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What are the impacts of climate change and biodiversity on food security? A systematic literature review

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Abstract

Food security (FS) remains a pressing issue at the global scale. Current literature about FS points to a plethora of causes of food insecurity, among which climate change and the loss of biodiversity are critical to all facets of food security. Building on this notion, we advocate for a comprehensive understanding of drivers of food security, thus contributing by examining climate change and biodiversity as drivers of food security. The interest in this subject stems not only from the scientific community, but also from practitioners and policymakers. However, holistic encapsulation of the relevant literature addressing this subject is currently lacking. This review systematically analyses and categorises the drivers of FS induced by climate change and biodiversity. Following the Systematic Literature Review approach, 342 peer-reviewed studies were selected and synthesised. Our findings identified 11 categories of climate change drivers and 9 categories of biodiversity drivers of FS. These drivers were found to impact the habitats, phenology, physiology, behaviours, and resilience of crops and animals, which are key for food production and, subsequently, FS. The impacts of these drivers are discussed, linking them to the four pillars of FS, including availability, accessibility, utilisation, and stability. Findings from the literature strongly indicate adverse impacts from various climate change drivers, notably increased temperature, precipitation changes, and increased sea temperature. On the other hand, biodiversity drivers are found to be beneficial to food security when adopted to the current food system. The literature highlights diversity in plants and crops, diversity in soil biota, and agroforestry as some important drivers. Moreover, we found that the availability and accessibility pillars of FS are most mentioned in the reviewed studies, whereas the stability and utilisation pillars can be further investigated.

Keywords Food security pillars, Impact, Driver, Ecosystem

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Introduction

Food security (FS) is a pressing issue, especially when the Earth's population is rapidly increasing. From 1961 to 2000, the population of the Earth nearly doubled in number, and it is further anticipated that there will be 9.7 billion people in 2050, requiring approximately 70% more food than what is consumed today [1]. Recent estimations have shown that, in 2022, up to 783 million people were in a constant state of chronic hunger, and an alarming number of 2.4 billion people suffered from moderate or severe food insecurity [2]. Moreover, while FS issue might often be associated with developing nations' issues, food insecurity has been found to appear in all countries across the globe [3].

A plethora of factors contribute to and influence FS. Among them, climate change, biodiversity loss, and the benefits of a biodiverse environment are critical determinants of FS [1, 3, 4]. Climate change refers to shifts in temperatures and weather patterns, which have been accelerated by the overuse of and overreliance on fossil fuels (coal, oil, and natural gas) [5]. Climate change phenomena, such as increasing temperatures and precipitation variability, continue to be observed in modern times, with apparent consequences for FS, e.g., reduced food outputs, disrupted food distribution, and a decreased household budget for food purchases [6–8]. On the other hand, biodiversity is the underlying ingredient of today's food systems. Biodiversity refers to the variety of organisms, species, and populations, the genetics among them, and their complex assemblages of communities and ecosystems [9]. The impacts of biodiversity factors in this study can be understood as the effects of both biodiversity gain and biodiversity loss. The loss of biodiversity, for various reasons, such as monoculture practices, overemphasising a few domesticated breeds, and the expansion in size of areas under intensive agricultural activities, can be extremely harmful to the production capacity of the food system [10]. On the other hand, the presence of biodiversity greatly strengthens and stabilises ecosystem services and ecosystem functions and neutralises threats to food production from climate change, subsequently increasing the stability and security of the food supply [11, 12].

The climate change – biodiversity – FS nexus encompasses a complex network of interrelationships and effects among the three areas. From an FS viewpoint, climate change and biodiversity are acknowledged as two major trends of influence, as highlighted in various summits, reports, webinars, and scientific studies [13, 14]. In 1992, the Earth Summit in Rio de Janeiro introduced conventions on biodiversity and climate change, signalling a formal acknowledgement of their global importance. A landmark study published in 2005, the Millennium Ecosystem Assessment, connected ecosystem health directly to human well-being, of which FS is a major aspect [15]. The Sustainable Development Goals, developed and agreed upon by members of the United Nations (UN), explicitly link FS with climate change and biodiversity [16]. The call for further efforts, including scientific research, in expanding the understanding of climate change and biodiversity as drivers of FS is contemporary and has been raised in both recent studies about FS [2, 4] and governmental FS reports (e.g [17]).,.

Given the strong desire across different domains to expand the body of knowledge regarding the interaction between climate change, biodiversity, and FS, we anticipate that more research efforts will continue to be put into examining this subject. Therefore, our study aims to contribute to ongoing conversation by providing a systematic literature review on the subject of climate change and biodiversity as drivers of FS. In this context, a"driver" was defined by Nelson [18] as "any natural or human-induced factor that directly or indirectly causes a change in an ecosystem" (p.74). Thus, this review synthesises climate change and biodiversity factors that drive changes in FS. In this vein, while we use the term "climate change driver", it should be understood as a climate change factor that can affect various aspects of FS and should not be mistaken for the term "driver of climate change", which could accelerate changes in the climate, such as the use of fossil fuels. Therefore, we are interested in nonanthropogenic factors with effects on FS in the context of this study. We acknowledge that certain factors, such as land use and fossil fuel consumption, can lead to the exacerbation of climate change, which then leads to implications for FS. However, such interaction is beyond the scope of this study.

We aim to answer two research questions (RQs):

RQ1: What are the key climate change and biodiversity drivers of FS?

RQ2: What are the impacts of those drivers on FS?

Our motivation for conducting this study is twofold. First, this work contributes to a holistic encapsulation of the impacts of climate change and biodiversity on FS. There exist reviews of the literature regarding the nexus of climate change – biodiversity – food security. Table 1 presents a number of recent reviews on the topic. These studies are informative and serve as good references, nevertheless, we observed that current reviews either lack a systematic approach to synthesise the extant literature [6, 7, 13, 19, 20], or provide an overview of the relevant studies without synthesis and discussion of impacts of climate change and biodiversity on FS [21], or focus only specific facets of the food systems [20, 22]. We aim not only to systematically synthesise the outstanding drivers of climate change and the biodiversity of FS but also to provide in-depth discussions on the specific impacts those drivers on the four pillars of FS (availability, accessibility,

Table 1 A number of reviews on the subject of climate change – biodiversity – food security

Authors	Topics being studied
Mbow et al. [6]	This study analyses in-depth the impacts of climate change on various facets of FS.
Muluneh [7]	This study focuses on how climate change can affect FS and how climate change can alter the current state of global biodiversity.
Renard and Tilman [12]	This study discusses a plethora of approaches, by which biodiversity can be cultivated and utilised to improve the food system, providing FS and sustainability.
Behnassi [13]	This book opens with an in-depth discussion about the nexus of climate change – biodiversity – food security, then follows with multiple cases demonstrating the interaction between each area and the others.
Ortiz et al. [19]	This study investigates the bi-directional relationship between agriculture and biodiversity. The study also addressed how agriculture and biodiversity can contribute to climate change.
El-Beltagy and Madkour [20]	This study reviews the impacts of climate change on agriculture in arid lands across the globe, with implications for FS.
Sweihleh [21]	This study provides an overview of research activity on FS in the context of climate change. The bibliometric analysis of the study revealed four main themes of crop yield, water security/scarcity/supply and precipitation, household dimension of FS, and food availability.
Kishaija et al. [22]	This study analyses the recent studies on the topic of climate change, livelihoods, and adaptation/mitigation measures under smallholder coffee farming.

utilisation, and stability), thus adding comprehensive insights to the current conversation in the literature. Second, our study contributes to the ongoing call for further discussion regarding the impact of critical global trends (including climate change, the benefits of biodiversity, and the loss of biodiversity) on the status of FS, as put forth by both scholars (e.g [4])., and policymakers [17].

Methodology

Study design

Systematic Literature Review (SLR) is the adopted methodology for examining the relevant literature and answering the research question. SLR is the method of choice for the review because such a method of reviewing literature can provide a scientific, robust, and replicable process for identifying pertinent literature, synthesizing key insights, and minimizing bias [23]. Following Tranfield et al. [23] guidelines for conducting an SLR, a procedure for reviewing relevant literature is developed (Fig. 1), where the research procedure has three main phases: planning, analysing, and reporting.

Phase 1 determines the scope of the review, which is based on the research question. Consequently, the literature areas of interest are climate change, biodiversity, and FS (see Fig. 2). Phase 2 – Analysing focuses on selecting key studies for the review and synthesising key insights from those studies to answer the research question. The details of Phase 2 are articulated further in the following subsections. Phase 3 – Reporting is presented in the "Descriptive analysis" and "FS drivers: thematic analysis of the literature" sections.

