

Review

Climate Change and Sustainable Maize Production: Risks, Response and Resilience Pathways

Magdoline Mustafa Ahmed Osman ^{1,2,3,*} , Ronald Kuunya ^{1,2} , Erastus Wasikoyo ^{1,2} , András Tamás ^{1,2} ,
Árpád Illés ^{1,2} , Adrienn Széles ^{1,2}  and Tamás Rátonyi ^{1,2}

¹ Institute of Land Use, Engineering and Precision Farming Technology, Faculty of Agricultural and Food Sciences and Environmental Management, University of Debrecen, 138 Böszörményi Street, 4032 Debrecen, Hungary; kuu79ron@mailbox.unideb.hu (R.K.); ewasikoyo@mailbox.unideb.hu (E.W.); tamas.andras@agr.unideb.hu (A.T.); illes.arpad@agr.unideb.hu (Á.I.); szelesa@agr.unideb.hu (A.S.); ratonyi@agr.unideb.hu (T.R.)

² Kálmán Kerpely Doctoral School, University of Debrecen, 138 Böszörményi Street, 4032 Debrecen, Hungary

³ Environment, Natural Resources and Desertification Research Institute, National Centre for Research, Khartoum 1111, Sudan

* Correspondence: magdoline.osman@agr.unideb.hu

Abstract

Climate change significantly threatens maize (*Zea mays* L.) production through rising temperatures, erratic precipitation, and extreme weather events, thereby jeopardising global food security. This review synthesises current knowledge on the impacts of climate change, abiotic stresses, crop simulation models, and adaptation strategies for maize. A bibliometric analysis of 485 articles published between 2015 and 2025 and indexed in the Web of Science was conducted using VOSviewer. The results showed a significant increase in publications (Mann–Kendall test, $p = 0.0001$; $R^2 = 0.8207$), with dominant research themes shifting toward climate-smart agriculture and sustainable intensification. Heat stress, drought, and nutrient deficiencies were identified as the primary abiotic constraints. DSSAT-CERES-Maize and APSIM emerged as the most widely used models for assessing climate impacts and the effectiveness of adaptation strategies. Effective adaptation measures include the use of resilient varieties, optimised water management, conservation agriculture, and diversified cropping systems. Future research should focus on integrated adaptation approaches, improved model validation, and long-term field studies to enhance maize resilience. This study provides a comprehensive overview of the research landscape and highlights critical pathways for ensuring sustainable maize production under changing climate scenarios.

Keywords: *Zea mays*; bibliometric analysis; abiotic stress; crop simulation models; climate-smart agriculture; adaptation strategies; food security



Academic Editors: Anna Kocira and Mariola Staniak

Received: 15 August 2026

Revised: 22 September 2026

Accepted: 27 September 2026

Published: 30 September 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Climate change represents one of the greatest challenges to global agricultural sustainability by altering temperature regimes, precipitation patterns, atmospheric carbon dioxide (CO₂) concentrations, and the frequency of extreme climatic events [1]. These changes have profound effects on agricultural systems by influencing water availability, soil quality, crop productivity, and rural livelihoods [2–4]. Climate variability directly affects crop phenology, growth duration, and yield formation, with irregular rainfall and increasing temperatures contributing to drought periods, shortened crop maturity cycles,

and reduced production stability [5,6]. Consequently, climate change threatens agricultural development, food security, and poverty reduction efforts, particularly in regions highly dependent on climate-sensitive farming systems [7].

Among major cereal crops, maize (*Zea mays* L.) is particularly vulnerable to climate change due to its sensitivity to temperature increases, water availability, and environmental variability [8,9]. Maize plays a fundamental role in global food and economic security, providing an important source of dietary energy and supporting millions of farming households worldwide [10–12].

Maize production has generally increased in recent years, supported by expansion of harvested area, technological progress, improved management practices, and advances in stress-tolerant cultivars. However, this overall increase masks substantial year-to-year variability in yield. As shown in Figure 1, harvested area increased from approximately 186,000 ha in 2014 to 210,000 ha in 2024, whereas yield fluctuated considerably over the same period. These fluctuations highlight the continuing sensitivity of maize productivity to environmental variability and climate-related stresses [7]. In particular, rising temperatures, heat stress, drought, erratic precipitation, extreme weather events, and nutrient limitations can adversely affect crop establishment, flowering, pollination, grain filling, and final yield [5,6,8,9,13,14]. The development of resilient varieties, improved water and nutrient management, conservation agriculture, and other climate-smart practices has contributed to reducing these risks; nevertheless, increasing climatic variability continues to pose a major challenge to stable and sustainable maize production.

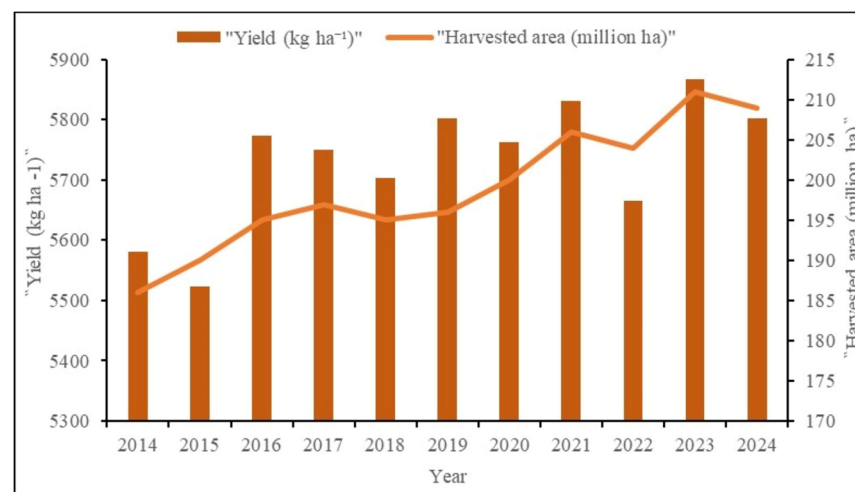


Figure 1. Maize production trends and vulnerability to climate-related abiotic stresses. Source: FAO (Accessed 1 July 2026) (2014–2024).

However, climate-driven changes in environmental conditions increasingly threaten maize productivity by disrupting physiological processes, crop development, and yield stability [13,14]. Several studies project maize yield reductions of 12–28% by the end of the twenty-first century, even when adaptation strategies are considered; however, the magnitude of these losses depends on the region, climate scenario, crop system, and modelling approach [15,16]. Previous studies have demonstrated strong relationships between maize yield variability and climatic factors, including temperature, precipitation, and radiation, highlighting the need to understand climate-crop interactions under future scenarios [17–20].

The impacts of climate change on maize production are primarily manifested through increasing abiotic stresses, particularly heat stress, drought, water scarcity, and soil fertility decline. Among these stresses, rising temperatures and extreme heat events are major

constraints affecting maize growth and yield formation. Temperatures above 30 °C during the reproductive stages can reduce pollen viability, increase kernel abortion, impair pollination, and ultimately decrease grain yield [18,21–23]. Although moderate warming may extend the growing season in some regions, excessive temperatures negatively affect reproductive development by reducing pollen fertility and disrupting kernel formation [24]. Heat stress has been shown to affect maize reproductive development more severely than vegetative growth, with high temperatures during early vegetative stages reducing ear development and heat stress during tasselling affecting reproductive success [25,26]. One cross-study estimate reported an approximate 7.4% decrease in maize yield for each 1 °C increase in mean temperature [9,27]. This estimate should be interpreted as an average temperature-response relationship rather than a uniform yield-loss rate applicable to all regions and production systems [9,27].

Drought and water scarcity further increase the vulnerability of maize production under changing climate conditions. Drought stress reduces photosynthetic capacity, carbon assimilation, and biomass accumulation while accelerating leaf senescence, ultimately limiting yield potential [28,29]. Water deficits during critical developmental stages reduce maize productivity by decreasing leaf expansion, impairing photosynthesis, and reducing grain filling [29]. The increasing frequency and intensity of drought events associated with climate change have contributed to greater instability in global maize yields. In severely drought-affected regions, maize yield reductions of approximately 25–30% have been reported [30]. This range represents conditions in particularly vulnerable production environments and should not be interpreted as a global average [30]. Furthermore, changes in rainfall distribution influence soil moisture dynamics, evapotranspiration, and water productivity, creating additional challenges for maize production systems [31,32].

Beyond climatic stresses, declining soil fertility and unsustainable nutrient management practices represent additional threats to sustainable maize production. Excessive mineral fertiliser application has contributed to nutrient losses, greenhouse gas emissions, and soil acidification [33–35]. Climate change combined with soil fertility decline can reduce crop productivity and increase vulnerability among smallholder farmers, highlighting the importance of sustainable soil management practices that enhance soil health and nutrient-use efficiency.

Addressing climate-related risks requires a better understanding of crop responses through advanced assessment methods and effective adaptation strategies. Crop simulation models have become important tools for evaluating climate impacts on crop growth, yield potential, soil water balance, and nutrient cycling under different environmental scenarios [36,37]. Models such as CERES and CROPGRO have been widely applied to simulate interactions among climate, soil, crop genetics, and management practices and to assess impacts on productivity and environmental outcomes, including soil organic carbon dynamics and greenhouse gas emissions [38,39]. Coupling crop models with climate projections from General Circulation Models (GCMs) and Representative Concentration Pathways (RCPs) provides valuable information for evaluating future production risks and adaptation options [40–44].

Developing resilient maize production systems requires integrated responses that combine improved agronomic management, sustainable resource use, and climate-resilient crop improvement. Conservation agriculture has emerged as an important climate-smart approach for improving soil quality, conserving water resources, and enhancing food security [45]. Similarly, drought-tolerant maize genotypes and locally adapted varieties offer promising strategies to reduce climate vulnerability and improve farmers' adaptive capacity [46,47]. Other complementary responses, such as adjusting planting dates and crop management practices, water and nutrient management, and the use of climate-adapted

crop varieties, can further strengthen adaptation capacity [36,37,40–44]. However, individual adaptation approaches may not be sufficient to address the multiple stresses associated with climate change. This underscores the growing need to build long-term resilience by integrating technological, agronomic, ecological, and management interventions [47]. Therefore, a comprehensive understanding of climate change risks, appropriate response options, and pathways towards resilient maize production is essential for sustaining productivity and supporting global food security under future climate scenarios [45]. However, evidence on climate-driven stresses, modelling approaches, and adaptation strategies is dispersed across different aspects of maize production, making an integrated synthesis particularly important [46]. The working hypothesis of this review is that climate change-induced abiotic stresses, particularly heat stress, drought, water scarcity, and declining soil fertility, negatively affect maize productivity and yield stability, but that their impacts can be reduced through the integration of climate-resilient varieties, improved agronomic and resource management, and appropriate crop modelling and adaptation strategies. We further hypothesise that an integrated approach combining climate-risk assessment, crop modelling, sustainable agronomic practices, and climate-smart adaptation measures can provide a more effective pathway for strengthening the resilience and sustainability of maize production under future climate scenarios. This review therefore synthesises recent advances in understanding the effects of climate change on maize productivity, with particular emphasis on climate-driven abiotic stresses, crop modelling approaches, and sustainable adaptation strategies. By linking climate-related risks with assessment approaches and adaptation responses, the review highlights pathways for enhancing maize resilience and sustaining production under future climate scenarios.

2. Materials and Methods

2.1. Data Source and Search Strategy

A bibliometric analysis combined with a focused qualitative synthesis was conducted to examine scientific literature on maize (*Zea mays* L.) production under climate change. The bibliometric analysis assessed publication trends, influential authors and countries, collaboration patterns, research themes, and intellectual structure, while the qualitative synthesis examined climate risks, maize productivity, modelling, adaptation, resilience, and food security.

The Web of Science (WoS) Core Collection was used because of its broad coverage of peer-reviewed literature and availability of standardised bibliographic and citation data. The search was conducted on 1 July 2026 using: (“maize” OR “corn” OR “*Zea mays*”) AND (“climate change” OR “climate variability” OR “global warming”) AND (yield OR productivity OR production) AND (adaptation OR mitigation OR resilience OR sustainability).

The initial search identified 3973 records. Sequential filtering reduced the dataset to 3228 records for 2015–2025 (−745), 1258 in the Agriculture research area (−1970), 1246 English-language records (−12), 695 open-access records (−551), 596 Research Articles (−99), and finally 485 records classified under Sustainable Development Goal 2 (SDG 2: Zero Hunger) (−111).

The 485 records constituted the bibliometric dataset and were all included in the bibliometric analysis. A separate relevance and eligibility screening of these 485 publications identified 85 studies for the qualitative synthesis. Thus, exclusion during qualitative screening did not affect the bibliometric dataset.

Open-access and SDG 2 filters were used to facilitate full-text assessment and improve alignment with food security and sustainable agricultural production, respectively. However, these database-based criteria may exclude relevant studies that are not open access

or are not classified under SDG 2. Therefore, the resulting dataset represents a predefined subset of the WoS literature rather than the complete maize–climate-change literature, and this potential selection bias was considered when interpreting the findings.

