil alteration	Loss of soil fertility is connected to a greater erosion process created by a greater frequency and intensity of floods and a lower capacity of the soil to fix nitrogen and decompose organic matter. Mainly, the erosion of runoff waters determines the removal of the surface part of the soil, which is the richest in organic matter. Climate change will negatively affect the content of organic carbon in soils.	[21,35,74]
6	Increase in soil salinity	This effect can be facilitated by poor groundwater recharge. Indeed, the combined effect of overexploitation of groundwater and reduction in rainfall can produce a mixing between freshwater and saline intrusion water. Therefore, this phenomenon can lead to an enrichment of the salinity of the soils connected to the use of well water with a high saline concentration.	[21,35,74]
7	Negative impact on production costs	Farmers, to reduce the effects of climate change on agricultural productivity, use greater inputs of natural resources (for example, irrigation, fertilization, and weeding).	[21,35,52,74]
8	Change in crop types	Farmers are pushing for a change in the use of agricultural crops and types of livestock that are more profitable and adapted to grow in difficult climatic conditions.	[21,35,74]
9	Reduction in the pollination process	Negative impact on agricultural productivity linked to the pollination process, which could reduce its effectiveness as a result of high temperatures. The population of pollinators could be reduced by an increase in pesticides to fight pests.	[71,75]
10	Intense fires	Fires in agricultural areas subject to intensive cultivation can reach such intensities as to completely damage the surface organic layer, with consequent impoverishment of the soils and intensification of erosion processes.	[76–78]
11	Product quality alteration	High temperatures or drought events can alter the production of secondary metabolites in plants, which are essential to defining the quality of the product. CO_2 concentrations can influence the quantity of nutrients in food products (vitamin B, protein, and micronutrients).	[49,79–81]
12	Increase crop productions	An increase in CO_2 concentrations is a factor favorable for crop production because it is the precursor of the photosynthetic activity of plants and primary production.	[35,44,46,82,83]
13	Increase in the cost of food	The reduction in crop yield can increase food costs in the global market, which has a negative effect on food accessibility for the global population.	[22,37,52,84,85]

3.2. The Impact of Climate Change on Provisioning Ecosystem Services and Food Security

Food security, as well as the agroecosystem, is strongly subjected to climate change [52,86,87]. Many agronomic plant species could have to adapt their growth to harsh environmental conditions (water crises and stress, erratic and often abundant rainfalls, drought, high temperatures, soil quality due to the changed nutrient composition) [87]. Drought escape and dehydration avoidance are strategies to cope with water stress generated by adverse climate conditions that exhibit more drastic morphological, physiological, and biochemical changes to survive. These adaptative strategies of single plants produce negative direct impacts on the quantity and quality of provisioning ecosystem services generated by agroecosystems in terms of food security, resulting in reduced crop production and less desirable edible products (Figure 3).

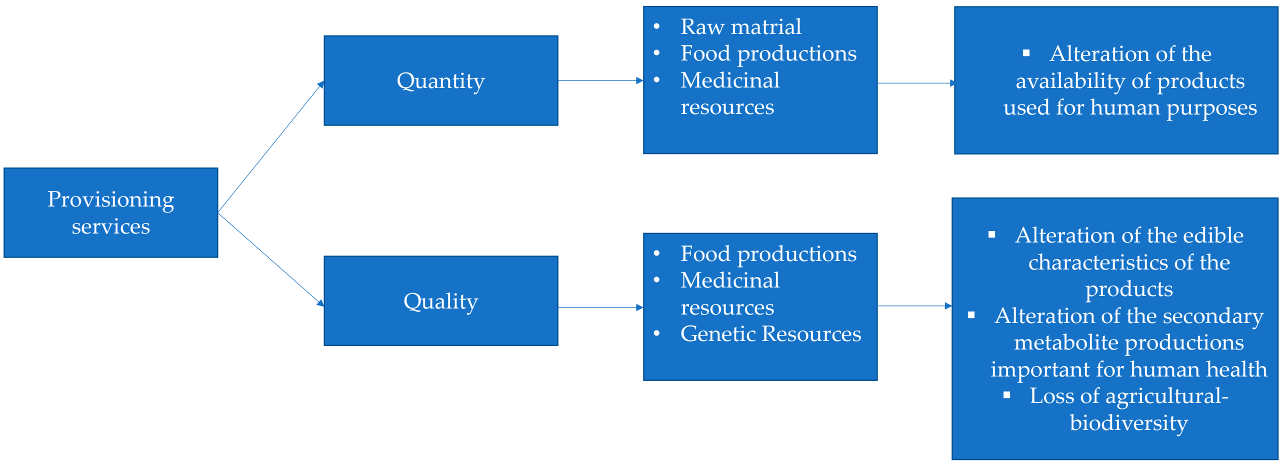

Figure 3. Impacts of climate change on ecosystem services connected to food security. We consider the ecosystem services classification by TEEB.