Data source and search strategy

An adequate search string is imperative to ensure that the review consists of the most relevant studies. At the beginning of this study, two authors conducted a group discussion with 15 fellow academics with relevant research backgrounds and expertise. During this discussion, the objective of the review was presented, and the group nominated suitable keywords relevant to the three key areas of food security, climate change, and biodiversity. Afterwards, the group discussed and evaluated the lists of possible keywords to carefully select the final

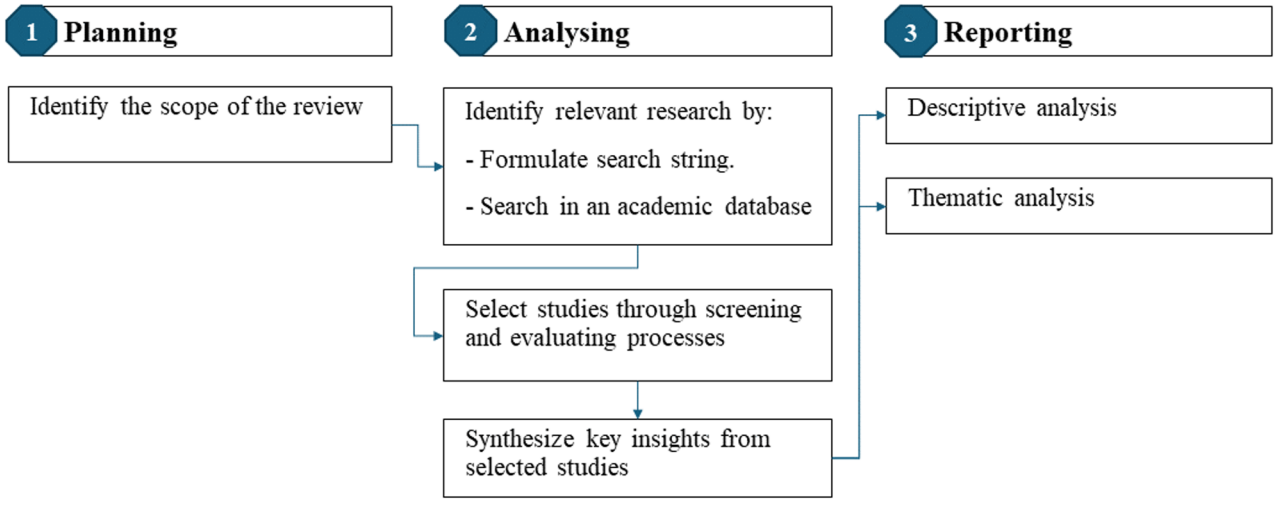


Fig. 1 The SLR procedure

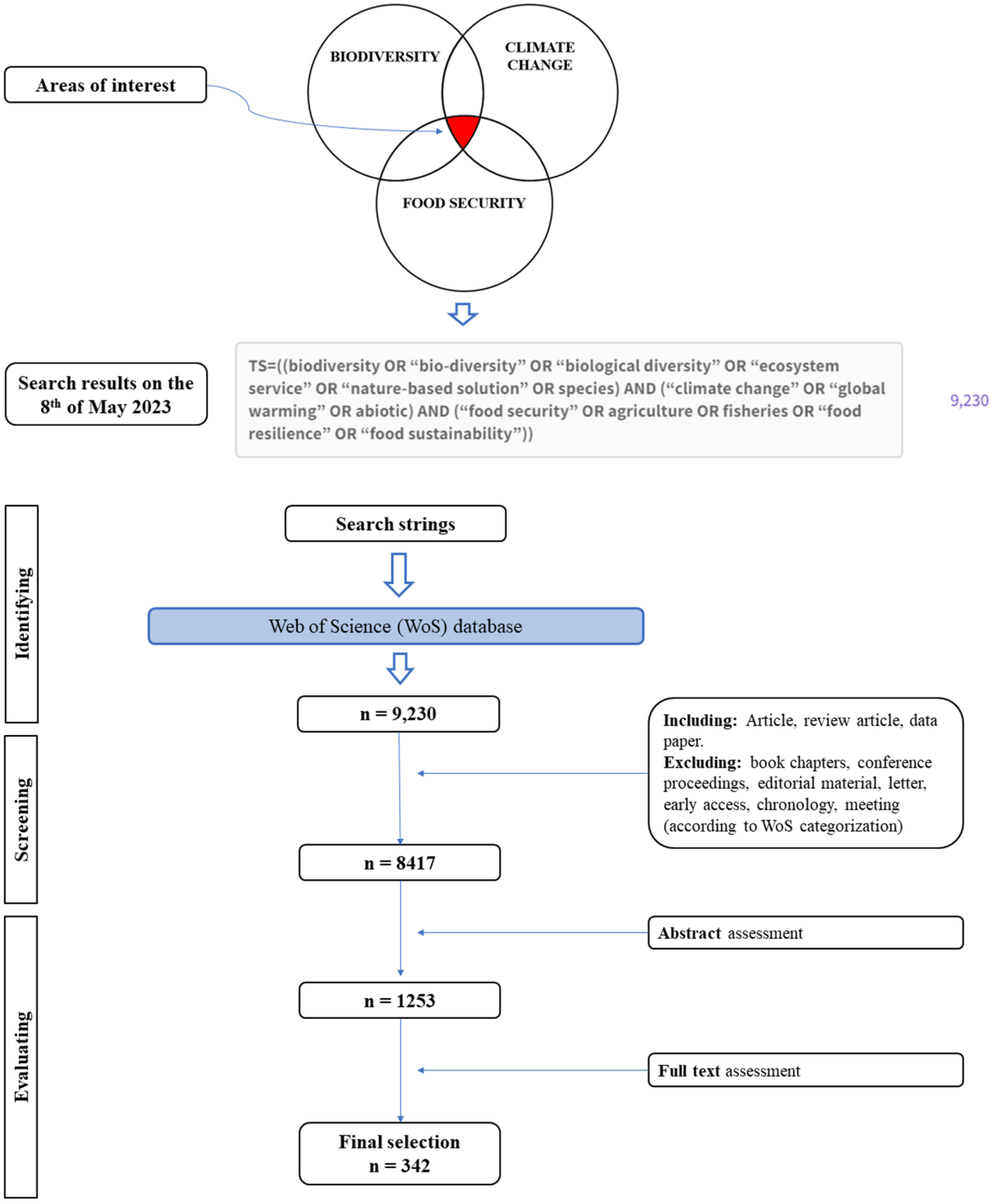


Fig. 2 Process of searching, evaluating, and selecting papers for the review, following PRISMA approach [25]

ones, aiming for a search string that is both comprehensive and concise. The final search string is as follows:

(biodiversity OR "bio-diversity" OR "biological diversity" OR "ecosystem service" OR "nature-based solution" OR species) AND ("climate change" OR "global warming" OR abiotic) AND ("Food Security" OR agriculture OR fisheries OR "food resilience" OR "food sustainability").

This SLR considers a search horizon from 1970-April 2023, aiming to capture the rich body of literature regarding climate change and biodiversity. The Web of Science database was used to locate relevant studies for this review and was chosen because it is among the most reputable sources for academic literature and is frequently used for SLRs [24].

Eligibility check

This study follows the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) approach [25]. Figure 2 depicts the PRISMA flow diagram for the selection of papers to be included in this review.

The initial search revealed 9,230 studies addressing the topic of climate change – biodiversity – FS. Exclusion and inclusion criteria were introduced in the screening round, retaining only written-in-English peer-reviewed papers that went through a rigorous process of review before publication for reliable insights and findings. A total of 8,417 papers remained after this round.

Next, two rounds of evaluation were conducted by two research team members. The first round assessed the relevance of a paper on the basis of its abstract, and a paper would pass this round if the abstract:

1. Indicates that the study addresses the relationships between climate change – FS and/or biodiversity – FS.
2. Demonstrates relevancy by a strong focus on FS.
3. Highlights that the findings of the study are related to FS.

After the first evaluation round, 1,253 papers remained. The second round evaluated the full texts of the papers. The full-text screening criteria included the following:

1. The scope of a study must be highly relevant. This is indicated by whether the objective of the study is to explore the impacts of climate change on FS, biodiversity impacts on FS, or both.
2. Our review aims to synthesise findings/perspectives/claims that are strongly grounded in empirical data analysis. Hence, empirical research is prioritised, followed by review studies.
3. The findings of selected studies must address at least one of the aspects of FS.