2.2. Study Selection and Eligibility Criteria

The 485 publications were screened separately for inclusion in the qualitative synthesis. Eligible studies directly examined climate change or climate variability affecting maize production, including yield responses, drought, heat stress, water scarcity, climate projections, crop modelling, adaptation, resilience, sustainable production, or food security.

Studies were excluded if they (i) lacked a maize-specific analysis, (ii) did not explicitly address climate change or variability, (iii) examined maize traits unrelated to climate or production, or (iv) focused on downstream processes unrelated to climate-driven maize production. Exclusion reasons were recorded during screening.

Of the 485 publications, 400 were excluded during qualitative screening and 85 were retained. The study therefore used two nested datasets: 485 publications for bibliometric analysis and 85 studies for qualitative synthesis. The complete filtering and screening process is presented in Figure 2.

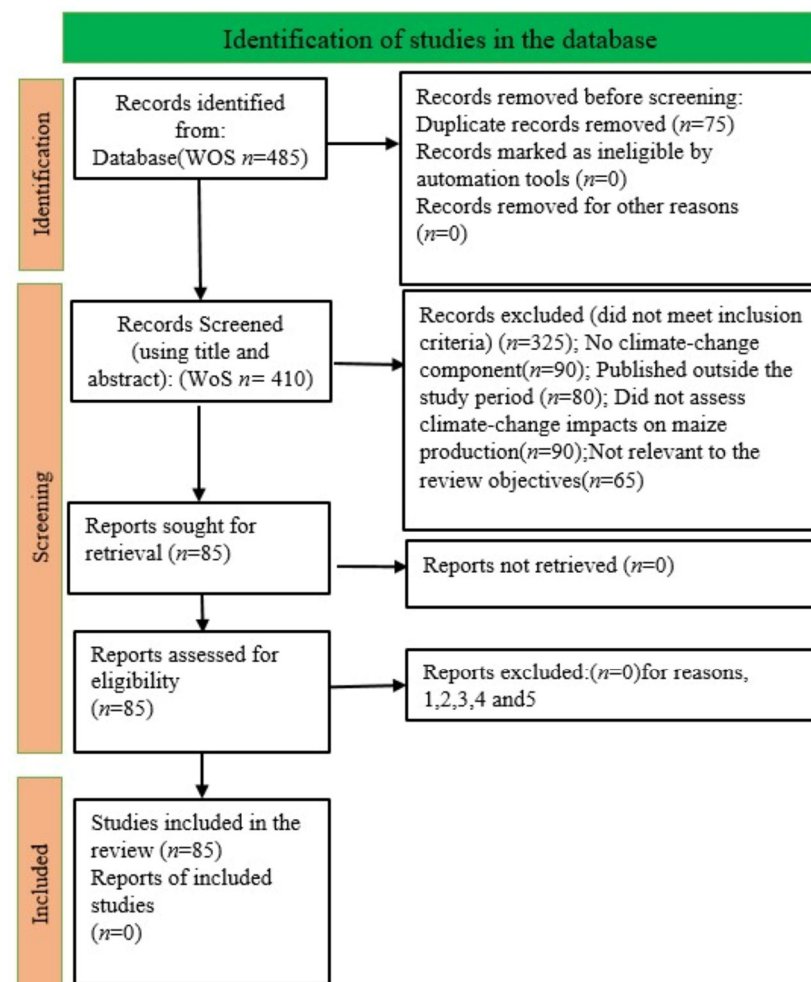


Figure 2. PRISMA flow diagram of literature screening and study selection.

2.3. Data Export and Bibliometric Analysis

Bibliographic data for the 485 publications were exported from WoS as a CSV file containing full records and cited references. Microsoft Excel was used for descriptive analysis, and VOSviewer version 1.6.20 [48] was used for bibliometric mapping.

The analysis included co-authorship, country collaboration, citation, keyword co-occurrence, bibliographic coupling, and co-citation analyses to identify major research themes, influential contributors, and the field's intellectual structure.

The 85 studies selected for qualitative synthesis were thematically analysed across three dimensions: (i) climate-related risks and abiotic stresses; (ii) crop modelling and assessment of climate impacts; and (iii) adaptation, resilience, and sustainable production. Findings were compared across climate hazards, geographical contexts, modelling approaches, and management conditions.

The bibliometric and qualitative findings were interpreted jointly to identify dominant themes, emerging research directions, evidence gaps, and priorities for climate-resilient maize production.

3. Results

3.1. Publication Trends of the Selected Studies

The Mann–Kendall test showed a significant increasing trend ($p = 0.0001$) in the number of research publications on climate change and maize production. The annual publication trend is presented in Figure 3. Publications increased from 14 in 2015 to 112 in 2025, although some year-to-year variation was observed. This increase indicates growing research interest in climate change and maize production based on the publication data analysed in this study. In Figure 3, each blue bar represents the number of publications in a given year, and the orange dotted line shows the exponential trendline fitted to these annual counts. The fitted equation ($y = 11.554e^{0.1903x}$) indicates an average growth rate of about 21% per year ($e^{0.1903} \approx 1.21$). The R^2 value of 0.8207 shows that the exponential model explains about 82% of the variation in annual publication counts, indicating a strong and consistent upward trend. The slight decline in 2023 falls below the trendline, but output recovered in 2024 and rose sharply in 2025.

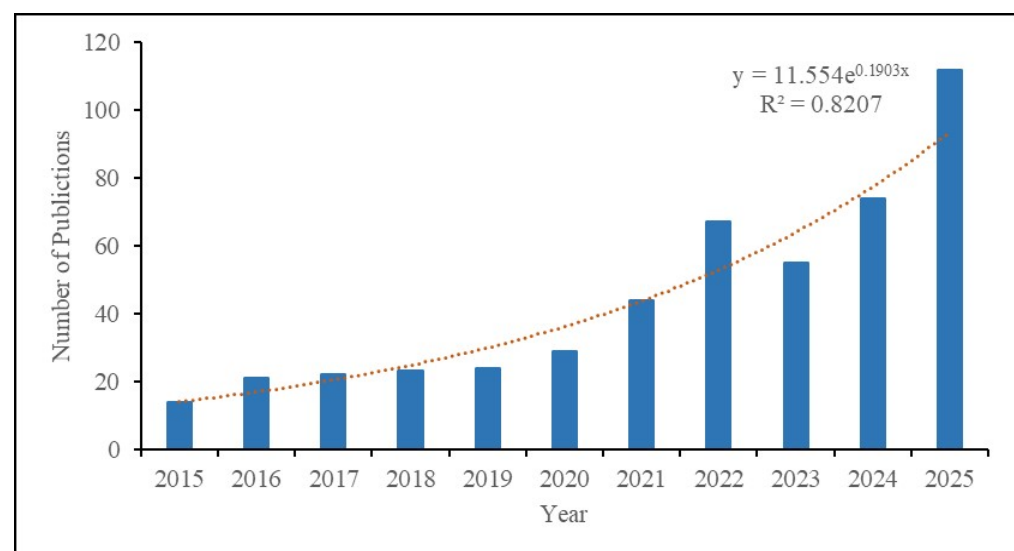


Figure 3. Annual Trend of Publications Indexed in Web of Science (2015–2025).

The increasing number of publications reflects growing scientific attention to climate-related challenges in agricultural systems. Previous studies have documented the effects of rising temperatures, altered precipitation patterns, and extreme weather events on maize production and crop productivity [49–53]. Climate change has also increased concerns about agricultural sustainability and food security [54]. Rising temperatures [55], erratic

rainfall and drought [56], and extreme weather events can affect maize growth and yield, highlighting the need for adaptation and resilient production systems [50–53].

The research literature increasingly addresses climate-resilient maize varieties [57], adaptation and mitigation strategies [58,59], and sustainable farming practices [60]. These themes indicate growing research attention to improving maize resilience, resource-use efficiency, and food security under changing climatic conditions [50,54].

Overall, the publication trend demonstrates increasing research interest in climate change and maize production rather than providing direct evidence of climate impacts. The Mann–Kendall test assessed the statistical significance of the temporal trend in publication numbers. The publication trend therefore complements, but does not replace, the scientific evidence on climate impacts discussed in the following sections [49–60].

3.2. Bibliometric Network Analysis of the Selected Literature

Figure 4 presents the temporal co-occurrence network of Author Keywords published between 2015 and 2025, while Table 1 lists the ten most frequently occurring author-supplied keywords and their total link strengths. In VOSviewer (v1.6.20), node size represents keyword occurrence, link thickness indicates co-occurrence strength, and node colour represents the average publication year, ranging from earlier (blue) to more recent (yellow) studies. Author Keywords are terms explicitly provided by authors to describe the main focus of their studies; therefore, they primarily reflect the terminology and themes that researchers themselves considered important.

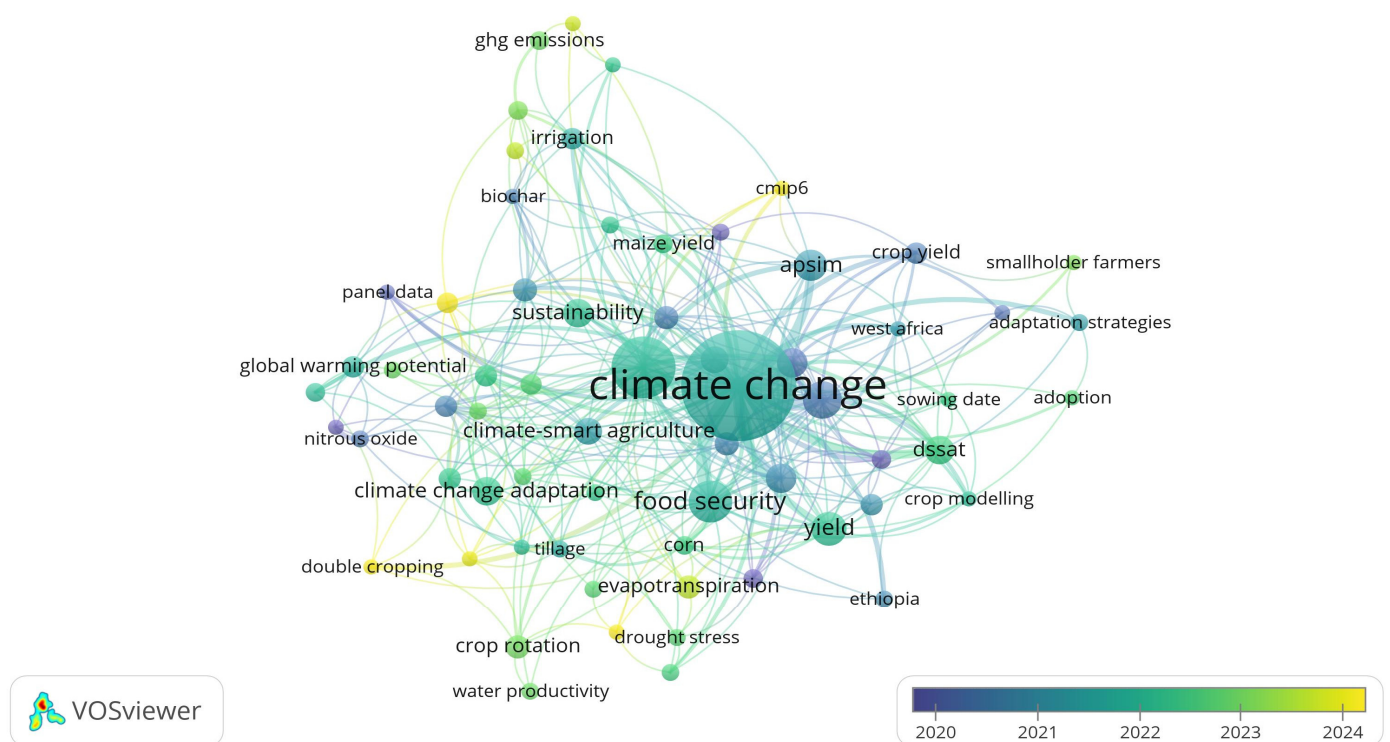


Figure 4. Co-occurrence network of Author Keywords (2015–2025) visualised using the VOSviewer overlay network.

In the Author Keyword network, climate change was the most frequently occurring term (132 occurrences; total link strength [TLS] = 180), followed by maize (50; 79), food security (27; 42), and adaptation (22; 47) (Table 1). Other frequently occurring terms included yield (19; 27), drought (15; 28), agriculture (15; 26), climate-smart agriculture (13; 18), heat stress (10; 19), and climate change mitigation (9; 19). These author-selected terms indicate that researchers explicitly framed their studies around climate impacts on

maize production, adaptation, food security, productivity, and sustainable agricultural practices [61].

Table 1. Top 10 Author Keywords by occurrence and total link strength in the maize–climate change literature. Source: WoS (2015–2025).

