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Systematic Review

Advancing Climate-Smart Agriculture: A Global Assessment of Climate Impacts on Crop Yield and Adaptation Effectiveness Across Arid and Semi-Arid Regions

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Abstract

Climate change is intensifying crop yield variability across arid and semi-arid regions, yet the effectiveness of widely implemented adaptation strategies remains insufficiently quantified. We systematically reviewed 157 crop modeling studies over two decades (2005–2024) to assess yield responses and adaptation effectiveness for five crops (maize, wheat, rice, sorghum, and barley). Using a predefined set of inclusion criteria across six databases (ProQuest, Web of Science, Scopus, Google Scholar, Taylor & Francis Online, and JSTOR) in an independent dual review, the results show that rising temperatures and erratic precipitation substantially reduced maize yields by 20.32% (range = 0.4–63%) and wheat yield by 15% (range = 0.05–64%), followed by rice (14.72%, range = 4–37%) and sorghum (14.54%, range = 1–36%). Localized adaptation partially offset approximately 12–19% of climate-driven reductions. An "adaptation effectiveness gap," representing the difference between local adaptation benefits and global mean potential, showed that most locations achieved 7% greater than global benchmarks for comparable strategies. East and South Asia, as well as Eastern Africa, underperformed, whereas Europe and North America exceeded the global average. Disparities emanated from data limitations, methodology, and local agronomic conditions. This review offers a transferable framework for guiding effective, region-specific climate adaptation planning.

Keywords: adaptation; climate change; crop modeling; arid and semi-arid regions

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1. Introduction

Agricultural crop production is fundamental to global food security. Current annual output must increase by up to 70% [1] to meet food demand for the world's growing population, which is projected to reach nine billion people by the mid-century [2]. Despite this pressure on crop production systems, climate change and variability continue to disrupt annual productivity, leading to heightened uncertainty in the food supply chain [3,4]. Crops are highly sensitive to climate change due to their reliance on the complex interactions that exist between crop growth processes and atmospheric dynamics [5], including temperature

changes, precipitation patterns, solar radiation, and atmospheric composition [6]. Changes in these environmental conditions, especially when abrupt or coinciding with critical crop growth and development stages of crop production, can affect biophysical processes in as many as twenty different forms [7], resulting in reduced productivity.

Climate-driven disruption in agricultural production is especially severe in arid and semi-arid regions. Producers in these regions face a multifold challenge, including addressing critical questions regarding how food production can be sustained under unusually extreme environmental conditions such as prolonged drought periods [8,9] and how best to manage limited resources to ensure sustainability and long-term agricultural viability [10]. In these regions, developing targeted interventions or adaptation strategies is not merely an option, but a critical necessity for sustaining food production [11]. However, the effectiveness of producers' choice of strategy may vary from location to location, depending on local conditions, including climate, soil properties, genotype, and management, such that locations within the same broad arid or semi-arid class may experience different productivity responses to climate change.

Adaptation strategies, which are commonly implemented through field experiments, statistical analysis, or process-based modeling frameworks, have evolved over the last century from conventional, reactive, and experience-based decision-making approaches to cutting-edge genetic modifications, customized and precise environmental management responses, and conservation-oriented strategies [12–15]. These strategies are designed either to reduce exposure to harmful conditions or to buffer crop responses when stress occurs [16]. For example, earlier sowing can help avoid terminal heat during reproduction in wheat [14] or maximize rainfall timing in sorghum [17], while irrigation scheduling, deficit irrigation, and mulching can improve water productivity in semi-arid maize systems [12–14]. Recent reviews also provide promising adaptation options for individual locations, cropping systems, or climate forcing scenarios, including syntheses of 35 studies on climate impacts and adaptation in West Africa [18], climate risks and technology-based interventions in dryland systems [19], and the value of crop models for adaptation assessment [20,21]. While these studies show that adaptation can reduce losses and sustain or improve productivity under suboptimal conditions, substantial disparities in crop responses persist even within arid and semi-arid regions, which possess similar climatic conditions. These studies rarely explain the underlying drivers of variations in the effectiveness of strategies across these regions. These inconsistencies constitute a significant knowledge gap that is yet to be sufficiently addressed. Adaptation strategies are often developed in response to localized environmental pressures. As a result, their design and implementation tend to be context-specific, shaped by regional climatic conditions, dominant cropping systems, technological capacity, and other related factors [22,23]. A comparative synthesis must therefore interpret adaptation outcomes, considering the environmental and methodological conditions under which they were generated.