A specific procedure was followed to ensure consistency between the two authors who evaluated the studies. For the abstracts screening round, the two authors first agreed on the set of evaluation criteria. Then, each author assessed the first 100 abstracts separately, and compared the results to improve the criteria and to make sure the criteria were understood and applied consistently across. When consensus was reached, the authors proceeded with the remaining materials. This process was extended to the full-text screening round.

Finally, 342 studies were selected for the literature review.

Results

The following sections discuss the main results of the review. First, a descriptive analysis of the selected study is presented, which provides the key statistics including publication by year, top 20 journals where the majority of the studies were published, and the dominant methodologies used by the selected studies. Second, a thematic analysis is provided to identify climate change and biodiversity-induced drivers of FS, and their impacts on the four key aspects of food security.

Descriptive analysis

This section provides the key descriptive statistics of 342 papers selected for this review.

The topic of climate change – biodiversity – FS continues to attract interest from the scientific community, with the number of papers steadily rising over time (Fig. 3). The literature search covered only the first 4 months of 2023; therefore, the number of selected studies published in 2023 is significantly lower than that in previous years. The years with no selected papers are not included in the figure. Our selected studies indicate that the topic of climate change – biodiversity – food security became more pertinent from the early 2000 s onwards.

Figure 4 lists the top 20 journals where the selected papers are published, representing the areas of environmental science, climate change, biology, food security and ecology. This arguably indicates that the selection of studies for this review come from journals with interests in climate change, biodiversity, and food security.

There is a wide variety of research methods employed by the 342 selected papers, contributing rich findings from numerous perspectives. Figure 5 presents the most common research methodologies used in the selected papers. The five most dominant methods are modelling, which accounts for 51.95% of the studies, followed by experiments (16.01%), data analysis, typically a statistical approach using panel data (14.05%), case studies (6.86%), and reviews (3.92%). Furthermore, as modelling is the most prominent methodology, we further classified

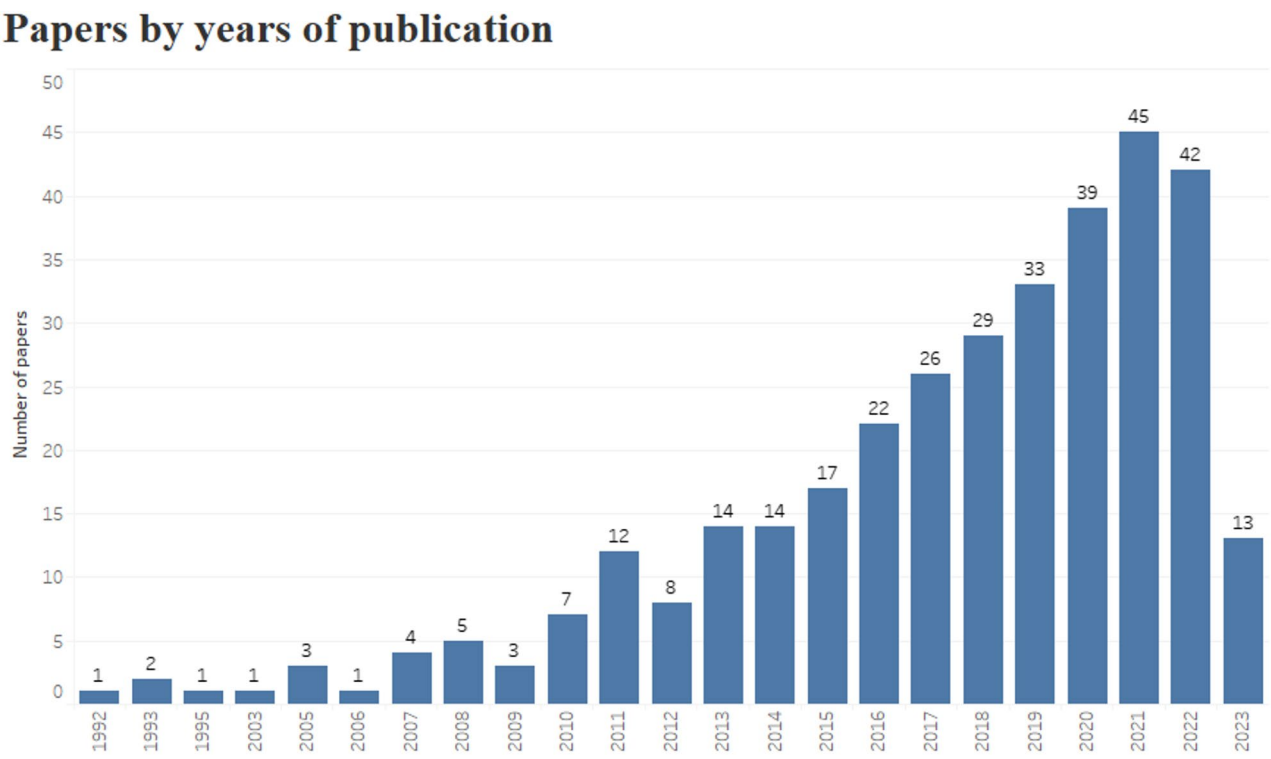


Fig. 3 Distribution of the selected papers over the year

specific approaches in modelling used by more than half of the selected studies. As shown by Fig. 5 part B, the majority of modelling papers aimed for Species Distribution Modelling (SDM) or Ecological Niche Modelling. The dominant modelling approaches include MaxEnt, Generalised additive model (GAM), and using ensemble models – using a variety of models including MaxEnt, GAM, and other approaches. CLIMEX is another approach to model species distribution. Finally, Dynamic Bioclimate Envelope Model (DBEM) is another notable modelling approach.

Thematic analysis of the literature

The following two subsections discuss the main findings of the thematic analysis. The aim of the thematic analysis is two-fold. First, it defines the key drivers of food security as highlighted by the selected papers. Second, it provides an in-depth discussion of the impacts of the drivers on FS. To understand such impacts, a baseline understanding of FS must be established. The most widely used definition of FS is that of the World Food Summit: "Food security exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life" [26, p1]. Furthermore, FS encompasses four key pillars of availability, access, utilisation, and stability [6]:

- Availability refers to the sufficiency and readiness of food from production and distribution activities.
- Access refers to people's ability to obtain food.
- Utilisation refers to the achievement of food potential through nutrition, cooking, and health.
- Stability means achieving the other three pillars in the long term without disruption.

NVivo software was used to manage the selected papers for the review, and to aid the thematic analysis. One author was tasked with analysing each paper to extract the key insights, such as topic, key findings, variables considered in the paper, and implications for food security. Concept codes, whereas a short term/phrase is used to capture the essence of a particular insight, were developed and grouped into larger and more abstract categories. All authors discussed and agreed on those categories, which were later turned into specific drivers and their impacts. Finally, drivers were grouped under two dimensions of climate change and biodiversity, whereas the impacts were grouped under the four dimensions representing the four pillars of food security.

In essence, climate change and biodiversity drivers can influence the habitat, behaviour, phenology, physiology, and resilience of exploited crops and animal species. In this context, exploited species refer to the flora and fauna that are farmed or harvested for human consumption. Habitat denotes the biophysical environment within