The following two sections report some vegetation adaptation strategies to climate change that reduce provisioning ecosystem services and food security.

3.2.1. Water Stress on Food Productions

Global warming and reduced rainfall, alternating with out-of-season floods, cause extreme environments that represent serious threats to biodiversity and agricultural crop yield [88]. Several herbaceous species are widely cultivated as important vegetable crops used for animal and human nutrition. The roots, leaves, stems, and flower buds of these vegetables are edible parts used as healthy foods because they are rich in fibers and bioactive compounds with human health benefits [89]. Water stress, caused by both drought and flooding, is one of the most harmful abiotic stressors that affects food production and has a subsequent impact on food security. Recently, the extent of drylands around the world has increased dramatically, leading to a total global loss of agricultural production of approximately USD 30 billion [90,91]. Flooding is the second-most important climate disaster after drought [92,93]. Due to the frequency and severity of droughts and floods, the global vegetation loss caused by these stresses is almost equivalent [94].

The response to adverse environmental conditions due to water stress is mainly visible in the morphology of the plants [95,96]. The leaf morphology frequently changes, appearing withered and curled as a result of drought and waterlogging. The lack of water and nutrients also affects chlorophyll synthesis, causing leaf yellowing and the inhibition of the photosynthetic process [94]. Furthermore, during drought stress, it has been observed that both meristematic cell division and expansion are inhibited, leading to a reduction in stem, leaf area, and thickness [94]. During waterlogging, the aerobic condition of the underwater roots determines the transfer of chemical signals to the whole plant organs that lead to the closure of the stomata. The latter phenomenon reduces the loss of the small amount of oxygen present in the plant [97,98] and also the capacity of CO_2 absorption. Thus, less availability of photosynthetic substrates causes a decrease in photosynthetic rate. To cope with the effect of waterlogging, some plants show morphological adaptations such as thin leaves or form special leaves facilitating and promoting CO_2 and in-organic nutrient absorption to improve gas exchange and maintain respiration under stress conditions [97–100]. Despite the different plant adaptation mechanisms, drought and flooding seem to maintain the same inhibitory effect on photosynthetic rate and transpiration capacity in leaves [94].

The roots undergo different morphological adaptations based on the type of water stress they must counteract. Different behaviors have been observed in roots under water stress. In drought conditions, a series of root adaptations have been observed to facilitate water flow or increase the water-absorbing capacity of the roots. To improve water flow, plants reduce the stele area and xylem vessel diameter and/or increase the number of vessels in the stem, while an increase in root length, functional root number, root hair, and density occurs, leading to a higher capacity to explore and find water in dried soil [101–105]. During flooding, the aerenchyma formation in the adventitious roots is the most characteristic feature that can improve the oxygen content under underwater conditions [106]. This modification is often associated with the appearance of a barrier to radial oxygen loss (ROL) in adventitious roots. ROL barriers are usually present in the roots of waterlogging-tolerant plants, as in the case of a waterlogging-tolerant maize species [107], where a reduction in the oxygen leakage during its transport from shoot to root tip is reported as impeding soil phytotoxin entry simultaneously [108,109]. Furthermore, an increase in primary and secondary cell-wall modifications, such as the suberization of rhizoderm and endoderm cells and the lignification of vascular bundle cortical cells, was observed in rice (*Oryza sativa* L.) grown in stagnant, deoxygenated conditions [108]. The increase in lignin deposition and suberization could represent a further useful barrier to prevent ion penetration in stagnant conditions and oxygen leakage. The aerenchyma formation could enhance the storage space in the cell during adverse conditions; a greater aerenchyma can maintain higher amounts of gas exchange during a flood, and therefore the plants continue to grow [98,99].

Obviously, plant responses to water stress and their capacity to survive in adverse environments are strongly related to the intensity and duration of water stress events [110–112] and to their co-presence with other stresses [113].