Keywords	Occurrence	Total Link Strength (TLS)
Climate change	132	180
Maize	50	79
Adaptation	22	47
Food security	27	42
Drought	15	28
Yield	19	27
Agriculture	15	26
Climate change Mitigation	9	19
Heat Stress	10	19
Climate-smart agriculture	13	18

Source: Web of Science (2015–2025). Author Keywords are terms supplied directly by the article authors.

The temporal overlay further indicates a shift in research priorities. Earlier studies were more strongly associated with crop models, APSIM, CMIP6, crop yield, and drought, reflecting an emphasis on climate-impact assessment, modelling, and adaptation. More recent studies show greater association with double cropping, carbon footprint, nitrous oxide, greenhouse gas emissions, and water productivity, suggesting increasing attention to sustainable intensification, resource-use efficiency, and climate mitigation [62].

Figure 5 and Table 2 show that the Keywords Plus network of maize research during 2015–2025 is dominated by maize, yield, and climate change. Maize and yield had the highest occurrence frequencies (105 each), followed by climate change (100), management (68), agriculture (59), and productivity (55). These three leading terms also had the highest total link strengths: maize (568), yield (544), and climate change (541), indicating strong connections with other concepts in the research network. In Figure 5, node colour represents the average publication year of each keyword, with purple and blue indicating earlier research themes and yellow indicating more recent ones. Keywords such as *Africa*, *smallholder farmers*, *conservation agriculture*, *soil fertility* and *N₂O* appear in purple and blue, showing that they were more prominent earlier in the period. Terms such as *management*, *irrigation*, *stress*, *quality*, *system* and *economic impacts* appear in yellow-green, indicating a more recent shift toward water and stress management, system-level analysis, and economic assessment. The dominant terms *maize*, *yield* and *climate change* sit in the green-blue middle of the scale, meaning they were central throughout the study period.

The network also highlights temperature, drought, adaptation, growth, and water-use efficiency, reflecting increasing research attention to climate-related effects on maize growth and yield [52,62,63] and to adaptive management strategies for maintaining productivity [63]. Unlike author keywords, keywords plus are generated from terms in the titles of cited references and therefore capture broader citation-based conceptual connections.

Overall, the results indicate that maize yield responses to climate change remain the dominant research focus, while increasing attention to adaptation, resource-use efficiency, and management suggests a broader shift toward improving the resilience and sustainability of maize production systems.

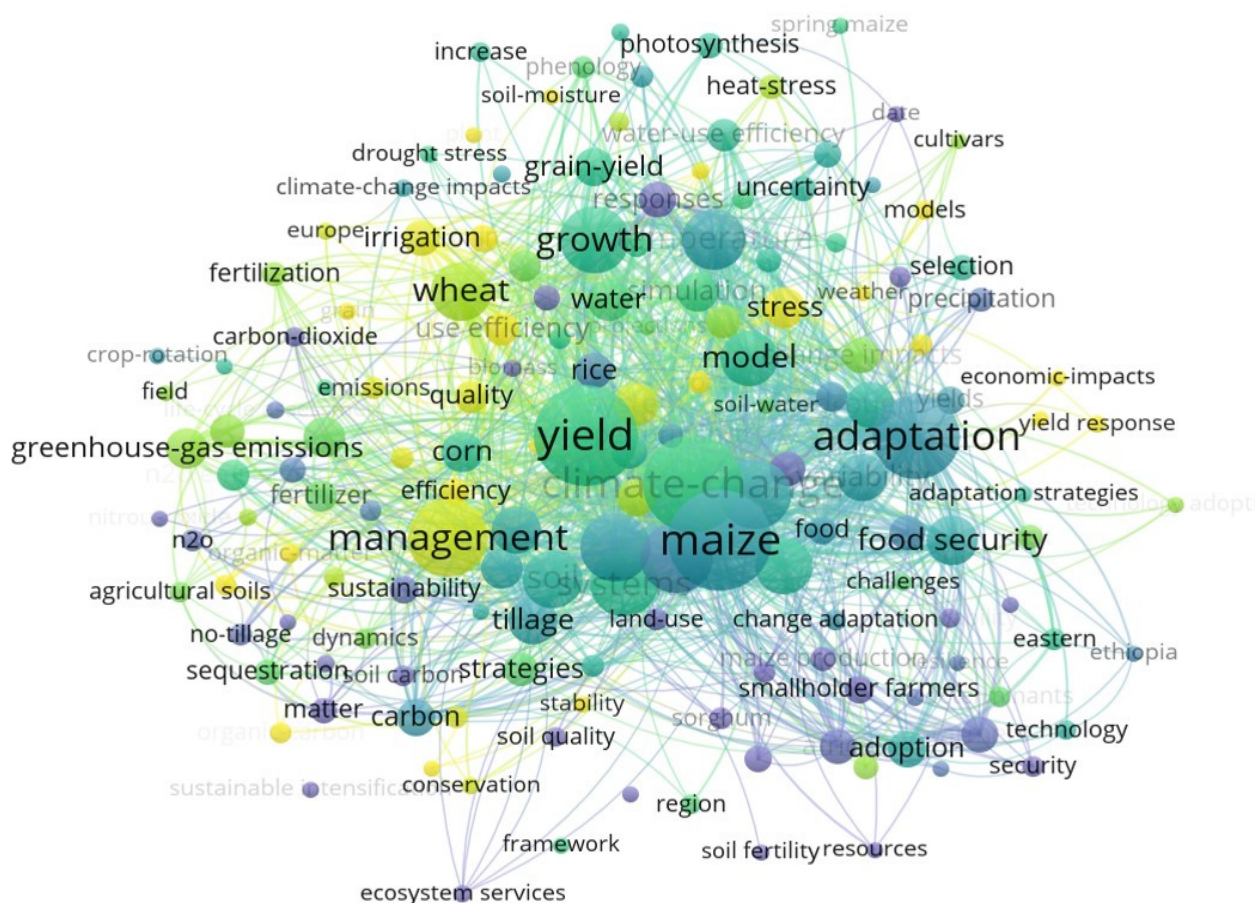


Figure 5. Co-occurrence network of Keywords Plus (2015–2025) visualised using the VOSviewer overlay network.

Table 2. Top 10 Keywords Plus by occurrence and total link strength in the maize–climate change literature. Source: WoS (2015–2025).

Keyword	Occurrence	Total Link Strength (TLS)
Maize	105	568
yield	105	544
Climate change	100	541
Management	68	366
Agriculture	59	333
Productivity	55	322
Impact	57	312
Growth	54	291
Temperature	46	257
Food security	33	179

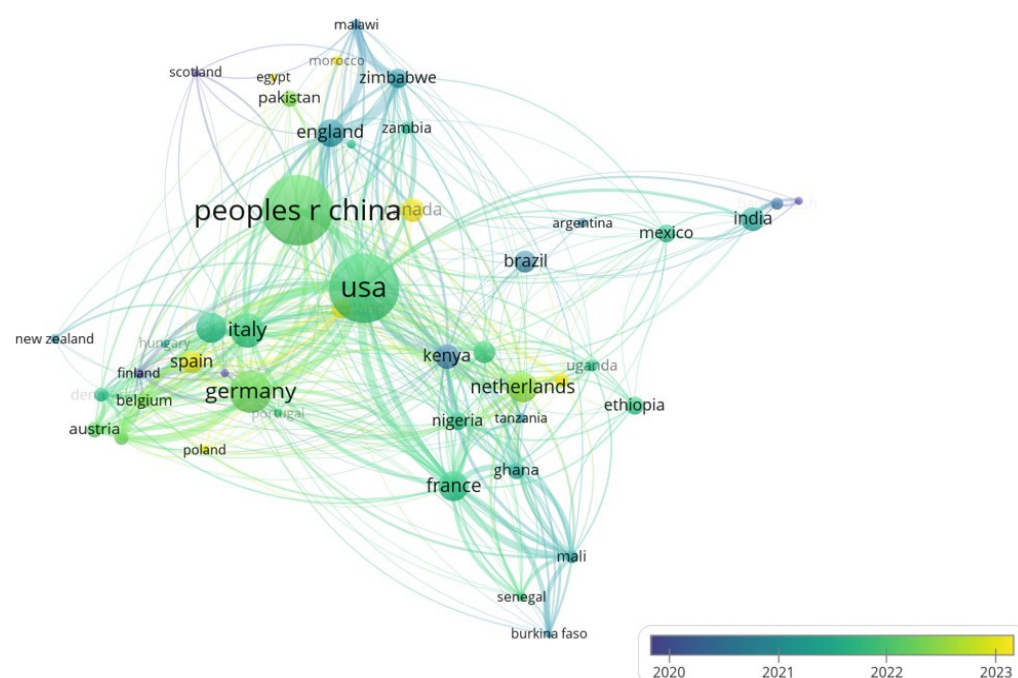
Source: Web of Science (2015–2025). Keywords Plus are generated by Web of Science from terms appearing in the titles of cited references.

Table 3 indicates that the USA and China are the foremost contributors to the research domain in terms of both publication volume and citation impact. China leads in publication productivity with 110 articles, marginally surpassing the USA's 108 publications. Nonetheless, the USA attains the highest citation count, totalling 2721 citations, reflecting a greater overall scientific influence despite its slightly lower publication output.

Table 3. Top 10 Most Productive Countries Based on Number of Publications and Citations. Source: WoS (2015–2025).

Rank	Country	Number of Publications	Citation
1	USA	108	2721
2	China	110	2566
3	India	23	1260
4	Germany	53	1143
5	England	29	1013
6	Italy	40	994
7	France	33	937
8	Australia	33	878
9	Nigeria	16	812
10	Spain	21	714

The international collaboration network depicted in Figure 6 corroborates the dominant roles of the USA and China as central nodes in global research cooperation. The USA occupies a pivotal position within the network, fostering extensive collaborative ties with several European nations, including Germany, Italy, Spain, Belgium, Austria, Portugal, and Poland. These partnerships align with the robust research output and citation impact of Germany (53 publications; 1143 citations) and Italy (40 publications; 994 citations) as reported in Table 3.

**Figure 6.** Country Collaboration Network and Research Productivity Analysis Based on Publications and Citations. Source: WoS (2015–2025).

Similarly, China anchors a distinct major collaboration cluster, maintaining strong research linkages with countries such as England, Canada, Pakistan, Egypt, and Morocco. Despite England's relatively modest publication count of 29, it has accrued 1013 citations, signifying notable research impact.

The collaboration network further reveals a discrete cluster centred on France and the Netherlands, which connects multiple African countries including Nigeria, Kenya, Uganda, Ethiopia, Ghana, Mali, and Senegal. Nigeria, with 16 publications, has garnered 812 citations, indicating substantial scholarly influence relative to its research output.

Additionally, India forms a regional collaboration cluster with Bangladesh, Mexico, and Argentina. Although India's publication count stands at 23, it has achieved 1260 citations, surpassing the citation impact of several countries with higher publication volumes. This underscores the significant scientific contribution and citation visibility of Indian research.

Collectively, the publication metrics (Table 3) and the international collaboration patterns (Figure 6) demonstrate the pre-eminence of the USA and China in both research productivity and global partnerships. Moreover, countries such as India and Nigeria exhibit high citation impact relative to their publication output, highlighting the critical role of international collaborations in amplifying research visibility and scientific influence.

The data suggest that while larger economies lead in absolute research production, countries like India and Nigeria are producing highly influential work that attracts a disproportionately high number of citations per paper.

3.3. Climate Change-Driven Abiotic Stress Factors Influencing Maize Productivity

Climate change poses a critical challenge to global agriculture by shifting temperature and precipitation regimes, degrading soil, and reducing water availability. These alterations increase the frequency of droughts and floods, thereby threatening maize productivity and global food security [37,64–66]. Elevated atmospheric CO₂ and greenhouse gas concentrations have accelerated global warming and extreme climatic events. Projections indicate temperature increases of 2.6–4.8 °C in major production zones by the late 21st century, posing severe risks to agricultural sustainability [55,67,68].

Heat stress is a primary constraint on maize, particularly during sensitive reproductive stages where rising temperatures and frequent heatwaves impair development [69]. While maize tolerates 8–34 °C during vegetative growth, exceeding 30 °C during tasselling and silking shortens reproductive duration, disrupts pollination, and reduces kernel set [70–73]. Long-term simulation studies have projected yield declines of 44–75% under severe-warming conditions; however, these estimates are scenario- and region-specific and should not be directly compared with empirical estimates obtained under current climatic conditions [74] (Table 4). Empirical data confirm negative correlations between productivity and accumulated heat stress [75], which reduces chlorophyll, leaf area, and biomass [76]. Adaptive measures like those that delayed planting must balance heat avoidance against increased frost risks in cooler regions [15].

Table 4. Reported maize yield-loss estimates under different warming conditions, regions, and modelling approaches.