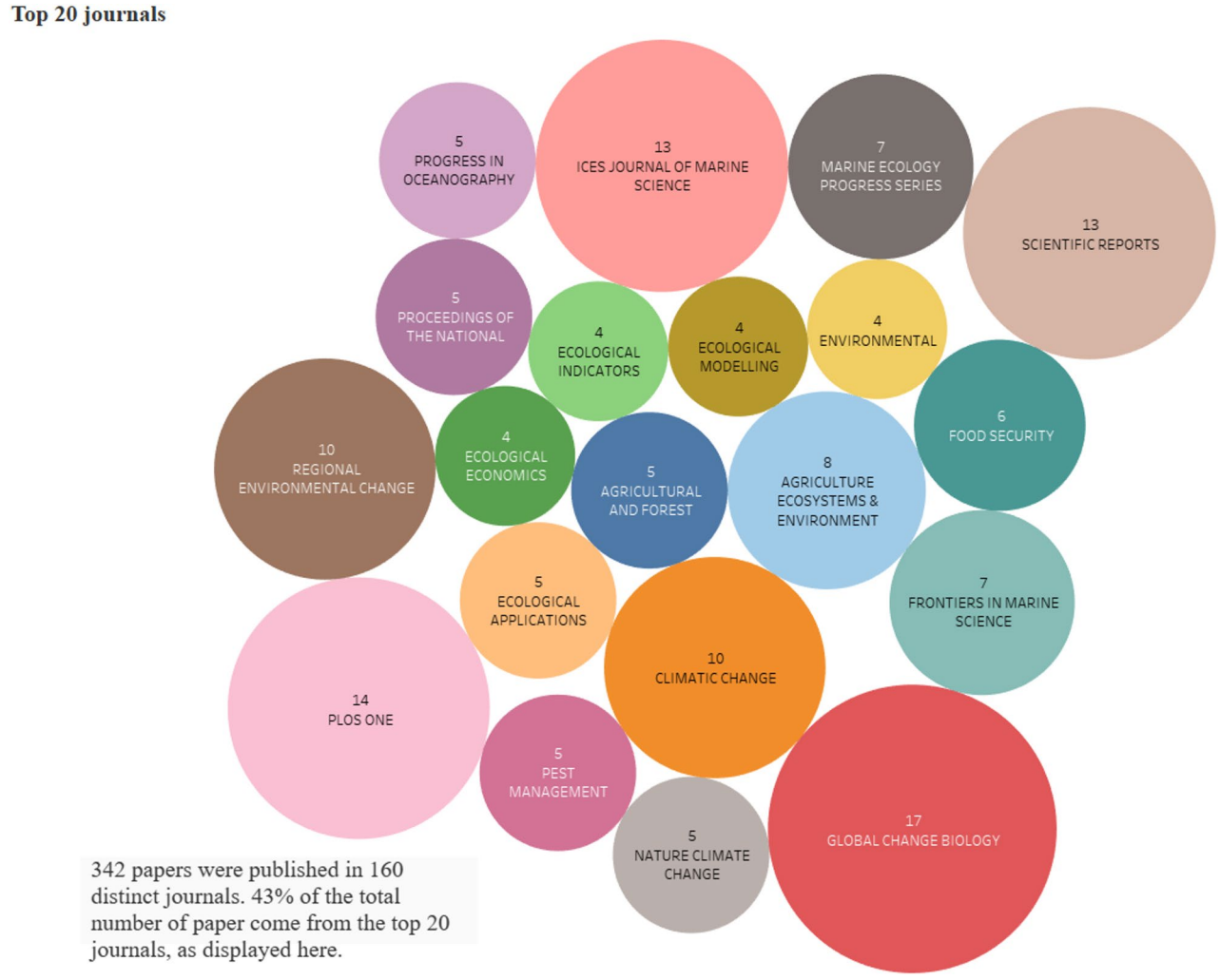


Fig. 4 Top 20 journals where 342 papers selected for this review were published. (the size of a bubble is proportional to the number of papers in the journal represented by the bubble, and the number is shown inside each bubble)

which these species exist, while behaviour describes how they respond to climatic fluctuations and shifts in surrounding biodiversity. Phenology refers to the timing of key life-history events, such as reproduction, spawning, and maturation. Physiology encompasses the biological functioning, growth, and overall health of these species, and resilience is conceptualised as a species' capability to recover from disturbances. Collectively, these dynamics exert significant influence on the yields of food systems, the economic returns derived from food production and provision, the nutritional quality of food commodities, and the stability of food production, thereby ultimately determining the state of food security.

Climate change drivers of FS

Table 2 summarises the climate change-induced drivers of FS as synthesised from the 342 selected studies. The impacts of climate change are complex, diverse, and manifold. Climate change can directly impact the habitat, phenology, physiology, and productivity of exploited species, which are important for food production [27].

Impact on availability

To achieve FS, one important aspect is to have sufficient food available to people. Food availability depends on various processes and operations in the food system, including production, storage, processing, distribution, and exchange [6]. The majority of the selected studies on climate change identified a clear and consistent relationship between climate change drivers and food production, suggesting that the food availability pillar is the most affected by these drivers. We identified 273 papers examined the effects of climatic variables on food systems, among which 126 papers discussed the implications of climate change on food production and food availability.

First and foremost, findings from the selected literature primarily pointed to the negative effects of climate

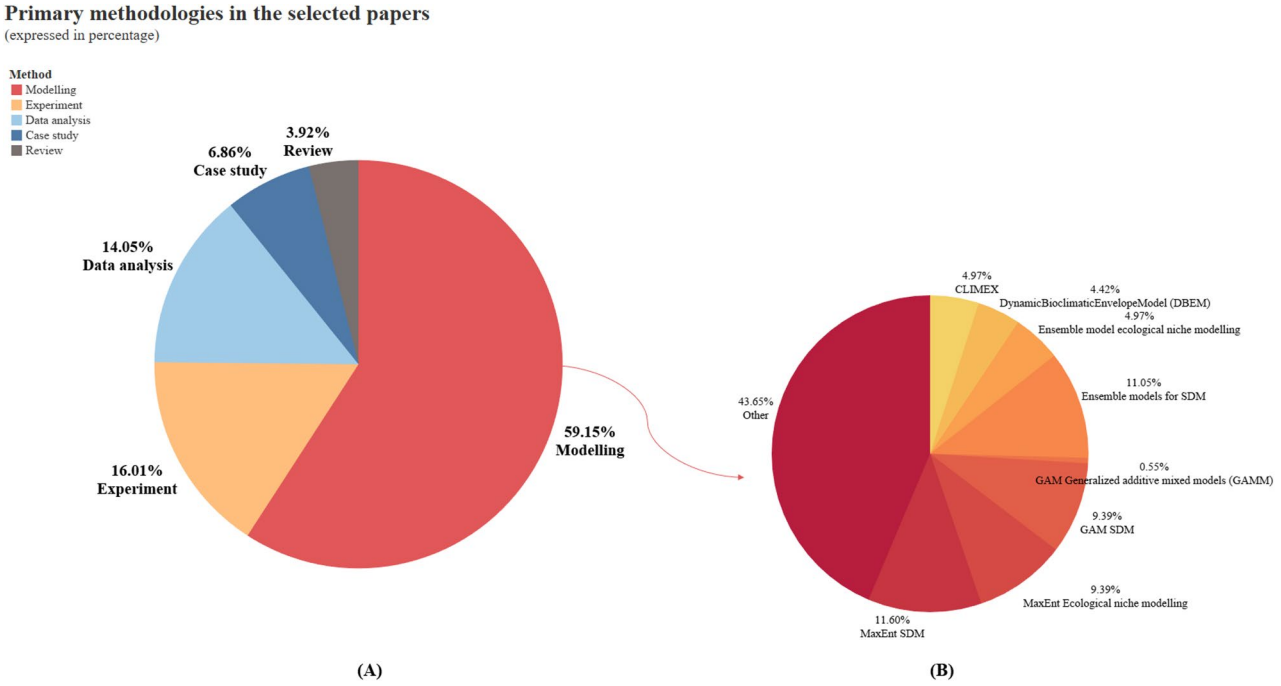


Fig. 5 Dominant research methodologies used by the selected papers for this review. (Part A shows the top 5 methodologies employed in the 342 selected papers. Part B elaborates the most common modelling approaches within the Modelling category)

change drivers on food production, with significant implications for food availability. These negative effects may arise either directly or indirectly from climate change phenomenon. The literature further identified increased surface temperature, precipitation changes, and extreme weather events as the common drivers contributing to the direct effects of climate change. On land, studies have shown that warmer climate and variation in rainfall are the main causes of losses to crops and cattle (for example, see [29, 40–44]). These climate change drivers intensify abiotic stress on organisms, and when environmental conditions exceed tolerance thresholds, crops and livestock experience high mortality rate, thereby reducing the overall outputs of agricultural output. The literature presents numerous examples of vital crop loss due to excessive heat and waterlogging in the field, including maize [29, 40] and wheat [29, 45]. Heat stress associated with rising temperatures also increases the incidence of heat strokes and other health disorders in livestock, resulting in increased mortality [46], while a higher average number of rainy days can promote the spread of ruminant diseases and negatively affect cattle health [39]. Extreme weather events are natural phenomena; however, under the influence of climate change, they are more stochastic, intense, prolonged, and frequent [47]. Unlike increased surface temperature and precipitation, which often have effects in the medium to long term (at least one production cycle), extreme weather events cause the immediate loss of crops and animals. The literature highlights flood [42, 48], hurricane [49], drought [46, 47], marine heatwaves [50], and marine cold spells [51] as particularly detrimental events for agriculture, husbandry, and fisheries.