This systematic review synthesizes the current state-of-the-science on process-based modeling studies published from 2005 to 2024 to assess climate impacts and adaptation strategies for five globally dominant cereal crops (maize, wheat, rice, sorghum, and barley), which collectively make up about half of global cereal production [1], in arid and semi-arid regions, defined based on Koppen-Geiger climate classification [24]. By comparing evidence across crops and regions, the review aims not just to clarify the main climate stressors affecting cereal production and widely adopted adaptation measures, but also to assess the drivers of variation in adaptation outcomes and highlight the research gaps that continue to limit stronger climate resilience planning. Specifically, the study addresses the following key research questions:

- What are the most prominent climate stressors affecting crop production in arid and semi-arid regions?
- What are the most widely applied adaptation measures, and how does their effectiveness vary across locations with similar climatic conditions?
- What underlying factors drive the disparities in adaptation effectiveness?
- What research gap persists, and what future strategies are capable of enhancing resilience?

The study findings will aid in providing data for making well-informed decisions towards fixing inefficiencies in implementations, and facilitating knowledge transfer and strategic implementation of strategies with demonstrated effectiveness across regional boundaries, thereby bolstering global agricultural resilience amid the changing climate. The following section outlines the systematic review methodology, including literature selection and exclusion criteria. The results are then presented on prominent climate stressors, adaptation strategies, and their relative effectiveness. The implications of these findings are further discussed, and the review concludes with key insights, research gaps, and recommendations for future adaptation strategies.

2. Literature Review Methodology

Given the vast and rapidly evolving body of research on the impacts of climate change on crop production systems, as well as adaptation efforts in response to these impacts, a systematic and transparent review methodology was adopted to ensure that the literature analyzed is directly aligned with the stated objectives. The review process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework [25], which adopts a rigorous and robust multi-step approach, encompassing the stages of identification, screening, eligibility assessment, and full-text review (Figure 1). This structured approach minimized bias and ensured reproducibility of the process.

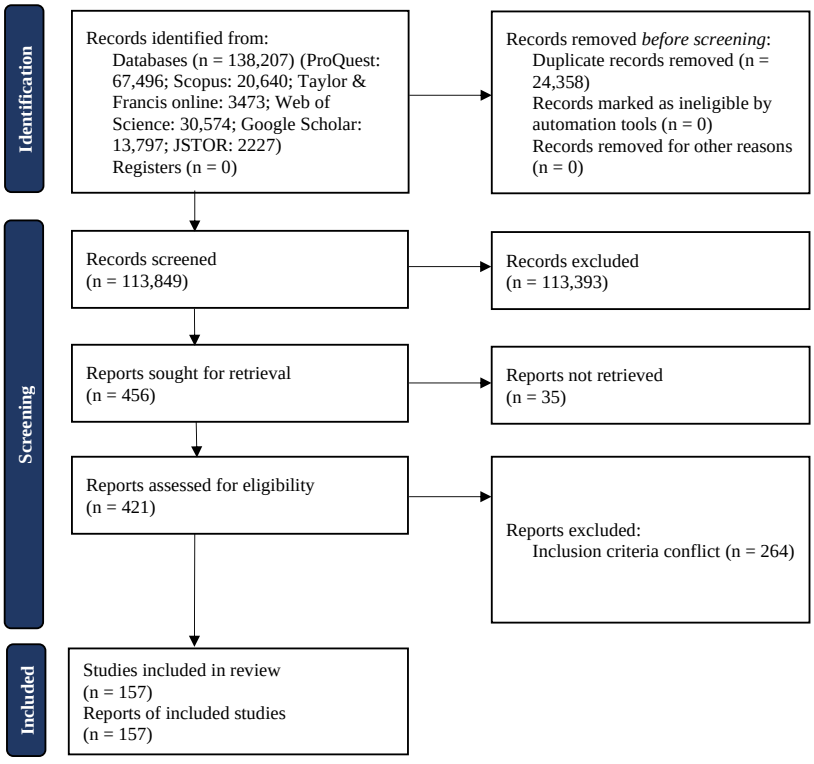


Figure 1. PRISMA systematic review flowchart methodology. The multi-step screening process refined 113,849 initial records down to a final corpus of 157 process-based crop modeling studies for full-text analysis.