Yield-Loss Estimate	Warming/Scenario	Region or Production Context	Crop/Model/Method	Source
12–28%	End-of-century climate projection; adaptation considered	China, Global	APSIM maize crop model, Linear mixed-effects models	[15,16]
7.4% per 1 °C increase	Temperature-response estimate	Global	Multi-method synthesis	[9,27]
44–75%	Severe-warming scenario	U.S.	Nonlinear temperature–yield model	[74]
25–30%	Severe drought or water-deficit conditions	U.S.	Multiple linear regression	[30]
Approximately 30% by the 2080s	Future climate projection; insert scenario	Global	EPIC model	[52]

Across the reviewed studies, there is strong agreement that increasing temperature is a major threat to maize productivity, particularly when heat occurs during tasseling and silking. However, the magnitude of yield loss varies considerably among studies because it depends on the timing, duration, and intensity of heat exposure, as well as cultivar characteristics, soil conditions, and management practices. Simulation studies generally project larger yield reductions under severe warming scenarios than empirical studies conducted under current climatic conditions, indicating that projected losses should be interpreted as scenario-dependent rather than as fixed estimates [69–76]. Thus, the evidence is strong regarding the direction of the heat-stress effect, but the magnitude of the response remains context-specific.

Water scarcity and drought further limit maize production, especially in rain-fed systems where altered rainfall patterns reduce potential yields [62,77]. Smallholder farmers, reliant on precipitation and lacking irrigation infrastructure, are particularly vulnerable [45,78,79]. Drought during critical growth stages impairs grain filling and biomass accumulation [49,56,80], a trend expected to intensify under future scenarios [81,82]. Moisture deficits restrict photosynthesis by limiting leaf expansion and inducing stomatal closure [83,84], necessitating improved water-use efficiency to maintain productivity [85].

Evidence for drought-related yield losses is similarly consistent, but the severity of the response differs among production environments. Rain-fed and smallholder systems generally show greater vulnerability because limited irrigation capacity reduces the ability to buffer rainfall deficits [45,62,77–82]. Physiological evidence provides strong support for the mechanisms through which drought reduces leaf expansion, stomatal conductance, photosynthesis, biomass accumulation, and grain filling [56,80,83,84]. Nevertheless, the magnitude of yield reduction depends on drought timing, soil water-holding capacity, cultivar characteristics, and management. Therefore, drought should not be interpreted as producing a uniform yield penalty across maize-growing environments.

Climate change also accelerates soil degradation; rising temperatures increase evaporation and carbon loss, while extreme rain promotes erosion and nutrient depletion [86]. These processes undermine soil fertility and systemic resilience [54,87,88]. Vulnerability is exacerbated in nutrient-poor or inadequately fertilised systems where nutrient depletion and acidification reduce soil quality [89,90]. Paradoxically, agriculture contributes significantly to climate change, accounting for approximately 66% of anthropogenic N₂O emissions, which facilitates global warming while reducing nitrogen-use efficiency [91–94].

Compared with heat and drought, the evidence linking climate change directly to soil degradation and subsequent maize yield losses is more indirect and strongly dependent on local soil and management conditions. The literature consistently indicates that warming, intensified rainfall, erosion, carbon loss, nutrient depletion, and declining soil quality can progressively reduce the capacity of soils to sustain maize production [54,86–90]. However, these processes generally operate over longer timescales and interact with soil type, organic matter management, fertilisation, and land use, making their individual contribution to yield loss more difficult to isolate. Consequently, heat and drought have relatively well-established direct physiological effects, whereas soil degradation represents a cumulative pathway through which climate change can progressively reduce production-system resilience.

Importantly, these abiotic stresses should not be considered independently. Heat and drought may occur simultaneously, with water deficits potentially increasing crop sensitivity to high temperatures, while degraded soils can further reduce water and nutrient availability. The combined occurrence of these stresses may therefore produce greater yield instability than would be predicted from individual stressors considered separately.

Collectively, extreme heat, drought, and soil degradation represent the primary abiotic constraints on maize under shifting climates. One future-climate assessment projected maize yield reductions of approximately 30% by the 2080s without effective adaptation [52]. Because this projection is associated with a specific scenario, region, baseline period, and modelling framework, it should be interpreted as a context-specific estimate rather than a universal global value [52]. Developing resilient production systems requires a thorough understanding of the physiological and environmental mechanisms underlying these stresses to ensure future food security.

The estimates summarised in Table 4 are not contradictory; they represent different climatic, geographical, temporal, and methodological conditions. Regional differences in baseline temperature, precipitation, drought frequency, soil water-holding capacity, and management practices influence maize sensitivity to climate stress. In addition, heat and drought occurring during reproductive stages may cause greater losses than similar stresses occurring during less sensitive growth stages. Therefore, yield-loss estimates from empirical observations, statistical models, and process-based simulations should be interpreted within their respective contexts rather than combined as a single universal estimate.

Overall, the reviewed evidence demonstrates substantial agreement that climate change affects maize productivity through multiple interacting abiotic stresses rather than through a single climatic factor. However, the magnitude of impacts varies among environments because genotype, soil properties, water availability, management practices, and the timing and intensity of climatic stress modify maize vulnerability. This distinction is important for interpreting future projections and for designing adaptation strategies that are appropriate to specific production contexts.

3.4. Integrated Climate Change Adaptation Strategies

Adapting cropping systems is vital to mitigate climate change impacts, with irrigation and water management serving as primary adaptation pillars [58,59]. Effective strategies, including new crop varieties resistant to pests, diseases, and environmental stresses (heat, drought, salinity), as well as crop rotation and row planting, help maintain production reliability [95–98]. Shorter growing cycles, precision agriculture, and efficient water management are also critical, alongside broader technological innovations [62]. Most long-term assessments of maize vulnerability rely on simulations projecting significant yield reductions due to heat affecting physiological processes [27]. Despite the IPCC highlighting the importance of adaptation, research often focuses more on impact assessment than on simulating adaptation measures such as breeding new cultivars, optimising soil nutrient management, adjusting sowing dates, and implementing conservation tillage [63,99,100]. Crop rotation improves soil quality and microbial diversity, while legumes further mitigate climate effects [101].

The effectiveness of these adaptation strategies is not uniform across environments because different interventions address different components of climate vulnerability. Adjusting sowing dates and deploying heat- or drought-tolerant cultivars primarily reduce crop exposure or sensitivity to climatic stress, whereas irrigation directly buffers water deficits and is therefore particularly effective where adequate water resources and infrastructure are available [58,59,102,103]. In contrast, conservation agriculture, crop rotation, residue retention, and organic amendments primarily improve soil water retention, nutrient cycling, and soil structure, providing broader but often slower improvements in system resilience [101,104–106].

Crop growth models serve as quantitative laboratories to evaluate genetics, management, and environmental conditions [54,107]. DSSAT-CERES-Maize is widely applied to project climate impacts and evaluate strategies, including fertiliser optimisation [36,108–113]. Addi-

tionally, the MaxEnt model assesses crop suitability, while optimised sowing dates mitigate yield losses [3,114]. Local calibration of the CERES-Maize model remains necessary for accurate phenology and yield assessments [43,50,115–117].

The reviewed modelling approaches differ in their objectives and applicability. DSSAT-CERES-Maize and APSIM are process-based crop models that simulate interactions among climate, soil, genotype, and management, making them suitable for assessing yield responses to sowing dates, irrigation, fertilisation, and cultivar traits [36,54,107–117]. However, both require appropriate parameterisation and local calibration, particularly for phenology, soil water dynamics, and yield formation.

In contrast, MaxEnt focuses on environmental suitability rather than physiological crop responses, making it more suitable for assessing potential shifts in maize-suitable areas under future climates [3,114]. Thus, DSSAT-CERES-Maize and APSIM are better suited to management-specific yield assessment, whereas MaxEnt is more appropriate for spatial suitability analysis. These models are therefore complementary, and their reliability depends on appropriate calibration, validation, and context-specific application.

To address water scarcity, drip and subsurface irrigation enhance productivity by reducing evaporation and runoff [118–123]. Adopting weather-resistant varieties and appropriate sowing dates significantly influences yield potential [102,103], offering local benefits that complement global emission reduction efforts [124,125]. Conservation agriculture (CA) and climate-smart agriculture (CSA) sustainably increase resilience through drought-tolerant germplasm and intercropping [46,104–106,126]. Genetically engineered (GE) varieties and optimised fertilisation further support yield resilience and soil health under climate variability [58,127–130]. Overall, irrigation and improved heat tolerance are critical for mitigation [130–133].

The evidence suggests that adaptation measures are complementary rather than substitutable. Irrigation reduces water stress, improved cultivars increase heat and drought tolerance, and soil-health practices strengthen long-term resilience [58,59,101,102,104–106,130,132,133]. However, their effectiveness depends on local water availability, soil conditions, infrastructure, resources, and access to technology [45,58,59,78,124,125].

Overall, an integrated approach is more appropriate than relying on a single intervention. Evidence is strongest for practices with well-established mechanisms, such as irrigation and stress-tolerant cultivars, while broader system-level benefits remain more context-dependent [58,59,95–98,104–106,131].

The evidence reviewed in this section supports the second component of the working hypothesis, which proposes that the impacts of climate change can be reduced through appropriate adaptation strategies. However, the evidence indicates that adaptation effectiveness depends on the interaction between intervention, environment, and production system [58,59,101–106]. Therefore, adaptation strategies should be selected according to local climate risks and resource constraints, while crop modelling can provide a useful framework for comparing alternative management combinations under current and projected climate conditions [36,54,107–117].

3.5. Resilience Pathways for Sustainable Maize Production

Implementing climate-smart practices and policy interventions is critical for mitigating risks from shifting maize suitability zones and ensuring regional economic stability [3]. Crop yield remains the primary measure of agricultural sustainability [89]. Enhancing soil health through soil organic matter (SOM) accumulation is a key resilience mechanism, fostering biodiversity and nutrient reservoirs [60,134]. SOM improves structural stability and reduces erosion, promoting sustainable production [61,135], while organic amendments sustain long-term productivity. Integrated nutrient management, specifically NPK

fertilisers combined with organic manure (NPKM), improves yield sustainability more effectively than mineral fertilisers alone [89,136].

The evidence indicates that soil-health interventions contribute to resilience through mechanisms that differ from those of short-term climate adaptation. Whereas irrigation or altered sowing dates can directly reduce exposure to immediate climatic stress, SOM accumulation, organic amendments, and integrated nutrient management improve soils' underlying capacity to retain water and nutrients and sustain productivity over time [60,61,89,134–136]. Their benefits may therefore become more apparent over repeated growing seasons rather than through immediate yield responses.

Agronomic practices, such as delaying sowing or selecting open-pollinated cultivars, effectively mitigate heat stress [54]. Conservation Agriculture (CA) reverses land degradation, improves water conservation, and bolsters drought resilience [137–140]. CA systems, strengthened by crop diversification and residue retention, offer higher economic viability than conventional tillage [141–143]. Diversified systems, including double cropping, further enhance land-use efficiency [67]. Technological advancements in irrigation and plant breeding for drought tolerance also augment resilience [65,144], with drought-tolerant hybrids effectively mitigating impacts for smallholders [145]. Integrating agroforestry into maize systems enhances yields and delivers ecosystem services such as erosion control, biodiversity, and carbon sequestration.

However, the literature also indicates important trade-offs and applicability limits. Irrigation can provide strong protection against rainfall variability but is less feasible where water resources or infrastructure is limited. Drought-tolerant cultivars may be more suitable for water-limited smallholder systems, but their benefits depend on seed availability, genotype–environment interactions, and appropriate agronomic management [65,144,145]. Similarly, conservation agriculture and diversification can improve soil and water conservation, but their performance may vary with soil type, rainfall regime, residue availability, labour requirements, and farm resources [137–143]. Agroforestry provides additional ecosystem services but may involve competition for light, water, and land depending on system design and environmental conditions [146].

Policy frameworks are essential to facilitate these strategies, promoting drought-tolerant varieties, soil conservation, and conservation tillage [147]. Investments in fertilisation and delayed planting significantly enhance the adaptive capacity of low-input communities [148]. Sustainable maize production necessitates integrating soil health, optimised management, genetic resilience, and robust policy support to advance food security [149,150].

The evidence suggests that resilience depends on the combined capacity of production systems to withstand climatic shocks, maintain productivity, and recover from adverse conditions. No single intervention provides all these functions; genetic improvement, water management, soil-health practices, diversification, and policy support address different dimensions of resilience [60,65,89,134–150].

Evidence for individual interventions is generally stronger when their mechanisms are direct and measurable, whereas long-term system resilience is more context-dependent because outcomes depend on interactions among climate, soil, management, and socio-economic conditions. Thus, resilience strategies should focus on combinations of practices suited to specific production environments.

Overall, Sections 3.3–3.5 show that climate change affects maize through interacting abiotic stresses, while adaptation requires complementary interventions. Heat and drought have well-established physiological effects, whereas soil degradation represents a longer-term pathway. Similarly, DSSAT-CERES-Maize and APSIM are suited to assessing yield and management responses, while MaxEnt is more appropriate for spatial climate-suitability

assessment [3,36,54,107–117]. Appropriate model calibration and validation are therefore essential for reliable projections.