For the negative indirect impacts of climate change drivers, the literature highlights the shift and/or contraction of suitable habitats for crops and exploited marine species as a consequence of climate change. In our selection of studies, 69 studies reported this result, with 41 studies on commercial fishery and aquaculture and 28 studies on staple crops (not including cash crops). Crops and animals are dependent on climate conditions to grow and thrive; thus, a shift in climatic suitability forced by climate change drivers threatens the ability of a region to successfully grow and harvest food [33, 52]. The concept of climate suitability refers to the degree of agreement between climate resources and the requirements of a specific organism to develop [53]. To this end, several climate change drivers were found to be mainly responsible for changing climate suitability. On land, increased surface temperature and changes in precipitation were found to be major contributors, as 50 pieces of evidence of the link between the two factors and the change to climate suitability were found in 28 studies. This effect applies to a wide range of crops, ranging from essential staple crops such as potatoes [53], rice [54], maize [52, 55], and wheat [56] to regionally important crops such as enset, a wild relative of banana [57]. The impacts of increased surface temperature and precipitation change on crop climatic

Table 2 Summary of climate change drivers of food security. (The drivers are identified in the selected papers for this review. One driver can encompass more than one climate change phenomenon being studied in a paper, for example, increased ocean surface temperature and increased ocean bottom temperature are grouped into one driver of "increased ocean temperature")

Important climate change driver	Description
Increased surface temperature	Refers to increases in the atmosphere temperature of the Earth's surface. While the warming of the Earth's surface is the result of both natural and human forcing [28], there is insurmountable evidence of anthropogenic activities speeding up the warming rate (notably by releasing greenhouse gas emissions) far more than natural causes [29].
Increased ocean temperature Increased freshwater and estuary temperature	Refers to increases in water temperature. The bottom and surface of the oceans are warming at an alarming rate, leading to changes in marine fisheries productivity [30]. The trend of water temperature increasing is also experienced in freshwater bodies, such as lakes and rivers [31], and in estuaries across the world [32]
Precipitation changes	Refers to variability in duration, amount, and frequency of rainfall. As a result of climate change, rainfall occurrence, duration, and amount become difficult to predict [33].
Elevated Greenhouse gases (GHGs)	Refers to the rise of GHGs concentration in the atmosphere [34].
Ocean acidification	Is a direct effect of rising CO_2 in the atmosphere, as atmospheric CO_2 is absorbed in the global oceans, increasing hydrogen ions, and raising ocean acidity as a result [35].
Ocean deoxygenation	Increased atmosphere temperature leads to a global decline of oxygen levels in the sea, due to a reduction in O_2 solubility, increased stratification, and reduced ventilation [36].
Salinity	Refers to the amount of soluble salt in terrestrial or marine environments. Large-scale warming and climate change-induced fluctuations in evaporation and precipitation can generate extremes in soluble salt in global seas and soil [37].
Climatic variability	Refers to irregular patterns of weather caused by climate change. Under the impacts of climate change, seasons and other climate events express fluctuations in their frequency, intensity, spatial extent, duration, and timing [38].
Extreme weather events	Describes a phenomenon considered as the variability of climate, however, these events are more stochastic and intense (e.g., drought, hurricanes, marine heatwaves, floods, summer heatwaves, etc.).
Glacier retreat and reduced sea ice cover	Refers to the ongoing contraction of glaciers and the significant decline of sea ice cover [39].

suitability have been investigated at multiple national levels (for example, see [52] and [58]) and specific national or regional levels (for example, see [53, 54]), implying a holistic understanding of the extant literature on these two drivers. At sea, increased sea temperatures have been found to have the greatest impact on the climatic suitability of species for fishery (32 studies linking increased surface and bottom temperature of the ocean to shift in fishery species), forcing them to migrate horizontally (e.g., to higher latitudes) and/or vertically into deeper water [59–63]), followed by several climate change drivers, including ocean acidification [64, 65], ocean deoxygenation [59, 66], and increased seawater salinity [67–69]. The migration of exploited marine animals for commercial fisheries has negative implications for output, as the catching range can extend further than fishing vessels' capabilities [70, 71]. The affected species include important fish for the fishery industry, such as cod [60], seabass [62], and mackerel [68, 72], and other highly desirable ones, such as lobsters [64], squids [61], and swimming crabs [73]. The shifting of marine animals' habitats due to the effects of climate change drivers, was found to happen at various levels, including global [64, 70, 74], regional [61, 62, 75], and specific countries [65, 69, 73]. Furthermore, the number of studies reporting on the climatic suitability shifting phenomenon for terrestrial and aquatic species has increased in number in recent years (28 papers were published from 2021 to 2023 alone from 69 studies reporting on the phenomenon). These observations show that the issue is widespread and severe, and the literature is striving for a comprehensive and nuanced understanding of the implications of climate change for fisheries. Besides the effects of climate change drivers on habitats, other indirect consequences of climate change on food availability were found in the literature, comprising a comprehensive understanding of the issue. Specifically, climate variability can affect the phenology of organisms, referring to important life events of species, and indirectly lead to a reduction in yields. For example, the winter wheat growing period can be greatly reduced, affecting the plan for sowing seeds [76]; temperature fluctuations during winter were found to impact the dormancy period, leading to a reduction of yields for typical orchard trees and deciduous fruit trees (e.g., apple, pear, nuts, cherry, plums, etc.) [77, 78]; and winter severity can affect the recruitment rate and process of lake fishery species such as walleye and yellow perch [79].

Overall, from the discussion thus far, the selected literature indicates a strong link between climate change drivers and the availability pillar of FS through food production. These impacts are dominantly adverse, suggesting a firm warning of the negative effects of climate change on the outputs of food products via critical means such as farming, husbandry, and fisheries. Furthermore, findings from the literature suggest that these negative impacts are found across the globe. Notably, food availability does not include only food production, as other activities, such as food storage and transport, also play a critical role in maintaining the availability of food and

related products. We only found limited papers addressing the negative impacts of climate change on other facets of the food availability pillar. De Goote et al. [80] and DaMatta et al. [81] specifically linked climate change impacts on storage, attributing food loss to the rise in temperature. Sinclair and Rawlins [40], Thorton et al. [38], and KC [82] acknowledged the impacts of climate change, notably warming climate and precipitation changes, on food storage and transportation; however these studies only mentioned such effects as implications of their main findings.

On the other hand, 26 among 126 papers linking climate change to food availability, acknowledged instances of positive impacts of climate change drivers on food production. We identified 9 studies in our selection that found positive impacts of climate change on food production due to elevated GHGs, among which four found increased CO_2 in the atmosphere to be beneficial while the other five reported both positive and negative impacts in their findings. Higher CO_2 concentrations in the air can strongly stimulate the growth of C3 plants (which include important crops such as rice, wheat, barley, and soybean) [83, 84], and experiments have shown that crop yield and resilience (to adverse conditions such as drought) can be enhanced when these plants are exposed to increased CO_2 [84]. The shift in habitats of key crops and animals for food can surprisingly benefit certain regions, as now they can grow/harvest such species more effectively. For instance, the albacore (*Thunnus alalunga*) population in the California Current is projected to move northward and closer to shore in the future, enabling communities in the Pacific NorthWest (including three States of the US and one province of Canada) to access this fishery resource more easily in the future [85]. Glacier retreat and reduced ice cover open territories for species to occupy, leading to more opportunities to increase fisheries output [39]. Harmful insects and pathogens might be contracted in this range due to a drier and warmer climate (for example the global distribution of Fusarium dry root rot in common beans [86], and global distribution of desert locusts [87]). While positive impacts were reported significantly less often than negative impacts were reported, these findings suggest that the selected literature strives for a critical view of the impacts of climate change drivers on FS. Moreover, studies that found positive effects of climate change drivers also indicated that, due to the adverse effects of climate change elsewhere, regional temporary gains can be easily offset [61, 81]. Furthermore, when a region becomes more climatically suitable for a certain crop, lacks of infrastructure and fragmentation of land and water due to anthropogenic activities can prevent such region from taking advantage [29].

Impact on access

The access pillar of FS concerns whether people have physical, social, and economic access to sufficient food to meet their dietary needs [6]. There are two main tenets to this pillar. First, food needs to be available for individuals to obtain. Second, individuals must have adequate resources to acquire food. In this vein, insights from the literature regarding the impacts of climate change drivers on food outputs, as discussed in the previous section, also provide important implications for the accessibility pillar of FS.