Several studies have been conducted on the water stress responses of important crops. Wheat, being a dryland crop, is sensitive to flooding stress [114], and when exposed to waterlogging stress, it significantly experiences a decrease in the dry mass of both the shoot and root and a reduction in the root/shoot ratio, indicating that root growth is inhibited more seriously than shoot growth [115,116]. Wheat would appear to tolerate water deficit stress better than flooding. A study conducted using the moment-based maximum entropy (MBME) model on the effect of drought on *Triticum aestivum* from 1985 to 2011 in Kansas revealed a reduction of approximately 22% of crop yield [117]. Maize was also intolerant of waterlogging stress, and the trefoil stage was the most sensitive period for it [118,119]. Water stress has a different impact on crops mainly based on the stage of plant development; such stress is especially critical during reproductive development, and seed germination is drastically affected by water availability [120,121]. Furthermore, drought experienced during flowering has been reported to lead to infertility in wheat [122].

Waterlogging inhibited maize growth, resulting in reduced plant height, ear height, dry weight, leaf area index, and grain characteristics (such as grain number per ear and 1000-grain weight) [123].

In 2003, interesting research conducted in Central Africa (Nigeria), where rainfall is unpredictable in quantity and distribution, analyzed the ability to tolerate drought in six different genotypes of maize. Water deficits significantly reduced the grain yield of landrace maize ecotypes, up to 90% in the Borno-AccNo10 native genotype. The hybrid genotypes analyzed in this study tolerated the absence of water better, with a reduction in grain yield ranging between 57 and 59% [124].

The growth and grain yield of soybeans are also affected by flooding [103]. At the seedling stage, the root growth of soybeans is severely suppressed after submergence lasts for 10 days [104]. Yield reduction in soybean crops under drought conditions is around 58.5% [125], frequently accompanied by a stem length decrease [126].

Rice, unlike other cereals, is highly tolerant of water stress, either from submergence (in which part or all of the plant is under water) or waterlogging (in which excess water in the soil limits gas diffusion) [127]. On the other hand, rice is highly susceptible to water deficits, and it has been reported that this stress can cause a decrease in crop yield of approximately 72.5% [128,129]. During the reproductive stage, drought leads to a significant reduction in grain yield [130,131]. The magnitude of yield loss depends on the growth stage and the duration and severity of drought stress [132,133]. In one trial, severe drought stress applied at the vegetative stage and moderate drought stress applied at the flowering stage in rice resulted in 20% and 28% yield losses, respectively [134].

Even if plants survive water stress, all the morphological and anatomical changes that plants undergo to cope with water stress could lead to the loss of aesthetically perfect or eye-catching products, which are increasingly preferred by demanding consumers today. The actions put in place by agriculture to counteract these stress-induced events, such as maximum irrigation or the construction of extended greenhouses, have a significant negative impact from an economic and environmental point of view.

For these reasons, the identification of new ecological strategies to minimize the negative effects of climate change on food availability and biodiversity appears to be extremely urgent.

3.2.2. Global Change Impact on Food Quality

Some studies have reported that elevated CO_2 results in more rapid growth rates but reduced plant protein content and micronutrients such as calcium, iron, and zinc [135].

A decrease in macro- and micronutrients and an increase in polyphenols and total antioxidant capacity were observed in lettuce and spinach following elevated CO_2, indicating the complex response of plants to yield and nutritional quality [136]. In fact, high levels of variability can be observed across plant species, their cultivars or varieties, and their responses to environmental conditions. In general, temperature variations, rainfalls, and solar radiation have been shown to have an impact on secondary metabolites such as polyphenols, terpenoids, and alkaloids in various fruit and vegetable crops, with direct consequences on their nutritional or organoleptic qualities [137]. For instance, variations in antioxidant activity and total polyphenol and flavonoid content were observed in different sweet chestnut cultivars in association with climatic and environmental factors and regions of growth [138]. In this case, increased levels of antioxidant activity and bioactive compounds were reported following lower environmental temperature exposure, higher precipitation, altitude, and a longer duration of sunlight Martinez et al., 2022 [138]. On the other hand, elevated temperatures may also affect flavors due to the changes in sugar in apples [139,140], sugar and acid content in grapes [141,142], and firmness and aroma volatile components in avocado fruits [143]. High temperatures have also been shown to increase antioxidant capacity and flavonoid content in strawberries [144], but reduce vitamin content in other fruits, such as kiwifruits [145].