Overall, the findings support the working hypothesis that climate-related stresses constrain maize productivity and that their impacts can be reduced through integrated, context-specific adaptation strategies.

4. Discussion

Climate change poses a major challenge to sustainable maize production because rising temperatures, changing precipitation, drought, and water scarcity can occur simultaneously and reduce crop growth and yield. The literature reviewed indicates that these stresses can interact and intensify yield losses [66,69,74]. Therefore, maize adaptation should consider multiple stresses together rather than addressing them independently. This integrated approach is important for improving productivity and long-term resilience.

Heat stress, drought, water scarcity, and soil degradation are particularly important in climate-vulnerable maize-growing regions. The effectiveness of individual adaptation measures may be limited when farmers face several constraints simultaneously. Stress-tolerant varieties, for example, may perform differently depending on water availability, soil fertility, and planting time. Thus, resilience should consider yield, water-use efficiency, soil health, nutrient management, and production sustainability.

Key adaptation strategies include stress-tolerant varieties [95–98], suitable planting dates, efficient irrigation, improved nutrient management, soil conservation, and climate-smart practices [62,63,99,100]. Combining complementary practices may provide more stable benefits than relying on a single measure under multiple stresses. Conservation practices can also improve soil moisture retention and soil conditions [141]. However, their effectiveness depends on local climatic, soil, and socioeconomic conditions.

Crop modelling can help assess climate impacts and evaluate adaptation strategies under different environmental conditions. Models can support decisions on planting dates, water management, and crop responses to temperature and drought. However, reliable results require local calibration and validation using field observations. Combining modelling with field experiments can therefore improve the development of locally appropriate adaptation strategies.

Important research gaps remain regarding the long-term effectiveness of integrated adaptation strategies and interactions among multiple stresses. Adoption is also influenced by costs, access to technology and irrigation, farmer knowledge, and institutional support. These factors are particularly important in climate-vulnerable regions with limited resources. Future research should therefore integrate climate science, agronomy, modelling, and socioeconomic analysis.

Emerging technologies such as remote sensing, artificial intelligence, and machine learning can support site-specific monitoring and management of climate risks. Their effectiveness, however, depends on reliable data, validation, and accessibility. Overall, improving maize resilience requires an integrated combination of stress-tolerant varieties, improved water and soil management, appropriate agronomic practices, and locally suitable technologies.

5. Conclusions

Climate change poses increasing risks to sustainable maize production through rising temperatures, changing precipitation patterns, drought, water scarcity, soil degradation, and extreme weather events, with potential consequences for productivity and global food security. The bibliometric analysis based on the 485-paper dataset revealed a significant increase in research on climate change and maize production during 2015–2025, with

increasing emphasis on climate impacts, adaptation, climate-smart agriculture, sustainable management, and food security.

The findings from the 85-paper dataset indicate that heat stress, drought, water scarcity, and soil degradation are important constraints to maize productivity. Building resilient production systems therefore requires integrated approaches combining climate-resilient varieties, optimised planting dates, efficient irrigation and nutrient management, conservation agriculture, and climate-smart practices. Crop modelling can further support the assessment of climate impacts and adaptation options under future climate scenarios.

Based on the evidence synthesised from the 85-paper dataset, the findings support the working hypothesis that integrated genetic, agronomic, technological, and management interventions can strengthen maize resilience under climate change. In contrast, the 485-paper bibliometric dataset provides evidence of the development and structure of the research field, including major research themes, emerging priorities, publication trends, and collaboration patterns.

Future research should focus on interacting climate stresses, improved crop modelling and field validation, digital and AI-based technologies, and the economic and social feasibility of integrated adaptation strategies, particularly in climate-vulnerable regions. Strengthening international collaboration and investment will be important for supporting sustainable maize production and long-term food security.

Author Contributions: M.M.A.O. and R.K. conducted the literature search, performed data analysis, and drafted the initial manuscript. M.M.A.O.: formal analysis. R.K.: investigation and writing—review and editing. E.W.: writing—review and editing. A.T.: writing—review and editing. Á.I., and A.S.: writing—review and editing. T.R.: conceptualisation, supervision, and writing—review and editing. M.M.A.O. was responsible for conceptualisation and methodology development. All authors have read and agreed to the published version of the manuscript.

Funding: This study is part of Project no. TKP2021-NKTA-32 Vízvel kapcsolatos kutatások, implemented at the University of Debrecen Institute of Land Use, Engineering and Precision Farming Technology with support from the Ministry of Culture and Innovation of Hungary from the National Research, Development and Innovation Fund, financed under the TKP2021-NKTA funding scheme. The János Bolyai Research Scholarship of the Hungarian Academy of Sciences (BO/00068/23/4) provided additional support.

Data Availability Statement: The data presented in this study are available in the article.

Acknowledgments: During the preparation of this manuscript, the authors used AI-assisted tools solely for language editing, including grammar, spelling, punctuation, and improving the clarity and readability of the text. The authors reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

DSSAT	Decision Support System for Agro-technology Transfer
CERES	Crop-Environment Resource Synthesis
APSIM	Agricultural Production Systems sIMulator
CO ₂	Carbon Dioxide
CROPGRO	Crop Growth
GCMs	General Circulation Models
RCPs	Representative Concentration Pathways
WOS	Web of Science
CMIP6	Coupled Model Intercomparison Project Phase 6

SDG	Sustainable Development Goal
IPCC	Intergovernmental Panel on Climate Change
CA	Conservation Agriculture
CSA	Climate-Smart Agriculture
GE	Genetically Engineered
SOM	Soil Organic Matter
NPK	Nitrogen, Phosphorus, Potassium
NPKM	Nitrogen, Phosphorus, Potassium, Manure
AI	Artificial Intelligence

References

1. Wilson, A.B.; Avila-Diaz, A.; Oliveira, L.F.; Zuluaga, C.F.; Mark, B. Climate extremes and their impacts on agriculture across the Eastern Corn Belt Region of the U.S. *Weather Clim. Extrem.* **2022**, *37*, 100467. [\[CrossRef\]](#)
2. Waongo, M.; Laux, Kunstmann, H. Adaptation to climate change: The impacts of optimized planting dates on attainable maize yields under rainfed conditions in Burkina Faso. *Agric. For. Meteorol.* **2015**, *205*, 23–39. [\[CrossRef\]](#)
3. Tikuye, B.G.; Ray, R.L. Predicting future corn suitability zones under climate change scenarios in the United States of America. *J. Agric. Food Res.* **2025**, *22*, 102129. [\[CrossRef\]](#)
4. Jägermeyr, J.; Müller, C.; Ruane, A.C.; Elliott, J.; Balkovic, J.; Castillo, O.; Faye, B.; Foster, I.; Folberth, C.; Franke, J.A.; et al. Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nat. Food* **2021**, *2*, 873–885. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Duncan, J.M.A.; Dash, J.; Atkinson, P.M. Elucidating the impact of temperature variability and extremes on cereal croplands through remote sensing. *Glob. Change Biol.* **2015**, *21*, 1541–1551. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Ankrah, D.; Okyere, C.; Mensah, J.; Okata, E. Effect of climate variability adaptation strategies on maize yield in the Cape Coast Municipality, Ghana. *Cogent Food Agric.* **2023**, *9*, 2247166. [\[CrossRef\]](#)
7. Freduah, B.S.; MacCarthy, D.S.; Adam, M.; Ly, M.; Ruane, A.C.; Timpong-Jones, E.C.; Traore, P.S.; Boote, K.J.; Porter, C.; Adiku, S.G.K. Sensitivity of Maize Yield in Smallholder Systems to Climate Scenarios in Semi-Arid Regions of West Africa: Accounting for Variability in Farm Management Practices. *Agronomy* **2019**, *9*, 639. [\[CrossRef\]](#)
8. Kim, K.-H.; Lee, B.-M. Effects of Climate Change and Drought Tolerance on Maize Growth. *Plants* **2023**, *12*, 3548. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Zai, F.H.; McSharry, E.; Hamers, H. Impact of climate change and genetic development on Iowa corn yield. *Front. Agron.* **2024**, *6*. [\[CrossRef\]](#)
10. Ignaciuk, A.; Mason-D'Croz, D. Modelling Adaptation to Climate Change in Agriculture. OECD Food, Agriculture and Fisheries Papers 2014. Available online: https://www.oecd.org/en/publications/modelling-adaptation-to-climate-change-in-agriculture_5jxrclljnbxq-en.html (accessed on 16 July 2026).
11. Nuss, E.T.; Tanumihardjo, S.A. Quality Protein Maize for Africa: Closing the Protein Inadequacy Gap in Vulnerable Populations. *Adv. Nutr.* **2011**, *2*, 217–224. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Du, S.; Xiong, W. Weather Extremes Shock Maize Production: Current Approaches and Future Research Directions in Africa. *Plants* **2024**, *13*, 1585. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Zhang, Z.; Wei, J.; Li, J.; Jia, Y.; Wang, W.; Li, J.; Lei, Z.; Gao, M. The impact of climate change on maize production: Empirical findings and implications for sustainable agricultural development. *Front. Environ. Sci.* **2022**, *10*, 954940. [\[CrossRef\]](#)
14. Wang, S.; Sun, N.; Zhang, X.; Hu, C.; Wang, Y.; Xiong, W.; Zhang, S.; Colinet, G.; Xu, M.; Wu, L. Assessing the impacts of climate change on crop yields, soil organic carbon sequestration and N₂O emissions in wheat–maize rotation systems. *Soil Tillage Res.* **2024**, *240*, 106088. [\[CrossRef\]](#)
15. Han, X.; Dong, L.; Cao, Y.; Lyu, Y.; Shao, X.; Wang, Y.; Wang, L. Adaptation to Climate Change Effects by Cultivar and Sowing Date Selection for Maize in the Northeast China Plain. *Agronomy* **2022**, *12*, 984. [\[CrossRef\]](#)
16. Tran, B.-L.; Tseng, W.-C.; Chen, C.-C. Climate change impacts on crop yields across temperature rise thresholds and climate zones. *Sci. Rep.* **2025**, *15*, 23424. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Ummenhofer, C.C.; Xu, H.; Twine, T.E.; Girvetz, E.H.; McCarthy, H.R.; Chhetri, N.; Nicholas, K.A. How Climate Change Affects Extremes in Maize and Wheat Yield in Two Cropping Regions. *J. Clim.* **2015**, *28*, 4653–4687. [\[CrossRef\]](#)
18. Tao, F.; Zhang, Z.; Zhang, S.; Rötter, R.P.; Shi, W.; Xiao, D.; Liu, Y.; Wang, M.; Liu, F.; Zhang, H. Historical data provide new insights into response and adaptation of maize production systems to climate change/variability in China. *Field Crops Res.* **2016**, *185*, 1–11. [\[CrossRef\]](#)
19. Lobell, D.B.; Tebaldi, C. Getting caught with our plants down: The risks of a global crop yield slowdown from climate trends in the next two decades. *Environ. Res. Lett.* **2014**, *9*, 074003. [\[CrossRef\]](#)