While not all selected studies on the impacts of climate change drivers on food availability explicitly mention food accessibility, a meaningful connection can be inferred from the findings. The literature specifically highlighted that negative impacts from climate change drivers provide immediate implications for people and communities whose livelihoods depend on food production activities (e.g., farmers, fishermen, cattlemen, and others in the supply chain). Two main findings emerged from the selected literature. First, climate change drivers can hinder economic gains from food production, leading to a reduction in the budget for purchasing food. The agriculture and fisheries industries play a vital role in sustaining large populations in numerous countries by generating revenues and providing employment; thus, a decrease in the productivity of these industries under the forcing of climate change drivers (e.g., increased surface temperature [53, 88], precipitation changes [53, 89], increased sea temperature [63, 90]) gradually impedes the ability of people and households to procure food. The literature further highlighted that cash crops such as coffee [89], grapevine [88], and cacao [91] are under adverse effects of climate change, thereby impeding the economic viability of the growers. Severe weather events such as flooding cause immediate loss to crops, animals, equipment, and food production facilities, impairing the major source of revenue for farming individuals and households [48]. Extreme events such as storms physically prevent fishermen from catching fish, lowering productivity and income [49]. Moreover, climate change drivers make maintaining the current level of operation more expensive, lowering the profit and economic status of food producers. When exploited marine species migrate deeper or further from shore, fishermen must invest heavily in gear and vessels to retain the current level of catches without ensuring a net profit [90]; competition between nations might arise because fish crossing different jurisdictions [27], and aquaculture may find it economically infeasible to continue the current operation, forcing a change in production site, unemployment, and investment risks [92]. Similarly, farmers might have to switch to different and more suitable crops under climate change, which can be costly and less profitable at the same time [89].

Second, access to food can be inhibited when food prices hike due to the impacts of climate change. When food production encounters climate change-induced difficulties, the immediate supply of food sources to communities/regions/countries declines, and as a result, food prices rise globally and locally [38, 70, 93], exacerbating the issue of food accessibility further.

Impact on utilisation

The food utilisation pillar concerns how people use food to meet their nutritional needs [6]. Two main facets of this pillar are food safety (ensuring that food is safe to consume) and nutrition (ensuring that food is adequately nutritious to sustain human activities and health). Among all the pillars of FS, utilisation is the least explored in the reviewed literature of this study. We found 10 studies addressing how climate change drivers can affect the nutritional value of food products. For example, Toreti [84] reported that high CO_2 concentrations lead to reductions in protein, mineral, and vitamin concentrations in a wide range of crops, such as barley, wheat, rice, potato, and leafy vegetables. The rising temperature during the period of flowering to grain maturity in crops causes a considerable reduction in crop quality, represented by starch accumulation and carbohydrate composition [81]. Furthermore, degrading marine environments can directly reduce/distort the nutritional value of seafood (e.g., lipid content, protein, and mineral concentration) [94, 95], affecting the population with habits of consuming seafood regularly [96]. Overall, climate change drivers have a moderate impact on food utilisation. However, it can also be suggested that this subject is underexplored.

Impact on stability

The stability pillar of FS encompasses all other pillars, meaning that FS cannot be achieved if the availability of food, people's access to food, and the effective utilisation of food are only momentary. Therefore, threats to the long-term stability of any of the other three FS pillars would consequently jeopardise food stability. Many of the effects of climate change drivers on food stability are derived from the selected studies addressing climate change drivers and food production, making stability a key topic of the selected literature. There are 105 studies projecting future impacts of climate change using modelling approach, which include long-term future trajectories (e.g., 2050, 2100) under different climate change scenarios (most notably, the representative concentration pathway - RCP, i.e., a GHG concentration trajectory) (e.g [29, 54, 61, 93, 97]).,. The results suggest that if the climate change rate continues at the same pace, the food supply will experience perpetual declines and instability, leading to worsening food stability over a long period. There are some notable caveats to this insight. First, several models anticipate that intense interventions to address climate change issues can largely negate the adverse impacts of climate change drivers on food production yields (for example [98]),. In this context, intense interventions refer to large-scale and global efforts in meeting the target of 1.5-degree warming, which is the most optimistic RCP scenario where greenhouse gas emissions are comprehensively reduced. Second, one limitation of the modelling method is the omission of a species' ability to adapt to changes in the climate over time. This means that a species can evolve to cope with changes in its habitat over time, which is difficult to capture when models are based on the tolerance of the current species [99]. Thus, one could argue that the impacts of climate change might not be as severe as the extant literature has portrayed. While acknowledging this criticism, we cannot ignore that all the predictions and modelling results allude to a catastrophic future (especially under high-emissions scenarios such as RCP 8.5).

Biodiversity drivers of FS

Table 3 summarises the biodiversity-induced drivers of FS identified in the literature. The selected literature is generally divided into two main domains when discussing the impacts of biodiversity. On the one hand, many studies explore practices that involve the utilisation of biodiversity factors (e.g., promoting the use of diverse crop portfolios, crop rotation, inter-cropping, agroforestry, etc.). In this vein, biodiversity drivers are embedded in these anthropogenic activities, as they are the key enablers of such practices. On the other hand, numerous studies have focused on the effects of different biodiversity factors on food production (e.g., introducing rhizobacteria into the soil to increase crop yields [100]). In these studies, biodiversity drivers were directly studied.

Impact on availability

Similar to climate change drivers, insights from the review literature regarding the impacts of biodiversity drivers on FS strongly suggest that the availability pillar of FS is most affected. Among the different activities that constitute food availability, food production again is strongly linked to biodiversity drivers.

Two main themes emerged from the selected studies regarding the effects of biodiversity drivers on food availability. First, food outputs can increase from the use of biodiversity factors in the production stage, and the diversity of the surrounding nature can offer more available food for household consumption. Both of these impacts can strengthen the availability pillar of FS. Second, biodiversity drivers can affect the environments of agriculture and fisheries, increasing harvests in the medium to long term.

Table 3 Summary of biodiversity drivers of FS

Important biodiversity drivers	Description
Diversity in plants and crops	Refers to the utilisation of different upper-ground biotic components in a farm system. There are different approaches to adopting diversity in plants and crops, including *using diverse crop portfolios* in the field, *crop rotation*, *intercropping (intraspecies or interspecies)*
Diversity in soil biota	Soil biota refers to organisms living in or on the soil, including microorganisms, soil animals, and plants. Diversity in soil biota drivers describes the utilisation of groups of soil organisms to strengthen a wide range of ecosystem services associated with the provision of food such as supporting crops and controlling soil-borne pest [102]
Agroforestry	Refers to the practice in which woody perennials are deliberately integrated into the farmland [92]. While being an anthropogenic-driven decision, agroforestry utilises the principle of biodiversity by capturing multiple benefits from tree inclusion within an agricultural production system.
Animal and crop integration system	Refers to a different type of species diversity in one ecosystem, in which organisms from different trophic levels – animal and crop plants in this case – are introduced in the same agroecosystem.
Ecosystem services	Ecosystem services are benefits of ecosystems to human such as provision of food and air quality regulation [103]. As a biodiversity driver, ecosystem service in this context refers to services that are made available due to the biodiversity of ecosystems (e.g., forest provisioning, pollination, natural pest control) in the same geographic location and species within an ecosystem.
Underwater biodiversity	Explains how the diversity of underwater plants and species can influence important commercial aquatic animals.
Pest invasion	Refers to harmful organisms, such as insects, weeds, pathogens, rodents, nematodes, and invasive underwater species.
Underutilised crop species	Sometimes referred to as orphan crops, including fruits, vegetables, legumes, grains, and roots that are niche to a specific region/country and are not mass commercialised [57]
Wild crop relatives	Very important sources of useful genetic variations to stabilise and even improve yields under adverse conditions, sometimes even replace crops that are no longer suitable for new climatic conditions [104]

With respect to the first theme, a diverse number of biodiversity drivers emerged from the selected studies without any particular emphasis on any of them, indicating that these drivers can be considered equally important. Moreover, diverse efforts in researching multiple biodiversity drivers as seen in the literature indicate that the body of knowledge is at a developing stage. The majority of food products benefiting from this use of biodiversity drivers are from farming (there are 72 studies linking biodiversity factors to food availability, in which positive effects on crops and livestock were recorded in 31). The literature has shown that the outputs of crops can be strongly enhanced by utilising the complementary and harmonising effects between diverse species during agricultural activities. Experimental studies have shown that crop rotation and intercropping can lead to increases in yields by using space more efficiently, replenishing soil nutrients, and suppressing pests [104–106]. The evidence of the positive effects of crop rotation on yield was also corroborated by insights from farmers [107]. Livestock integration in crop systems has been studied and promoted to potentially harness the complementarities and synergies between plants and animals to increase yields of both [108, 109]. The extant literature also shows that biotic elements play important roles in sustaining the growth, fitness, biomass, and distribution of harvested aquatic organisms. Examples include primary production at sea, notably the use of phytoplankton as food sources for numerous fish [75] and coral reefs [110]. Finally, numerous studies highlight underutilised crop species and diversity in plants as the most critical drivers contributing to the increase in the variety of available food. A forest can supply small communities with fruits to their inventory [111], and additional products from agroforestry can enable households to feed for longer periods than those without [112]. Insects have been historically used as sources of protein for human consumption, and this trend is gaining increasing traction [113]. Underutilised crops and wild edible plants are traditionally grown in select regions and can increase the availability of food for local communities [53, 89, 114]. One caveat of the benefits of these biodiversity drivers is that the beneficiaries are often in small and remote communities. There are yet no studies on the impact of alternative and regionally niche food crops on a global scale.