Recent studies have reported that some plant species may incur larger impacts on both yield performance and product quality due to altered flowering and fruit development under a warmer future climate [146]. For example, in different tomato landraces (from Italy, URSS, Honduras, and Guatemala), plant responses in terms of yield, firmness, antioxidant activity, carotenoid content, ascorbate, and polyphenols have been observed following high temperature exposure in an open field during the critical stages of flowering and fruit setting. Unlike most of them, some of these tomato landraces presented both good fruit size and setting and increased levels of phytonutrients. Such data indicate that the combination of tolerance to high temperatures with medium–high yield performances and fruit nutritional quality can be considered in the selection and breeding programs of local tomato landraces [79].

Thus, extreme climate conditions are expected to alter the quality and nutritional value of foods since the composition of plant health-promoting phytonutrients can dramatically change [147]. However, there is a lack of evidence regarding the impact of climate change on human nutrition and health indicators. Therefore, additional studies are needed to understand climate change's impact on plant secondary metabolites potentially beneficial for human health and the composition of protein, amino acids, essential fatty acids, and micronutrients such as vitamin B12, zinc, iron, etc. [87].

3.3. Adaptation Strategies to Integrate Resilience Food Security into Climate Change

Food security resilience to climate change is influenced by the human capacity to develop agroecosystem adaptation to reduce the extreme event impacts on provisioning ecosystem services. The main strategies for adaptation to climate change in the agroecosystem have been described in Table 2. The table connects the adaptation or mitigation strategies to the impact of climate change on agroecosystems to address the audience's choice of solution in consideration of the problem.

The effects of climate change on food security require a new approach to agricultural crop management, increasing adaptation strategies capable of reducing the negative effects generated by perturbative events such as extreme temperatures [148–151]. Thus, the use of well-adapted and high-yielding varieties with resistance to water stress is important to reach maximum yield potential for as long as possible while minimizing the risk of climate change. However, more attention is needed to not encourage exclusively the use of intensive crops naturally tolerant to water stress and to not worsen fragmentation, habitat loss, and biodiversity. One of the key strategies to avoid such consequences due to climate change could be represented by biodiversity conservation and improvement, broadening food production to include locally adaptable, often underutilized, nutrient-rich species, and ensuring diversified, healthy diets [152,153].

Nonetheless, this solution could not be sufficient in consideration of the rate of climate change and population growth, so the important strategies should include the development of innovation-based solutions to reduce both the natural resource needs for crop production and the effect of extreme events on morphology adaptation and physiological and biochemical vegetation processes. Innovation-based solutions could be highlighted as technologies combined or applied to the agroecosystem to produce a new system able to ensure and improve ecosystem service flow.

Genetic diversity is a critical factor for crop variety improvement and selection by breeding and contributing to the genetic resources to pass down to future generations and to counteract the genetic erosion of many local species or landraces [154]. Principally, the identification of stress-related genes provides a strong tool for improving water stress tolerance. Indeed, a large number of stress-response genes are activated through complex signal transduction networks, promoting the synthesis of many functional proteins related to the capability to resist water stress in the tolerance mechanisms [120,155–159]. Several genes have been identified to increase drought tolerance in plants: high basal levels of the *CiLEA4* and *CiXTH29* genes in chicory seem to enhance drought tolerance [120]; a transcription factor involved in the pathway of *LEA* and dehydrin gene expression, TaNAC69, has the same effect in wheat [159]; and the heat shock protein HSP70-1 activates the drought stress tolerance mechanisms in tobacco [160]. Nevertheless, more details on plants' water status [161], abiotic stress biology [162], stress targets for modern genetic manipulation [163], new breeding crops for drought-affected environments, and climate resilience [164] can be found in the mentioned bibliography.

In this context, biofortification, which aims to improve the content of micro- and macronutrients and bioactive compounds beneficial for human health, can be an alternative strategy to implement in order to close the gap between climate change, food quality and production, and eventually food security. Smart solutions, by increasing knowledge and biofortification through either conventional or new emerging breeding technologies (NBTs, e.g., genome-editing technologies), could be useful. NBTs can further help to deal with climate change challenges, for example, by providing novel genetic solutions for stress tolerance.