20. Butler, E.E.; Huybers, P. Variations in the sensitivity of US maize yield to extreme temperatures by region and growth phase. *Environ. Res. Lett.* **2015**, *10*, 034009. [[CrossRef](#)]
21. Crafts-Brandner, S.J.; Salvucci, M.E. Sensitivity of photosynthesis in a C4 plant, maize, to heat stress. *Plant Physiol.* **2002**, *129*, 1773–1780. [[CrossRef](#)] [[PubMed](#)]
22. Lobell, D.B.; Hammer, G.L.; McLean, G.; Messina, C.; Roberts, M.J.; Schlenker, W. The critical role of extreme heat for maize production in the United States. *Nat. Clim. Change* **2013**, *3*, 497–501. [[CrossRef](#)]
23. Edreira, J.R.; Carpici, E.B.; Sammarro, D.; Otegui, M.E. Heat stress effects around flowering on kernel set of temperate and tropical maize hybrids. *Field Crops Res.* **2011**, *123*, 62–73. [[CrossRef](#)]
24. Kumar, N.; Kumar, N.; Shukla, A.; Shankhdhar, S.C.; Shankhdhar, D. Impact of terminal heat stress on pollen viability and yield attributes of rice (*Oryza sativa* L.). *Cereal Res. Commun.* **2015**, *43*, 616–626. [[CrossRef](#)]
25. Xu, X.Y.; Shao, C.X.; Sun, Z.G.; Long, B.J.; Dong, W.L. Research progress on the effect of heat stress on physiological characteristics of maize at key growth stage and the yield. *J. Maize Sci.* **2021**, *29*, 81–88.
26. Teng, L.I.; Zhang, X.-P.; Qing, L.I.U.; Jin, L.I.U.; Peng, S.U.I. Yield penalty of maize (*Zea mays* L.) under heat stress in different growth stages: A review. *J. Integr. Agric.* **2022**, *21*, 2465–2476. [[CrossRef](#)]
27. Zhao, C.; Liu, B.; Piao, S.; Wang, X.; Lobell, D.B.; Huang, Y.; Huang, M.T.; Yao, Y.T.; Bassu, S.; Ciais, P.; et al. Temperature increase reduces global yields of major crops in four independent estimates. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 9326–9331. [[CrossRef](#)] [[PubMed](#)]
28. Fan, X.; Hu, X.; Ma, Y.; Pang, Y.; Sun, J.; Hou, P. Influence of high temperature and drought stress at jointing stage on crop physiological responses and growth in summer maize plants (*Zea mays* L.). *Front. Plant Physiol.* **2024**, *2*, 1331421. [[CrossRef](#)]
29. Hu, J.; Zhao, X.; Gu, L.; Liu, P.; Zhao, B.; Zhang, J.; Ren, B. The effects of high temperature, drought, and their combined stresses on the photosynthesis and senescence of summer maize. *Agric. Water Manag.* **2023**, *289*, 108525. [[CrossRef](#)]
30. Kimm, H.; Guan, K.; Gentine, P.; Wu, J.; Bernacchi, C.J.; Sulman, B.N.; Griffis, T.J.; Lin, C. Redefining droughts for the US Corn Belt: The dominant role of atmospheric vapor pressure deficit over soil moisture in regulating stomatal behavior of Maize and Soybean. *Agric. For. Meteorol.* **2020**, *287*, 107930. [[CrossRef](#)]
31. Liu, W.; Shao, G.; You, R.; Dong, F.; Hu, B.X. Peak structure of extreme precipitation to temperature varies across climate patterns: Insights into intensity and frequency. *Atmos. Res.* **2025**, *315*, 107871. [[CrossRef](#)]
32. Qiu, R.; Katul, G.G.; Zhang, L.; Qin, S.; Jiang, X. The Effects of Changing Environments, Abiotic Stresses, and Management Practices on Cropland Evapotranspiration: A Review. *Rev. Geophys.* **2025**, *63*, e2024RG000858. [[CrossRef](#)]
33. Liu, L.; Yao, S.; Zhang, H.; Muhammed, A.; Xu, J.; Li, R.; Zhang, D.; Zhang, S.; Yang, X. Soil nitrate nitrogen buffer capacity and environmentally safe nitrogen rate for winter wheat-summer maize cropping in Northern China. *Agric. Water Manag.* **2019**, *213*, 445–453. [[CrossRef](#)]
34. Winiwarter, W.; Höglund-Isaksson, L.; Klimont, Z.; Schöpp, W.; Amann, M. Technical opportunities to reduce global anthropogenic emissions of nitrous oxide. *Environ. Res. Lett.* **2018**, *13*, 014011. [[CrossRef](#)]
35. Schroder, J.L.; Zhang, H.; Girma, K.; Raun, W.R.; Penn, C.J.; Payton, M.E. Soil Acidification from Long-Term Use of Nitrogen Fertilizers on Winter Wheat. *Soil Sci. Soc. Am. J.* **2011**, *75*, 957–964. [[CrossRef](#)]
36. He, W.; Yang, J.Y.; Qian, B.; Drury, C.F.; Hoogenboom, G.; He, P.; Lapen, D.; Zhou, W. Climate change impacts on crop yield, soil water balance and nitrate leaching in the semiarid and humid regions of Canada. *PLoS ONE* **2018**, *13*, e0207370. [[CrossRef](#)] [[PubMed](#)]
37. Wu, J.; Zhang, J.; Ge, Z.-M.; Xing, L.-W.; Han, S.-Q.; Shen, C.; Kong, F.-T. Impact of climate change on maize yield in China from 1979 to 2016. *J. Integr. Agric.* **2021**, *20*, 289–299. [[CrossRef](#)]
38. Jones, J.W.; Antle, J.M.; Basso, B.; Boote, K.J.; Conant, R.T.; Foster, I.; Godfray, H.C.J.; Herrero, M.; Howitt, R.E.; Janssen, S.; et al. Brief history of agricultural systems modeling. *Agric. Syst.* **2017**, *155*, 240–254. [[CrossRef](#)] [[PubMed](#)]
39. Basso, B.; Dumont, B.; Maestrini, B.; Shcherbak, I.; Robertson, G.P.; Porter, J.R.; Smith, P.; Paustian, K.; Grace, P.R.; Asseng, S.; et al. Soil Organic Carbon and Nitrogen Feedbacks on Crop Yields under Climate Change. *Agric. Environ. Lett.* **2018**, *3*, 180026. [[CrossRef](#)]
40. Hasegawa, T.; Wakatsuki, H.; Ju, H.; Vyas, S.; Nelson, G.C.; Farrell, A.; Deryng, D.; Meza, F.; Makowski, D. A global dataset for the projected impacts of climate change on four major crops. *Sci. Data* **2022**, *9*, 58. [[CrossRef](#)] [[PubMed](#)]
41. Wang, Y.; Guo, S.S.; Guo, P. Crop-growth-based spatially-distributed optimization model for irrigation water resource management under uncertainties and future climate change. *J. Clean. Prod.* **2022**, *345*, 131182. [[CrossRef](#)]
42. Tonnang, H.E.; Sokame, B.M.; Abdel-Rahman, E.M.; Dubois, T. Measuring and modelling crop yield losses due to invasive insect pests under climate change. *Curr. Opin. Insect Sci.* **2022**, *50*, 100873. [[CrossRef](#)] [[PubMed](#)]
43. Quan, H.; Ding, D.; Wu, L.; Qiao, R.; Dong, Q.; Zhang, T.; Feng, H.; Wu, L.; Siddique, K.H. Future climate change impacts on mulched maize production in an arid irrigation area. *Agric. Water Manag.* **2022**, *266*, 107550. [[CrossRef](#)]
44. Mohammed, A.; Yimer, E.; Gessese, B.; Eleke, E. Predicting Maize (*Zea mays*) productivity under projected climate change with management options in Amhara region, Ethiopia. *Environ. Sustain. Indic.* **2022**, *15*, 100185. [[CrossRef](#)]

45. Phiri, M.; Martinsen, V.; Simusokwe, G.; Smebye, A.B.; Obia, A.; Shitumbanuma, V.; Selby, J.; Cornelissen, G.; Makate, C.; Mulder, J. Enhancing yields and climate resilience through conservation agriculture: Multi-year regional on-farm trials in Zambia. *Plant Soil* **2025**, *513*, 489–505. [\[CrossRef\]](#)
46. Thierfelder, C.; Rusinamhodzi, L.; Setimela; Walker, F.; Eash, N.S. Conservation agriculture and drought-tolerant germplasm: Reaping the benefits of climate-smart agriculture technologies in central Mozambique. *Renew. Agric. Food Syst.* **2016**, *31*, 414–428. [\[CrossRef\]](#)
47. Hernández, V.A.G.; Cruz, E.L.; Onofre, L.E.M.; Varela, A.S.; Espinosa, M.A.G.; García, F.Z. Maize (*Zea mays* L.) landraces classified by drought stress tolerance at the seedling stage. *Emir. J. Food Agric.* **2021**, *33*, 29. [\[CrossRef\]](#)
48. Van Eck, N.J.; Waltman, L. Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* **2010**, *84*, 523–538. [\[CrossRef\]](#) [\[PubMed\]](#)
49. Trambay, Y.; Koutroulis, A.; Samaniego, L.; Vicente-Serrano, S.M.; Volaire, F.; Boone, A.; Le Page, M.; Llasat, M.C.; Albergel, C.; Burak, S.; et al. Challenges for drought assessment in the Mediterranean region under future climate scenarios. *Earth-Sci. Rev.* **2020**, *210*, 103348. [\[CrossRef\]](#)
50. Chekole, F.C.; Ahmed, A.M. Future climate implication on maize (*Zea mays*) productivity with adaptive options at Harbu district, Ethiopia. *J. Agric. Food Res.* **2023**, *11*, 100480. [\[CrossRef\]](#)
51. Chen, S.; Chen, X.; Xu, J. Impacts of climate change on agriculture: Evidence from China. *J. Environ. Econ. Manag.* **2016**, *76*, 105–124. [\[CrossRef\]](#)
52. Xiong, W.; Skalský, R.; Porter, C.H.; Balkovič, J.; Jones, J.W.; Yang, D. Calibration-induced uncertainty of the EPIC model to estimate climate change impact on global maize yield. *J. Adv. Model. Earth Syst.* **2016**, *8*, 1358–1375. [\[CrossRef\]](#)
53. Adesete, A.A.; Olanubi, O.E.; Dauda, R.O. Climate change and food security in selected Sub-Saharan African Countries. *Environ. Dev. Sustain.* **2023**, *25*, 14623–14641. [\[CrossRef\]](#) [\[PubMed\]](#)
54. Casali, L.; Herrera, J.M.; Rubio, G. Modeling maize and soybean responses to climatic change and soil degradation in a region of South America. *Agron. J.* **2021**, *113*, 1381–1393. [\[CrossRef\]](#)
55. Pachauri, R.K.; Allen, M.R.; Barros, V.R.; Broome, J.; Cramer, W.; Christ, R.; Church, J.A.; Clarke, L.; Dahe, Q.; Dasgupta, P.; et al. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2014; Volume 151. Available online: <https://epic.awi.de/id/eprint/37530/> (accessed on 28 July 2026).
56. Bodner, G.; Nakhforoosh, A.; Kaul, H.P. Management of crop water under drought: A review. *Agron. Sustain. Dev.* **2015**, *35*, 401–442. [\[CrossRef\]](#)
57. Lee, S.; Ji, Y.; Moschini, G. Agricultural innovation and adaptation to climate change: Insights from US maize. *J. Agric. Appl. Econ. Assoc.* **2022**, *1*, 165–179. [\[CrossRef\]](#)
58. Delgado, J.A.; D'adamo, R.E.; Villacis, A.H.; Halvorson, A.D.; Stewart, C.E.; Alwang, J.; Del Grosso, S.J.; Manter, D.K.; Floyd, B.A. Climate change and its positive and negative impacts on irrigated corn yields in a region of Colorado (USA). *Crops* **2024**, *4*, 366–378. [\[CrossRef\]](#)
59. Delgado, J.A.; Groffman, P.M.; Nearing, M.A.; Goddard, T.; Reicosky, D.; Lal, R.; Kitchen, N.R.; Rice, C.W.; Towery, D.; Salon, P. Conservation practices to mitigate and adapt to climate change. *J. Soil Water Conserv.* **2011**, *66*, 6. [\[CrossRef\]](#)
60. Thierfelder, C.; Paterson, E.; Mwafulirwa, L.; Daniell, T.J.; E Cairns, J.; Mhlanga, B.; Baggs, E.M. Toward greater sustainability: How investing in soil health may enhance maize productivity in Southern Africa. *Renew. Agric. Food Syst.* **2022**, *37*, 166–177. [\[CrossRef\]](#)
61. Lehman, R.M.; Cambardella, C.A.; Stott, D.E.; Acosta-Martinez, V.; Manter, D.K.; Buyer, J.S.; Maul, J.E.; Smith, J.L.; Collins, H.P.; Halvorson, J.J.; et al. Understanding and Enhancing Soil Biological Health: The Solution for Reversing Soil Degradation. *Sustainability* **2015**, *7*, 988–1027. [\[CrossRef\]](#)
62. Zilberman, D.; Lipper, L.; McCarthy, N.; Gordon, B. Innovation in Response to Climate Change. In *Climate Smart Agriculture 52*; Lipper, L., McCarthy, N., Zilberman, D., Asfaw, S., Branca, G., Eds.; Natural Resource Management and Policy 52; Springer International Publishing: Cham, Switzerland, 2018; pp. 49–74. [\[CrossRef\]](#)
63. Yin, X.; Olesen, J.E.; Wang, M.; Kersebaum, K.-C.; Chen, H.; Baby, S.; Öztürk, I.; Chen, F. Adapting maize production to drought in the Northeast Farming Region of China. *Eur. J. Agron.* **2016**, *77*, 47–58. [\[CrossRef\]](#)
64. Rezaei, E.E.; Webber, H.; Asseng, S.; Boote, K.; Durand, J.L.; Ewert, F.; Martre, P.; MacCarthy, D.S. Climate change impacts on crop yields. *Nat. Rev. Earth Environ.* **2023**, *4*, 831–846. [\[CrossRef\]](#)
65. Su, Y.; Lauerwald, R.; Makowski, D.; Viovy, N.; Guilpart, N.; Zhu, P.; Gabrielle, B.; Ciais, P. Future warming increases the chance of success of maize-wheat double cropping in Europe. *Eur. J. Agron.* **2025**, *170*, 127723. [\[CrossRef\]](#)
66. Fu, Z.; Liu, Z.; Guo, S.; Zhang, Z.; Lu, X.; Gong, J.; Dong, M.; Yang, X. Impact assessment of heat stress during post-silking period of summer maize in the Huang-Huai-Hai Plain, China. *J. Agric. Sci.* **2023**, *161*, 318–327. [\[CrossRef\]](#)
67. Piao, S.; Ciais, P.; Huang, Y.; Shen, Z.H.; Peng, S.S.; Li, J.S.; Zhou, L.P.; Liu, H.Y.; Ma, Y.C.; Ding, Y.H.; et al. The impacts of climate change on water resources and agriculture in China. *Nature* **2010**, *467*, 43–51. [\[CrossRef\]](#) [\[PubMed\]](#)