With respect to the second theme, biodiversity drivers can affect the environments in which crops and animals live, with implications for outputs. Underground biodiversity can support the growth of crops by increasing available nutrients in the soil for plants (especially nitrogen and phosphorus) [101] and stimulating plant growth, photosynthesis, and shoot biomass [115]. Some evidence from the literature includes the endophytic fungus *Piriformosporra indica*, which increases wheat root biomass [116]; *Trichoderma* fungi, which boost root and growth in rapeseed [117]; microbiome bacteria, which promote growth and mitigate drought in wheat [118]; and the diversity of rhizobacteria, which has positive impacts on velvet bean biomass during water deficit [100] and on soybean resistance to insects [119]. The soil biota (fauna and microorganisms) plays a strong role in engineering the soil structure (e.g., building soil macroaggregates, decomposing and cycling matter, breaking down the soil crust), leading to more fertile soil and preventing degradation [101]. Among the macrofauna in the soil biota,

the literature highlights the importance of earthworms, which mediate soil fertility and increase useful chemical content in soil (e.g., soluble Silicon for conferring plants resistance to abiotic stress) [120]. Agroforestry practices provide multiple benefits to the surrounding environment of crops, such as lowering the groundwater recharge rate; improving nutrient retention and nitrogen-fixing in soil [121, 122]; preventing windbreaks and soil erosion; attracting rain and compost [112]; and providing favourable microclimates for primary crops, fruits, or commercial plants underneath [123]. Furthermore, planting cover grazing crops between intensive cropping seasons can help restore soil conditions and facilitate indirect ecosystem services (e.g., weed control) while providing livestock at the same time [124]. Moreover, many natural services, stemming from biodiversity, can protect and increase agricultural outputs. Pollination services are vital to many agricultural systems worldwide, and diverse habitats around farmlands can increase pollination with spillover effects [125]. Natural means of controlling harmful species cannot be overlooked, as they prevent the overuse of pesticides, which can degrade the environment and climate [105]. In marine and freshwater environments, key supporting species (e.g., primary producer species, coral, kelp, mangrove, and undersea macroalgae) play a vital role in provisioning fish, sheltering them during bad weather, and providing nursery habitats for larvae to grow [70, 126].

On the other hand, studies also raised warnings about the effects of invasive taxa (31 studies). The spread of invasive alien plants, harmful insects, and pests can damage plants in the field; aggressively compete with crops for vital resources (e.g., nutrients and water); lead to parasitism, viruses, and pathogens; and inhibit the early development of young crops [28]. In aquatic habitats, cyanobacteria blooms [127] and harmful algae blooms [128] can cause mass mortality in fish and aquaculture species by inducing hypoxia and releasing toxic chemicals into the water. Novel invasive species [129] invade new territories to compete and/or prey on exploited fish species, reducing their abundance and possible yield. This highlights the criticality of the selected literature on the topic of the biodiversity drivers of FS.

Impacts on access

The impacts of biodiversity drivers on the accessibility pillar of FS can be considered an extension of the impacts on food production and food availability. Primary food producers, such as farmers, cattlemen, and fishermen, could obtain more income from their food production, leading to better access to food. The bulk of the selected studies revealed the connection between the use of biodiversity drivers and increased income. Some examples include the use of a more diverse crop portfolio, which is positively associated with an increase in household income [130]; plant and crop diversity, which stabilises income streams for farmers in difficult times [108, 131]; and the mixing of species into traditional farms, which can produce better yields and fetch a higher price for farmers [132]. Crop residues after harvesting provide feed for livestock, not only maximising resource efficiency but also providing extra income in dry seasons [124]. We specifically found 11 case studies that reported positive effects on household incomes and FS when biodiversity drivers were incorporated into food production activities. These cases are conducted in small and remote communities (for example, see [105, 108, 111]), who are often in danger of FS.

Impact on utilisation

With respect to the impacts of biodiversity drivers on the utilisation pillar of FS, the selected literature revealed positive effects from biodiversity drivers. Our selection of studies only included nine papers linking biodiversity drivers to food utilisation. The literature highlighted that the quality of food products can be enhanced by utilising biodiversity drivers during the food production process. For example, plant-promoting bacteria (e.g., *Funneliformis mosseae*, *Septoglomus viscosum*, *and Rhizophagus irregularis*) can positively affect the concentration of sugar, resulting in better-quality strawberries [115]. Second, the selected literature revealed four biodiversity drivers—diversity in plants and crops, agroforestry, underutilised crops, and ecosystem services (especially forest provisioning services)—with an enhancing effect on nutrient intake. For example, planting diverse species in fields and gardens, utilising niche and regional crops, and gathering extra food from nearby forests can significantly increase nutritional variety and value intake at the household level, strengthening FS [53, 111, 131, 134]. These studies focus mainly on communities struggling with food insecurity.

An interesting benefit of biodiversity, which is related to ecosystem services as a biodiversity driver, was discussed in three case studies. In these particular scenarios, remote communities rely greatly on firewood obtained from nearby forests as the main source of fuel for cooking [111, 112, 132], enabling the utilisation of food. This effect is relevant only to developing regions.

Impact on stability

From the discussion of the impacts of biodiversity drivers on food availability and accessibility pillars, it can be inferred that biodiversity drivers can have positive effects on the stability of those two pillars in the short and medium term and consequently positively impact the stability pillar of FS. For example, in the context of short-term disruptions to food systems (e.g., extreme

weather events, natural disasters, and crop failures), the use of biodiversity drivers such as agroforestry and ecosystem services can provide alternative food to affected households to overcome difficult times and regain stability [108, 111, 131]. In the medium term, field conditions can be strengthened against adverse conditions (notably drought, flood, and increased soil salinity) via drivers such as diversity in crops and plants and soil biota to stabilise yields [108, 109, 135–137].

Our selected studies included nine papers which highlighted the interesting impact of the biodiversity driver "wild crop relatives" on the long-term stability of food production. These types of crops provide important sources for breeding new varieties that can withstand and adapt better to drastic changes in climate and various growing conditions, retaining the stability of agriculture [103].

Conclusion

FS remains a pressing global issue. The UN reported that over 9% of the world population was facing hunger in 2023 – equivalent to between 713 and 757 million people or one out of 11 people in the world [2]. The current FS literature continues to advocate for further efforts to understand critical drivers of FS for developing effective and multifaceted solutions [3, 6, 12]. Therefore, this study aims to provide a holistic outlook of the current literature regarding climate change and biodiversity as drivers of FS, with the hope of promoting and building a foundation for future scientific investigations into these subjects.

On the one hand, climate change drivers have been well examined, and the majority of the literature insinuates a largely negative impact of climate change drivers on FS (218 studies found only evidence of negative impacts from climate change). Among the FS pillars, food availability is the most affected, followed by food accessibility and food stability. Very few studies have investigated the connection between climate change drivers and the utilisation pillar of FS (only 10 from the reviewed paper). The literature reports that the impacts of climate change drivers are widespread (i.e., covering a wide range of food sources and affecting numerous climatic regions around the globe) and complex (i.e., a species or region can be affected by multiple drivers). Over time, the focus of the literature has moved from a global perspective toward more investigations of climate change drivers in specific regions, implying a desire to understand the nuances of the impacts. On the other hand, the literature regarding the biodiversity drivers of FS is growing, exploring a wide range of factors and their impacts on FS. The primary theme of this body of literature is the potential and benefits of utilising biodiversity drivers to strengthen FS. Findings from selected studies indicate that biodiversity drivers have considerable impacts on all pillars of FS, with availability gaining more focus than the other three. Furthermore, one key characteristic of this body of literature is the orientation towards remote communities and developing countries, especially case study papers. One explanation for this premise is that these areas urgently lack FS, hence drawing more interventions utilising the benefits of natural biodiversity.

This work makes several contributions to the literature. First, this study contributes to the ongoing conversation in the FS literature, which recognises the critical roles of climate change and biodiversity in assessing FS [2, 4, 6, 7]. There are a number of existing reviews on the subject (e.g [6, 7, 12, 13]., that focus on explaining the mechanism by which climate change and/or biodiversity can affect FS (e.g., impacts of increased temperature on agriculture and FS, or how biodiversity can be cultivated to improve food systems and FS). Our study not only provides explanatory elements but also highlights key findings, directions, and potential areas for future research. Second, this study offers a specialised examination of the direct drivers of FS, stemming from climate change and biodiversity. Our compilation of climate change and biodiversity drivers of FS can serve as a useful foundation for future research. On a methodological note, this study demonstrates the usefulness of SLR for a systematic understanding of the relevant literature. As the majority of review studies on this subject used a narrative-led approach [e.g., 6, 7, 13, 19, 20], our study helps promote the variety of research approaches.