The climate change strategies for food security include the application of multifunctional projects that can combine agricultural production with energy production in order to create a winning mutualism between the two international strategies to reduce gas emissions and maintain food security. In particular, numerous studies have highlighted that agrivoltaic systems can be effective in reducing the water stress of plants by increasing productivity (Table 1). For example, some food productions can take more advantage of the combination of agricultural activities under photovoltaic panels than others. Generally, shadow-tolerant crops seem to benefit more from the agrivoltaic system. Such is the case of lettuce, which showed morphological adaptations without yield reduction [165]. Nonetheless, shadow is not the only important factor for the choice of vegetation. Amaducci et al. [166] showed that in the case of water stress and extreme events, some crops such as maize can benefit from the agrivoltaic system compared to cultivation in full light. Indeed, the agrivoltaic system helps the vegetation overcome the trouble caused by evapotranspiration and soil water balance, giving it more favorable conditions for growing than in open fields [166]. Barron-Gafford et al. [167] found that tomato and chiltepin pepper have more capacity to uptake CO_2 in agrivoltaic systems with more food production, whereas the water use efficiency was higher for jalapeno pepper and tomato in the agrivoltaic systems. For this reason, in this review, we promote the use of agrivoltaic systems as a possible ecological weapon to fight and contrast the harmful effects of climate change.

Another important technology that is spreading in agriculture production is the use of Climate-Smart Agriculture with IT applications based on remote sensing technologies and applications and field sensors to monitor vegetation parameters such as primary production and water stress to set in real-time natural resource input when vegetation needs them. Climate-Smart Agriculture, together with water-saving irrigation techniques, can reduce natural resource application and agricultural costs, improving food production at a low cost. On the other hand, the need to save water in agriculture has contributed to the awareness of the importance of water reuse. In particular, great importance has been attached to the concept of reuse in the agri-food cycle. For example, the large quantities of wastewater produced by food processing industries could be an important source of water if refined with tertiary treatment, converting a 'waste' into a 'resource' and contributing to the conservation of water resources in the environment [168].

Innovation-based solutions can be generated by integrating different technologies and approaches, such as NBTs and agrivoltaic and smart agricultural systems, to offer a way to create sustainable and resilient food systems and ensure healthy diets that are aligned with contextual ecosystem functions [52,169].

Table 2. The main strategies to address climate change impacts reported in the literature are highlighted in the table. The "ID" numbers refer to the impacts reported in Table 1.

ID Impacts from Table 1	Adaptation Strategies	Explanation	References
1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11	Crop diversification	Crop diversification can maintain soil fertility, reduce pests and insects, and minimize the negative consequences of extreme weather conditions on the yield of a whole farm operation. Crop diversification can improve the stability of agricultural production and reduce the risk of farm profitability loss caused by product loss in monoculture. Crop diversification has been adopted as an important strategy in many developing countries to meet the challenge of climate change.	[21,22,170–178]
1, 4, 5, 7, 11	Investment in suitable business equipment	Equipment is important to improve work efficiency, develop new cultivation methods, and promote the diversification of crops.	[22,35,62,177]

Table 2. *Cont.*

ID Impacts from Table 1	Adaptation Strategies	Explanation	References
1, 2, 3, 4, 5, 6, 7, 9, 10, 11	Change in management practices and cropping practices	Changes in farm management techniques, including changing fertilizer, pesticide, irrigation, and seed quality. Some examples are changing crop types and varieties, changing sowing and harvesting dates, crop rotation, and intercropping.	[21,22,35,178–181]
2, 3, 4, 6, 11	Water-saving irrigation techniques and water reuse	The use of drip irrigation is recommended for both groundwater depletion and global warming. Sprinklers and drip irrigation can help minimize climate change and improve the economy in the long run.	[21,22,35,168,180, 182]
1, 2, 3, 4, 6, 7, 11	Use of crops adapted to grow in the reference agricultural context	Reproductive plants are used in the reference agricultural context because they allow the development of new plant species in response to the present environmental conditions.	[35,68,178,183,184]
1, 2, 3, 4, 5, 7, 10, 11	Application of Climate-Smart Agriculture	Smart agriculture for climate change includes the application of technologies to support agricultural practices that use less water, pesticides, and fertilizers in relation to the physiological conditions of the plant. The soil structure is preserved, and water and nutrients are managed sustainably. These strategies are simple to implement and have great potential to assist farmers in increasing production and reducing costs.	[35,42,180,181,185]
1, 2, 3, 4, 5, 6, 7, 10, 11	Agrivoltaic application	The microclimate generated by the photovoltaic panels can reduce plants' water stress. Agrivoltaic systems seem effective in improving the productivity of some cereal crops and horticultural productions.	[24,166,167,186–194]
1, 2, 3, 7, 8, 9, 10, 11	Biodiversity development	Increasing both agricultural and natural biodiversity is important to support ecological processes that sustain local well-being. In particular, agricultural biodiversity is important to increase the specific resilience of agricultural activities in order to compensate for any losses in particular years of drought and heat waves. Biodiversity linked to natural vegetation is essential to increasing ecological processes supporting agriculture, such as anemophilous pollination.	[62,185,195]
1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11	Promotion of field research and dissemination of results	The effect of climate change on agricultural productivity in different cultures is a phenomenon to be explored, as currently there are mainly long-term projections. It is currently difficult to have a complete picture of the consequences of climate change on food production and, consequently, of the effectiveness of the different adaptation strategies to reduce negative impacts. Therefore, experimentation both in the laboratory and in the field becomes fundamental in order to test different solutions on different cultures and produce knowledge on the subject. In this regard, scientific dissemination is an important point for sharing results and identifying best practices.	[21,34,35]
1, 4, 7, 12	Use of adequate seed	The use of seed varieties more resistant to drought and high temperatures is recommended.	[22,178]