68. Yang, X.; Menefee, D.; Cui, S.; Rajan, N. Assessing the impacts of projected climate changes on maize (*Zea mays*) productivity using crop models and climate scenario simulation. *Crop Pasture Sci.* **2021**, *72*, 969–984. [\[CrossRef\]](#)
69. Soares, D.; Paredes; Paço, T.A.; Rolim, J. Projected Bioclimatic Changes in Portugal: Assessing Maize Future Suitability. *Agronomy* **2025**, *15*, 592. [\[CrossRef\]](#)
70. Hatfield, J.L.; Dold, C. Climate Change Impacts on Corn Phenology and Productivity. In *Corn—Production and Human Health in Changing Climate*; IntechOpen: Rijeka, Croatia, 2018. [\[CrossRef\]](#)
71. Ko, J.; Ahuja, L.R.; Saseendran, S.A.; Green, T.R.; Ma, L.; Nielsen, D.C.; Walthall, C.L. Climate change impacts on dryland cropping systems in the Central Great Plains, USA. *Clim. Change* **2012**, *111*, 445–472. [\[CrossRef\]](#)
72. Hatfield, J.L.; Boote, K.J.; Kimball, B.A.; Ziska, L.H.; Izaurrealde, R.C.; Ort, D.; Thomson, A.M.; Wolfe, D. Climate Impacts on Agriculture: Implications for Crop Production. *Agron. J.* **2011**, *103*, 351–370. [\[CrossRef\]](#)
73. Olesen, J.E.; Bindi, M. Consequences of climate change for European agricultural productivity, land use and policy. *Eur. J. Agron.* **2002**, *16*, 239–262. [\[CrossRef\]](#)
74. Schlenker, W.; Roberts, M.J. Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 15594–15598. [\[CrossRef\]](#) [\[PubMed\]](#)
75. Petersen, L.K. Impact of Climate Change on Twenty-First Century Crop Yields in the U.S. *Climate* **2019**, *7*, 40. [\[CrossRef\]](#)
76. Chukwudi, U.P.; Kutu, F.R.; Mavengahama, S. Influence of Heat Stress, Variations in Soil Type, and Soil Amendment on the Growth of Three Drought-Tolerant Maize Varieties. *Agronomy* **2021**, *11*, 1485. [\[CrossRef\]](#)
77. Ureta, C.; González, E.J.; Espinosa, A.; Trueba, A.; Piñeyro-Nelson, A.; Álvarez-Buylla, E.R. Maize yield in Mexico under climate change. *Agric. Syst.* **2020**, *177*, 102697. [\[CrossRef\]](#)
78. Makate, C.; Makate, M.; Mango, N.; Siziba, S. Increasing resilience of smallholder farmers to climate change through multiple adoption of proven climate-smart agriculture innovations. Lessons from Southern Africa. *J. Environ. Manag.* **2019**, *231*, 858–868. [\[CrossRef\]](#) [\[PubMed\]](#)
79. Lee, M.; Gambiza, J. The adoption of conservation agriculture by smallholder farmers in southern Africa: A scoping review of barriers and enablers. *J. Rural Stud.* **2022**, *92*, 214–225. [\[CrossRef\]](#)
80. Qi, Y.; Zhang, Q.; Hu, S.; Wang, R.; Wang, H.; Zhang, K.; Zhao, H.; Ren, S.; Yang, Y.; Zhao, F.; et al. Effects of High Temperature and Drought Stresses on Growth and Yield of Summer Maize during Grain Filling in North China. *Agriculture* **2022**, *12*, 1948. [\[CrossRef\]](#)
81. Flexas, J.; Ribas-Carbó, M.; Diaz-Espejo, A.; Galmés, J.; Medrano, H. Mesophyll conductance to CO₂: Current knowledge and future prospects. *Plant Cell Environ.* **2008**, *31*, 602–621. [\[CrossRef\]](#) [\[PubMed\]](#)
82. del Pozo, A.; Brunel-Saldias, N.; Engler, A.; Ortega-Farias, S.; Acevedo-Opazo, C.; Lobos, G.A.; Jara-Rojas, R.; Molina-Montenegro, M.A. Climate Change Impacts and Adaptation Strategies of Agriculture in Mediterranean-Climate Regions (MCRs). *Sustainability* **2019**, *11*, 2769. [\[CrossRef\]](#)
83. Mangani, R.; Tesfamariam, E.; Bellocchi, G.; Hassen, A. Modelled impacts of extreme heat and drought on maize yield in South Africa. *Crop Pasture Sci.* **2018**, *69*, 703–716. [\[CrossRef\]](#)
84. Mangani, R.; Gunn, K.M.; Creux, N.M. Projecting the effect of climate change on planting date and cultivar choice for South African dryland maize production. *Agric. For. Meteorol.* **2023**, *341*, 109695. [\[CrossRef\]](#)
85. Tester, M.; Langridge, P. Breeding Technologies to Increase Crop Production in a Changing World. *Science* **2010**, *327*, 818–822. [\[CrossRef\]](#) [\[PubMed\]](#)
86. Lal, R. Climate Change and Soil Degradation Mitigation by Sustainable Management of Soils and Other Natural Resources. *Agric. Res.* **2012**, *1*, 199–212. [\[CrossRef\]](#)
87. Steward, P.R.; Thierfelder, C.; Dougill, A.J.; Ligowe, I. Conservation agriculture enhances resistance of maize to climate stress in a Malawian medium-term trial. *Agric. Ecosyst. Environ.* **2019**, *277*, 95–104. [\[CrossRef\]](#)
88. Mullan, D. Soil erosion under the impacts of future climate change: Assessing the statistical significance of future changes and the potential on-site and off-site problems. *CATENA* **2013**, *109*, 234–246. [\[CrossRef\]](#)
89. Liu, P.; Zhao, H.; Li, Y.; Liu, Z.; Gao, X.; Zhang, Y.; Sun, M.; Zhong, Z.; Luo, J. Corn yields with organic and inorganic amendments under changing climate. *Nutr. Cycl. Agroecosyst* **2018**, *111*, 141–153. [\[CrossRef\]](#)
90. Guo, J.H.; Liu, X.J.; Zhang, Y.; Shen, J.L.; Han, W.X.; Zhang, W.F.; Christie, P.; Goulding, K.W.T.; Vitousek, P.M.; Zhang, F.S. Significant Acidification in Major Chinese Croplands. *Science* **2010**, *327*, 1008–1010. [\[CrossRef\]](#) [\[PubMed\]](#)
91. Abalos, D.; Cardenas, L.M.; Wu, L. Climate change and N₂O emissions from South West England grasslands: A modelling approach. *Atmos. Environ.* **2016**, *132*, 249–257. [\[CrossRef\]](#)
92. Xie, F.; Xia, Y.; Feng, W.; Niu, Y. Increasing Surface UV Radiation in the Tropics and Northern Mid-Latitudes due to Ozone Depletion after 2010. *Adv. Atmos. Sci.* **2023**, *40*, 1833–1843. [\[CrossRef\]](#)
93. García-Gutiérrez, S.; García-Marco, S.; Jiménez-Horcadada, R.; Montoya, M.; Vallejo, A.; Guardia, G. Maize residue input rather than cover cropping influenced N₂O emissions and soil–crop N dynamics during the intercrop and cash crop periods. *Agric. Ecosyst. Environ.* **2024**, *363*, 108873. [\[CrossRef\]](#)

94. Wang, Z.; Qi, Z.; Xue, L.; Bukovsky, M.; Helmers, M.J. Modeling the impacts of climate change on nitrogen losses and crop yield in a subsurface drained field. *Clim. Change* **2015**, *129*, 323–335. [\[CrossRef\]](#)
95. Lybbert, T.J.; Sumner, D.A. Agricultural technologies for climate change in developing countries: Policy options for innovation and technology diffusion. *Food Policy* **2012**, *37*, 114–123. [\[CrossRef\]](#)
96. Adzawla, W.; Alhassan, H. Effects of climate adaptation on technical efficiency of maize production in Northern Ghana. *Agric. Econ.* **2021**, *9*, 14. [\[CrossRef\]](#)
97. Zabel, F.; Müller, C.; Elliott, J.; Minoli, S.; Jägermeyr, J.; Schneider, J.M.; Franke, J.A.; Moyer, E.; Dury, M.; Francois, L.; et al. Large potential for crop production adaptation depends on available future varieties. *Glob. Change Biol.* **2021**, *27*, 3870–3882. [\[CrossRef\]](#) [\[PubMed\]](#)
98. Wu, L.; Elshorbagy, A.; Helgason, W. Assessment of agricultural adaptations to climate change from a water-energy-food nexus perspective. *Agric. Water Manag.* **2023**, *284*, 108343. [\[CrossRef\]](#)
99. Bryan, E.; Deressa, T.T.; Gbetibouo, G.A.; Ringler, C. Adaptation to climate change in Ethiopia and South Africa: Options and constraints. *Environ. Sci. Policy* **2009**, *12*, 413–426. [\[CrossRef\]](#)
100. Bernal-Morales, R.; Juárez-Sánchez, J.P.; Ramírez-Valverde, B.; Ocampo-Fletes, I.; de los Ángeles Velasco-Hernández, M. Impact of climate change on maize (*Zea mays* L.) planting dates in the eastern region of Puebla, Mexico. *Agrociencia* **2025**, 1–16. [\[CrossRef\]](#)
101. Reynolds, W.D.; Drury, C.F.; Yang, X.M.; Tan, C.S.; Yang, J.Y. Impacts of 48 years of consistent cropping, fertilization and land management on the physical quality of a clay loam soil. *Can. J. Soil. Sci.* **2014**, *94*, 403–419. [\[CrossRef\]](#)
102. Oriekhoe, O.I.; Adisa, O.; Ilugbusi, B.S. Climate change and food supply chain economics: A comprehensive analysis of impacts, adaptations, and sustainability. *Int. J. Appl. Res. Soc. Sci.* **2024**, *6*, 267–278. [\[CrossRef\]](#)
103. Baum, M.E.; Licht, M.A.; Huber, I.; Archontoulis, S.V. Impacts of climate change on the optimum planting date of different maize cultivars in the central US Corn Belt. *Eur. J. Agron.* **2020**, *119*, 126101. [\[CrossRef\]](#)
104. Nyagumbo, I.; Mutenje, M.; Setimela, P.; Chipindu, L.; Chisaka, A.; Simwaka, P.; Mwale, B.; Ngwira, A.; Mupangwa, W. Evaluating the merits of climate smart technologies under smallholder agriculture in Malawi. *Soil Use Manag.* **2022**, *38*, 890–906. [\[CrossRef\]](#)
105. Steward, P.R.; Dougill, A.J.; Thierfelder, C.; Pittelkow, C.M.; Stringer, L.C.; Kudzala, M.; Shackelford, G.E. The adaptive capacity of maize-based conservation agriculture systems to climate stress in tropical and subtropical environments: A meta-regression of yields. *Agric. Ecosyst. Environ.* **2018**, *251*, 194–202. [\[CrossRef\]](#)
106. Arslan, A.; McCarthy, N.; Lipper, L.; Asfaw, S.; Cattaneo, A.; Kokwe, M. Climate Smart Agriculture? Assessing the Adaptation Implications in Zambia. *J. Agric. Econ.* **2015**, *66*, 753–780. [\[CrossRef\]](#)
107. Lin, Y.; Feng, Z.; Wu, W.; Yang, Y.; Zhou, Y.; Xu, C. Potential Impacts of Climate Change and Adaptation on Maize in Northeast China. *Agron. J.* **2017**, *109*, 1476–1490. [\[CrossRef\]](#)
108. Jones, J.W.; Hoogenboom, G.; Porter, C.H.; Boote, K.J.; Batchelor, W.D.; Hunt, L.A.; Wilkens, P.W.; Singh, U.; Gijsman, A.J.; Ritchie, J.T. The DSSAT cropping system model. *Eur. J. Agron.* **2003**, *18*, 235–265. [\[CrossRef\]](#)
109. Ma, L.; Ahuja, L.R.; Islam, A.; Trout, T.J.; Saseendran, S.A.; Malone, R.W. Modeling yield and biomass responses of maize cultivars to climate change under full and deficit irrigation. *Agric. Water Manag.* **2017**, *180*, 88–98. [\[CrossRef\]](#)
110. Xie, W.; Ran, H.; Deng, A.; Jiang, K.; Ru, H.; Yao, N.; He, J.; Javed, T.; Hu, X. Climate change promotes shifts of summer maize yield and water productivity in the Weihe River Basin: A regionalization study based on a distributed crop model. *Agric. Water Manag.* **2025**, *314*, 109500. [\[CrossRef\]](#)
111. Amouzou, K.A.; Lamers, J.P.A.; Naab, J.B.; Borgemeister, C.; Vlek, L.G.; Becker, M. Climate change impact on water- and nitrogen-use efficiencies and yields of maize and sorghum in the northern Benin dry savanna, West Africa. *Field Crops Res.* **2019**, *235*, 104–117. [\[CrossRef\]](#)
112. Battisti, R.; Sentelhas, C.; Boote, K.J.; de S, G.M.; Farias, J.R.B.; Basso, C.J. Assessment of soybean yield with altered water-related genetic improvement traits under climate change in Southern Brazil. *Eur. J. Agron.* **2017**, *83*, 1–14. [\[CrossRef\]](#)
113. Kipkulei, H.K.; Boitt, M.; Eshetu, S.B.; Sieber, S.; Rotich, B. Modelling Maize Yield Sensitivity to Abiotic Stresses in East Africa: Integration of Crop Modelling and Synthetic Climate Change Scenarios. *Int. J. Plant Prod.* **2025**, *19*, 351–361. [\[CrossRef\]](#)
114. Kothiyal, S.; Prabhjyot-Kaur; Sandhu, S.S.; Kaur, J. Modelling the climate change impact of mitigation (RCP 2.6) and high emission (RCP 8.5) scenarios on maize yield and possible adaptation measures in different agroclimatic zones of Punjab, India. *J. Sci. Food Agric.* **2023**, *103*, 6984–6994. [\[CrossRef\]](#) [\[PubMed\]](#)
115. Markos, D.; Worku, W.; Mamo, G. Modeling performances of maize cultivars under current and future climate scenarios in southern central Ethiopian rift valley. *CABI Agric. Biosci.* **2024**, *5*, 29. [\[CrossRef\]](#)
116. Zelenák, A.; Szabó, A.; Nagy, J.; Nyéki, A. Using the CERES-maize model to simulate crop yield in a long-term field experiment in Hungary. *Agronomy* **2022**, *12*, 785. [\[CrossRef\]](#)
117. Getachew, F.; Bayabil, H.K.; Hoogenboom, G.; Teshome, F.T.; Zewdu, E. Irrigation and shifting planting date as climate change adaptation strategies for sorghum. *Agric. Water Manag.* **2021**, *255*, 106988. [\[CrossRef\]](#)