Moreover, this work provides several implications for practice. For climate change drivers, the majority of the impacts are negative, with scarce instances of surprising positive impact on food security from climate change. For biodiversity drivers, our findings indicate numerous benefits from utilising biodiversity for strengthening food production and food security. Thus, our findings advocate for strong consideration of climate change risks in planning and managing food production, and adoption of practices utilising/promoting biodiversity for a sustainable and stable food system. Furthermore, we strongly suggest future policies to consider these two determinants thoroughly during development. Not only do policies must recognise the effects of climate change and biodiversity on food security, but also, they should take into account how the food system contribute to climate change and the current state of biodiversity to prevent adverse consequences in the long-term. Furthermore, our work examined climate change and biodiversity as drivers of food security at a global scale, therefore we urge for careful consideration of regional context when evaluating the drivers of food security. Each specific region has their own core food products, unique climate, and particular biodiversity state. Thus, it is necessary for policy makers

to specify the most critical drivers of their regions to improve reach and impact of their policies.

Finally, several avenues for future research are proposed:

- *Linkages between climate change, biodiversity, and the pillars of food security*: The connection between climate change and biodiversity drivers and specific dimensions of food security warrants further investigation. Our synthesis of the literature reveals that the impacts of climate change on food security are evident across all four pillars—availability, accessibility, utilisation, and stability. However, existing research disproportionately emphasises the availability, accessibility, and stability dimensions. Future studies could therefore focus on the utilisation pillar, particularly examining how climate change affects food safety, food quality, and nutritional value. Moreover, research should explore how biodiversity utilisation contributes to dietary diversity and nutritional security, as well as its influence on the long-term stability and resilience of food systems.

- *Biodiversity and food security across socio-economic contexts*: Our analysis underscores the critical role of biodiversity in sustaining food security among disadvantaged communities, especially those in remote or developing regions. We believe the benefits of biodiversity are relevant globally; therefore, future studies should also investigate its role in achieving food security within developed nations. Such studies could inform context-specific strategies for optimising biodiversity conservation and utilisation to continue maintaining food security.

- *Practical and immediate responses to climate change*: The reviewed literature provides robust evidence of the adverse impacts of climate change on food security and projects the persistence of these effects under various RCP scenarios towards the mid- and late 21 st century (2050–2100). To fully capitalise on this knowledge about the long-term effects of climate change, future research could focus on the identification and implementation of appropriate measures at present to reduce vulnerability and strengthen preparedness for projected climate change.

- *Policy interventions*: Our synthesis discovered the pivotal role of policies in mitigating the adverse effects of climate change and biodiversity loss on food systems. Examples include the need for coordinated policy responses to address transboundary shifts in fish populations or the need for government programs to switch crops due to the loss of suitable agroecological conditions. Consequently, food policy emerges as a critical area for future research.

Limitation

As the body of literature regarding climate change – biodiversity – FS is growing at an impressive pace, we acknowledge that our selection of papers (which were concluded as of mid-2023) might not cover recent research. Another limitation of this study is the use of a single scientific database for locating relevant research. While there are examples of SLR works based on one database (e.g., [Reich 23]), we acknowledge that the use of multiple databases for cross-checking the search results can be useful. Future work can address this limitation, especially when the subject of study needs a revisit after a period of time. Nevertheless, we believe that our rigorous selection of papers and detailed analysis adequately captured the essence of the literature.

Appendix 1 – Summary of climate change impacts

Dimension	Impact	Drivers	Specific mechanism
Availability	Yield loss on agricultural activities on arable lands	Increased surface temperature Precipitation changes	Create unfavourable climatic conditions to farming land, leading to reduction in yields. Shifting climatic suitability leads to ineffective farming. Affecting livestock health and mortality rate.
		Extreme weather events	Causing immediate loss to crops and animals.
	Yield loss on fisheries and aquaculture	Increased ocean temperature Increased freshwater and estuary temperature Ocean acidification Ocean deoxygenation Salinity	Causing shifting of fish and other exploited species away from fishing grounds. Exerting abiotic stress on animal, thereby reducing stocks and biomass.
	Alter phenology of organisms, thereby indirectly affecting yields	Climatic variability	Affecting important life events, especially spawning and maturity.
	Increasing growth in plants	Elevated Greenhouse gases (GHGs)	Higher CO2 concentrations in the air can strongly stimulate the growth of C3 plants (which include important crops such as rice, wheat, barley, and soybean)
	New opportunities for growing crops and/or harvesting wild species	Increased surface temperature Precipitation changes Glacier retreat and reduced ice cover	A region can become climatically suitable to grow new crops. New fishing grounds and aquaculture sites are open due to less ice coverage.
Accessibility	Lower profit from food production activity	Increased surface temperature Precipitation changes Extreme weather events Increased ocean temperature Increased freshwater and estuary temperature Ocean acidification Ocean deoxygenation	Agricultural and fishery activities are limited, costlier, and less effective due to the stress of climate change. Fields, facilities, equipment are damaged/destroyed during severe weather events, thereby lowering profit. Extreme weather events and sporadic weather conditions preventing individuals to produce food.
	Price hike		Lower outputs from production has a cascading impacts on the food supply chain, hiking price locally and globally.
Utilisation	Lower nutritional value of food	Elevated Greenhouse gases (GHGs)	Leading to reductions in protein, mineral, and vitamin concentrations in crops
		Increased surface temperature	Reducing crop quality, represented by starch accumulation and carbohydrate composition
		Salinity Ocean acidification	Degrading marine environments can directly reduce/distort the nutritional value of seafood
Stability	Long term stability of food production	*Share similar drivers which causes yield loss for availability and accessibility pillar as this insights were concluded in same studies*	

Appendix 2- summary of biodiversity impacts

Dimension	Impact	Drivers	Specific mechanism
Availability	Positive direct impacts on yield	Diversity in plants and crops Animal and crop integration system Diversity in soil biota Agroforestry	Harmonising effects between diverse species during agricultural activities lead to increase in yields. Sustaining the growth, fitness, biomass, and distribution of harvested aquatic organisms by underwater biodiversity.
	Supplying alternative food source	Ecosystem services Underutilised crop species	Provisioning from forest can diverse the food intake of local communities. Alternative source of food such as insects can be exploited. Underutilised crop species can be regionally important for food security.
	Improving the environment, thereby increasing yield	Agroforestry Diversity in soil biota Underwater biodiversity Ecosystem services	Supporting the growth of crops by increasing available nutrients in the soil for plants (especially nitrogen and phosphorus) and stimulating plant growth, photosynthesis, and shoot biomass. Mixing woody trees in field providing favourable microclimates for primary crops, fruits, or commercial plants underneath, while improving nutrient retention and nitrogen-fixing in soil. Ecosystem services such as pollination and natural pests control are beneficial to fields. Underwater biodiversity provisions, shelters, and nurses fishes.
	Reduction of yield due to invasive taxa	Pest invasion	Harmful pests both on land and in water impede exploited species ability to survive and grow.
Accessibility	*Studies that link biodiversity to availability also provide implications to accessibility, since the income of food producer strongly depends on their ability to produce/harvest food.*		
Utilisation	Enhancement of food quality	Diversity in soil biota	Micro-organism in soil benefit crops to yield higher quality products
	Diversity nutrient intake	Diversity in plants and crops Agroforestry Ecosystem services Underutilised crop species	Providing alternative source of nutrients to local communities.
Stability	Short term stability in disturbance	Agroforestry Ecosystem services	Providing immediate source of food (food availability) in highly disruptive events such as storms and floods.
	Long term stability	Wild crop relatives	Providing important genes to improve staple crops in light of adverse climate conditions.

Abbreviations

FAO	Food and Agriculture Organisation
FS	Food security
GHG	Greenhouse gas
UN	United Nations
UNEP	United Nations Environment Programme
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses

Supplementary Information

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Supplementary Material 1

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Author contributions
All the authors contributed to the conceptualisation of the study. The literature search was performed by NV. The screening and selection of the final mix of papers were conducted by NV and MB. The original draft was prepared by NV. All the authors contributed to the revision of the draft into the final manuscript. All the authors read and approved the final manuscript.

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Data availability
The datasets used and/or analysed during the current study are available from the corresponding author upon reasonable request.

Declarations

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Not applicable.

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