Table 2. *Cont.*

ID Impacts from Table 1	Adaptation Strategies	Explanation	References
7, 11, 13	New emerging breeding technologies	Biofortification strategies and new breeding technologies (NBTs) can be alternative ways to conventional breeding to improve genetic traits, make them more tolerant to climate change, and guarantee the nutritional quality of foods.	[52,169]
1,2,3,4,5,6,7,8,9,10,11	Agroforestry	Agroforestry is a good strategy to reduce the impact of greenhouse gas emissions on climate change and their effects on the agroecosystem. Agroforestry systems are also good strategies to improve agricultural production by maintaining soil, air, and water quality and providing different sources of income.	[29,196–199]

In the end, agroforestry can be a good strategy for climate change adaptation. Indeed, if agroforestry could be negatively influenced by climate change by reducing the tree's growth and production, at the local scale, it could produce microclimate buffering on small productions. Moreover, on a global scale, agroforestry could have a strong role in reducing the impact of greenhouse gas emissions on climate change through carbon storage [196–199].

4. Conclusions

Due to its vast size and its sensitivity to meteorological variables, the agroecosystem is the most vulnerable sector to climate change, with significant social and economic consequences for human life [35].

This review aimed to give an insight into the impact of climate change on agroecosystems from a global to a gene scale to better highlight the negative impacts in terms of the provisioning of ecosystem services for food security. This has been a useful exercise involving different disciplines that helped to find the main adaptation strategies, giving a more complete approach to the problem. Hence, there is no one best strategy but a synergy of strategies to be applied to preserve the integrity and health of agroecosystems, such as biodiversity conservation and crop management. However, it is also important to strengthen the morphological, physiological, and biochemical processes on single plants that support provisioning ecosystem services that sustain food security and human well-being. There is a need to develop new innovative base solutions to adapt natural capital to climate change, including new technologies in agroecosystems such as Climate-Smart Agriculture and new emerging breeding technologies. Indeed, these strategies also need a cultural, social, and institutional approach to adapt human-derived capital to improve innovation-based solutions able to sustain natural capital flow and food security. This leads to the involvement of all stakeholders, where knowledge dissemination has a crucial role in informing and forming a new generation of decision-makers, manufacturers, and consumers.

Many studies have only focused on climate change's effects on food risk or potential strategies to counteract them. This review has tried to directly connect these two aspects, providing information on how the strategies are connected with specific climate change impacts on food risk (ID impacts from Table 1 column, reported in Table 2). Moreover, this review has applied a scaling approach to specify how the impact of climate change on food production is related to the adaptative strategies of crop plants to climate change, such as water stress and plant responses. This aspect could be useful in developing specific adaptative strategies for crop production to mitigate food risk. The future evolution of this work is to study the effects of strategies such as agrivoltaic and smart agriculture on crop vegetation responses to water stress and extreme temperatures that have not been fully explored yet.

Nevertheless, there are some gaps in this review; e.g., we describe the effects of climate change on food security in terms of the vegetation that characterizes the agroecosystem without developing consideration about the impact on animal husbandry. Therefore, in the future, new work could be developed to describe climate change in all food chains.

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