118. Hess, T.M. A microcomputer scheduling program for supplementary irrigation. *Comput. Electron. Agric.* **1996**, *15*, 233–243. [CrossRef]
119. Lamm, F.R. Cotton, tomato, corn, and onion production with subsurface drip irrigation: A review. *Trans. ASABE* **2016**, *59*, 263–278. [CrossRef]
120. Zhi, M. Environmental Impact of Water-Saving Irrigation for Rice. 1996. Available online: <https://www.cabidigitallibrary.org/doi/full/10.5555/19971908986> (accessed on 16 July 2026).
121. Quemada, M.; Baranski, M.; Lange, M.N.J.N.-D.; Vallejo, A.; Cooper, J.M. Meta-analysis of strategies to control nitrate leaching in irrigated agricultural systems and their effects on crop yield. *Agric. Ecosyst. Environ.* **2013**, *174*, 1–10. [CrossRef]
122. Kuang, W.; Gao, X.; Tenuta, M.; Zeng, F. A global meta-analysis of nitrous oxide emission from drip-irrigated cropping system. *Glob. Change Biol.* **2021**, *27*, 3244–3256. [CrossRef] [PubMed]
123. Monistrol, A.; Vallejo, A.; García-Gutiérrez, S.; Hermoso-Peralo, R.; Montoya, M.; Atencia-Payares, L.K.; Aguilera, E.; Guardia, G. Interaction between burial depth and N source in drip-fertigated maize: Agronomic performance and correlation with spectral indices. *Agric. Water Manag.* **2024**, *301*, 108951. [CrossRef]
124. Tol, R.S.J. Adaptation and mitigation: Trade-offs in substance and methods. *Environ. Sci. Policy* **2005**, *8*, 572–578. [CrossRef]
125. Hasson, R.; Löfgren, Å.; Visser, M. Climate change in a public goods game: Investment decision in mitigation versus adaptation. *Ecol. Econ.* **2010**, *70*, 331–338. [CrossRef]
126. Wang, R.; Rejesus, R.M.; Tack, J.B.; Aglasan, S. Do higher temperatures influence how yields respond to increasing planting density? *Agric. Resour. Econ. Rev.* **2021**, *50*, 273–295. [CrossRef]
127. Blair, N.; Faulkner, R.D.; Till, A.R.; Korschens, M.; Schulz, E. Long-term management impacts on soil C, N and physical fertility: Part II: Bad Lauchstadt static and extreme FYM experiments. *Soil Tillage Res.* **2006**, *91*, 39–47. [CrossRef]
128. Song, Z.; Gao, H.; Zhu, P.; Peng, C.; Deng, A.; Zheng, C.; Mannaf, A.; Islam, N.; Zhang, W. Organic amendments increase corn yield by enhancing soil resilience to climate change. *Crop J.* **2015**, *3*, 110–117. [CrossRef]
129. Fan, T.; Stewart, B.A.; Yong, W.; Junjie, L.; Guangye, Z. Long-term fertilization effects on grain yield, water-use efficiency and soil fertility in the dryland of Loess Plateau in China. *Agric. Ecosyst. Environ.* **2005**, *106*, 313–329. [CrossRef]
130. Dong, X.; Xu, W.; Zhang, Y.; Leskovar, D.I. Effect of Irrigation Timing on Root Zone Soil Temperature, Root Growth and Grain Yield and Chemical Composition in Corn. *Agronomy* **2016**, *6*, 34. [CrossRef]
131. Leng, G. Evidence for a weakening strength of temperature-corn yield relation in the United States during 1980–2010. *Sci. Total Environ.* **2017**, *605–606*, 551–558. [CrossRef] [PubMed]
132. Li, J.; Xu, X.; Liu, L.; Deng, X.; Wang, S. Impact of irrigation on cropland yield potential and scenario-based optimization in Northeast China. *Agric. Water Manag.* **2025**, *314*, 109522. [CrossRef]
133. Pörtner, H.-O.; Roberts, D.C.; Tignor, M.; Poloczanska, E.S.; Mintenbeck, K.; Alegría, A.; Craig, M.; Langsdorf, S.; Löschke, S.; Möller, V.; et al. Climate Change 2022: Impacts, Adaptation and Vulnerability. 2022. Available online: https://www.researchgate.net/profile/Vincent-Moeller/publication/362431678_Climate_Change_2022_Impacts_Adaptation_and_Vulnerability_Working_Group_II_Contribution_to_the_Sixth_Assessment_Report_of_the_Intergovernmental_Panel_on_Climate_Change/links/6529092e06bdd619c48be291/Climate-Change-2022-Impacts-Adaptation-and-Vulnerability-Working-Group-II-Contribution-to-the-Sixth-Assessment-Report-of-the-Intergovernmental-Panel-on-Climate-Change.pdf (accessed on 28 July 2026).
134. Schnitzer, M.; Khan, S.U. *Soil Organic Matter*; Elsevier: Amsterdam, The Netherlands, 1975; Volume 8, Available online: [https://books.google.com/books?hl=en&lr=&id=nUmMTWcaPkMC&oi=fnd&pg=PP1&dq=114.%09Schnitzer+M+and+Khan+SU+\(1975\)+Soil+Organic+Matter.+Amsterdam,+The+Netherlands:+Elsevier.+&ots=j98uxrwWy7&sig=NkQ3uNDM6cT67JBiSSVdugzSHEc](https://books.google.com/books?hl=en&lr=&id=nUmMTWcaPkMC&oi=fnd&pg=PP1&dq=114.%09Schnitzer+M+and+Khan+SU+(1975)+Soil+Organic+Matter.+Amsterdam,+The+Netherlands:+Elsevier.+&ots=j98uxrwWy7&sig=NkQ3uNDM6cT67JBiSSVdugzSHEc) (accessed on 28 July 2026).
135. Lal, R. Soil health and carbon management. *Food Energy Secur.* **2016**, *5*, 212–222. [CrossRef]
136. Li, Z.; Xu, M.; Zhang, H.; Zhang, S.; Zhang, W. Sustainability of crop yields in China under long-term fertilization and different ecological conditions. *Chin. J. Appl. Ecol./Yingyong Shengtai Xuebao* **2010**, *21*, 1264. Available online: <https://search.ebscohost.com/login.aspx?direct=true&profile=ehost&scope=site&authtype=crawler&jrnl=10019332&AN=52490017&h=wjiwh4fNJ%2BY2EUQv4ssZBAwPU8hnIjyVJDUXTinns%2F8n88ttZ4RBX%2F7ICZZ1L86crA7sPjxc0pftOmAxdw5wQQ%3D%3D&crl=c> (accessed on 16 July 2026).
137. Mugandani, R.; Mafongoya, P. Behaviour of smallholder farmers towards adoption of conservation agriculture in Zimbabwe. *Soil Use Manag.* **2019**, *35*, 561–575. [CrossRef]
138. Obia, A.; Cornelissen, G.; Martinsen, V.; Smebye, A.B.; Mulder, J. Conservation tillage and biochar improve soil water content and moderate soil temperature in a tropical Acrisol. *Soil Tillage Res.* **2020**, *197*, 104521. [CrossRef]
139. Devkota, M.; Devkota, K.P.; Kumar, S. Conservation agriculture improves agronomic, economic, and soil fertility indicators for a clay soil in a rainfed Mediterranean climate in Morocco. *Agric. Syst.* **2022**, *201*, 103470. [CrossRef]
140. Thierfelder, C.; Wall, P.C. Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. *Soil Tillage Res.* **2009**, *105*, 217–227. [CrossRef]

141. Dusingizimana, P.; Devkota, K.P.; Cherif, M.; Nduwumuremyi, A. Conservation agriculture for closing maize yield gap and enhancing climate resilience in semi-arid Eastern Rwanda. *Farming Syst.* **2025**, *3*, 100151. [[CrossRef](#)]
142. Gagliardi, L.; Sportelli, M.; Fontanelli, M.; Sbrana, M.; Luglio, S.M.; Raffaelli, M.; Peruzzi, A. Effects of Conservation Agriculture Practices on Tomato Yield and Economic Performance. *Agronomy* **2023**, *13*, 1704. [[CrossRef](#)]
143. Tesfaye, K.; Gbegbelegbe, S.; E Cairns, J.; Shiferaw, B.; Prasanna, B.M.; Sonder, K.; Boote, K.; Makumbi, D.; Robertson, R. Maize systems under climate change in sub-Saharan Africa: Potential impacts on production and food security. *Int. J. Clim. Change Strateg. Manag.* **2015**, *7*, 247–271. [[CrossRef](#)]
144. Santiago, R.; Malvar, R.A.; Revilla; Butrón, A. Maize landraces as useful donors of genetic diversity for resilience to drought. *J. Agric. Food Res.* **2025**, *23*, 102297. [[CrossRef](#)]
145. Obunyali, C.O.; Karanja, J.; Oikeh, S.O.; Omany, G.O.; Mugo, S.; Beyene, Y.; Oniang'O, R.K. On-farm Performance and Farmers' Perceptions of DroughtTEGO-Climate-Smart Maize Hybrids in Kenya. *Agron. J.* **2019**, *111*, 2754–2768. [[CrossRef](#)]
146. Chemura, A.; Yalew, A.W.; Gornott, C. Quantifying Agroforestry Yield Buffering Potential Under Climate Change in the Smallholder Maize Farming Systems of Ethiopia. *Front. Agron.* **2021**, *3*, 609536. [[CrossRef](#)]
147. Bedeke, S.; Vanhove, W.; Gezahegn, M.; Natarajan, K.; Van Damme, P. Adoption of climate change adaptation strategies by maize-dependent smallholders in Ethiopia. *NJAS-Wageningen. J. Life Sci.* **2019**, *88*, 96–104. [[CrossRef](#)]
148. MacCarthy, D.S.; Freduah, B.S.; Akinseye, F.M.; Adiku, S.G.K.; Dodor, D.E.; Kamara, A.Y. Exploring the use of nitrogen fertilization and shifting of planting dates as adaptation strategies to climate change in the Coastal Savannah of Ghana. *J. Agric. Food Res.* **2025**, *22*, 102126. [[CrossRef](#)]
149. Eckardt, N.A.; A Ainsworth, E.; Bahuguna, R.N.; Broadley, M.R.; Busch, W.; Carpita, N.C.; Castrillo, G.; Chory, J.; DeHaan, L.R.; Duarte, C.M.; et al. Climate change challenges, plant science solutions. *Plant Cell* **2023**, *35*, 24–66. [[CrossRef](#)] [[PubMed](#)]
150. Luo, Z.; Zhang, S.; Zhao, Z.; Minasny, B.; Chang, J.; Huang, J.; Li, B.; Shi, Z.; Wang, E.; Wang, M.; et al. Soil-smart cropping for climate-smart production. *Geoderma* **2024**, *451*, 117061. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.