2.1. Literature Search

The relevant literature was obtained from six selected scientific databases (Proquest, Web of Science, Scopus, Google Scholar, Taylor and Francis online, and JSTOR), using search strings developed from a predefined set of core terms. An initial set of 25 articles, deemed most relevant to the topic of the study, was used to generate a comprehensive list of key terms ("model", "crop", "adapt", "climate change", "impact" and "arid and semi-arid"). The key terms were combined using Boolean operators (AND/OR) to generate search queries tailored to the specific syntax requirements of each database. The full search strings for each database are provided in Table S1 in the Supplementary Material. To maintain consistency in articles found across databases, the literature search was restricted to peer-reviewed journal articles published in English between 1 January 2005 and 31 December 2024. The final search was completed on 23 August 2024. Articles extracted from each database were combined and then screened for duplicates using the 'litsearchr' package in R. A total of 113,849 articles were retrieved and imported into R Studio version 4.4.1 for additional screening.

2.2. Screening and Eligibility Criteria

Article eligibility was assessed through a structured two-step screening process focused on titles and abstracts of the selected articles. Because initial screening revealed that many studies, although addressing climate impacts, did not explicitly report any adaptation measures, we first filtered the 113,849 unique articles for the keyword "adapt" (including variations like "adaptation", "adapted" or "adapting") to isolate studies that explicitly reported adaptation measures. This step yielded 7898 articles. Two reviewers then independently evaluated this subset using the 'revtools' package in RStudio based on predefined inclusion criteria. Studies were included only if they: (i) focused on at least one of the five target crops (maize, wheat, rice, sorghum, or barley); (ii) reported on climate stressor impacts and adaptation outcomes in arid or semi-arid environments; and (iii) utilized a process-based crop model to assess adaptation strategy effectiveness. In cases of conflicts between the two reviewers regarding article inclusion, a third reviewer resolved the conflict and made the final inclusion decision. This conflict resolution process reduced the total number of articles from 456 to 192 relevant articles for full-text review. However, only 157 articles had retrievable full-text articles available online after the search. The 157 downloaded articles were then exported for data extraction. Included studies were grouped for synthesis by crop, climate stressor, adaptation strategy, and geographic region. Where appropriate, studies were also grouped by model type and by whether adaptation was evaluated as a single strategy or a combination of strategies.

2.3. Data Extraction and Synthesis

The data extraction process was designed to obtain relevant information that directly or indirectly addresses the study's objectives. Using the 'SysRev' tool, studies were randomly assigned to two independent reviewers in a blind review to prevent influence or bias in the extraction process. For each study, the following key information was extracted using a standardized extraction form: the year of publication, the country where the study was conducted, the climate region(s) of the study area (categorized as arid and/or semi-arid), the crop models utilized, the crops considered, the types of climate impacts addressed, the adaptation strategies implemented, the outcomes or effects of those adaptation strategies, and any identified research gaps. For studies reporting multiple crops, climate scenarios, or adaptation strategies, each distinct crop–scenario or crop–adaptation combination was extracted as a separate observation when reported separately in the source study. Adaptation gaps specific to each location and study were inferred from reported limitations, which

were categorized into modeling, data, methodological, and resource-related limitations, and proposed adaptation strategies considered likely to be effective in the future. A study was marked 'complete' within the SysRev platform only when both reviewers provided consistent labels. If discrepancies arose between their labels, the study was flagged as a conflict, which was then resolved by a third reviewer. Effect sizes were summarized as percentage change in yield, growing season length, and water-related variables relative to the relevant baseline or control condition. Where studies reported multiple effect measures, the primary reported outcome was used for synthesis. Studies were synthesized narratively and quantitatively by crop, adaptation strategy, and geographic region. Descriptive summaries, including mean, standard deviation, and range, were used to compare study characteristics and outcome patterns across locations. When studies reported comparable percentage changes, values were aggregated to estimate mean responses within each crop-adaptation category. Heterogeneity was explored by comparing outcomes across regions, crop types, model types, and reported limitations, and studies were deemed more uncertain where they were relatively sparse. Some studies evaluated multiple climate impact scenarios or adaptation strategies and therefore contributed more than one observation to the synthesis. No meta-analysis was conducted because the included studies differed substantially in design, assumptions, climate scenarios, and reporting formats.

3. Results and Discussion

3.1. Global Research Footprint and Study Statistics

3.1.1. Spatial and Temporal Distribution of Selected Studies

The 157 modeling-based studies span 34 countries across arid and semi-arid regions (Figure 2), indicating a broad global interest in climate adaptation practices for cereal production in these areas. The geographical distribution of the selected research studies was not uniform, but revealed a significant concentration of studies in South and Southwest Asia, which are both agriculturally intensive areas that are susceptible to climate-related challenges [26]. China and India contributed the largest portion, accounting for 24% and 18% of the total studies, respectively. In North America, the United States accounts for 10% of the total studies, while in Africa, Ethiopia (8%) and Nigeria (6%) were the most represented countries, likely reflecting the growing concerns about food security, and agricultural resilience across the continent's vulnerable regions. Within Europe, Italy had the highest representation at 5%, while several other countries, including Austria, appeared less frequently. Approximately 13% of the reviewed studies involved multiple countries or regions. This implies a broader interplay in the patterns and challenges of climate impacts across arid and semi-arid zones globally.

The temporal distribution of the literature shows an overall intensification in publications in 2017 (Figure 3c) and subsequently in 2020 and 2021. Together, these three years accounted for over one-third (approximately 38%) of the studies reviewed. This surge in the latter years was likely due to increased global awareness of climate-related agricultural challenges in arid and semi-arid regions and the growing availability and accessibility of crop modeling tools for climate impact and adaptation-related studies.

3.1.2. Distribution of Crops and Models Used

Across the five target cereals considered in the study (Figure 3a), wheat (41.9%) and maize (38.8%) were the predominant crops, while rice (9.3%), and sorghum (7.8%) were comparatively underrepresented. Very limited data were available for barley (2.3%), and, as such, it was excluded from the quantitative synthesis of climate impacts and adaptation effectiveness. The skewed distribution towards wheat-maize systems reflects both the global importance of these crops and their widespread cultivation across arid and semi-arid

regions. Rice was predominantly studied in Pakistan and India, showing its critical role in Asian agriculture, while studies on sorghum were conducted mainly in the United States and India.

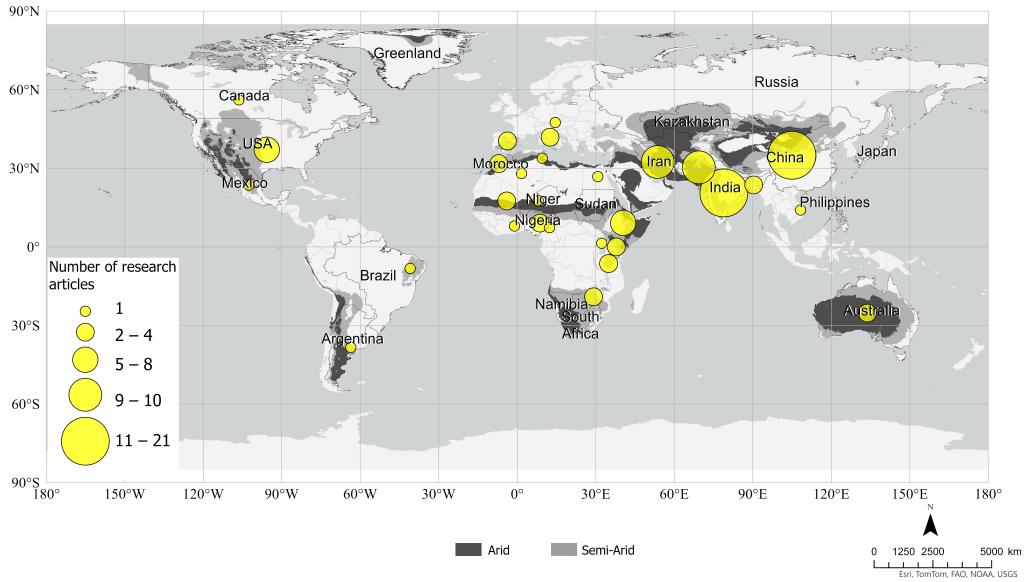


Figure 2. Geographical distribution of the 157 selected studies across arid and semi-arid climate zones. The literature is highly concentrated in agriculturally intensive regions of South and Southwest Asia, particularly China and India, highlighting regional priorities in climate adaptation research.

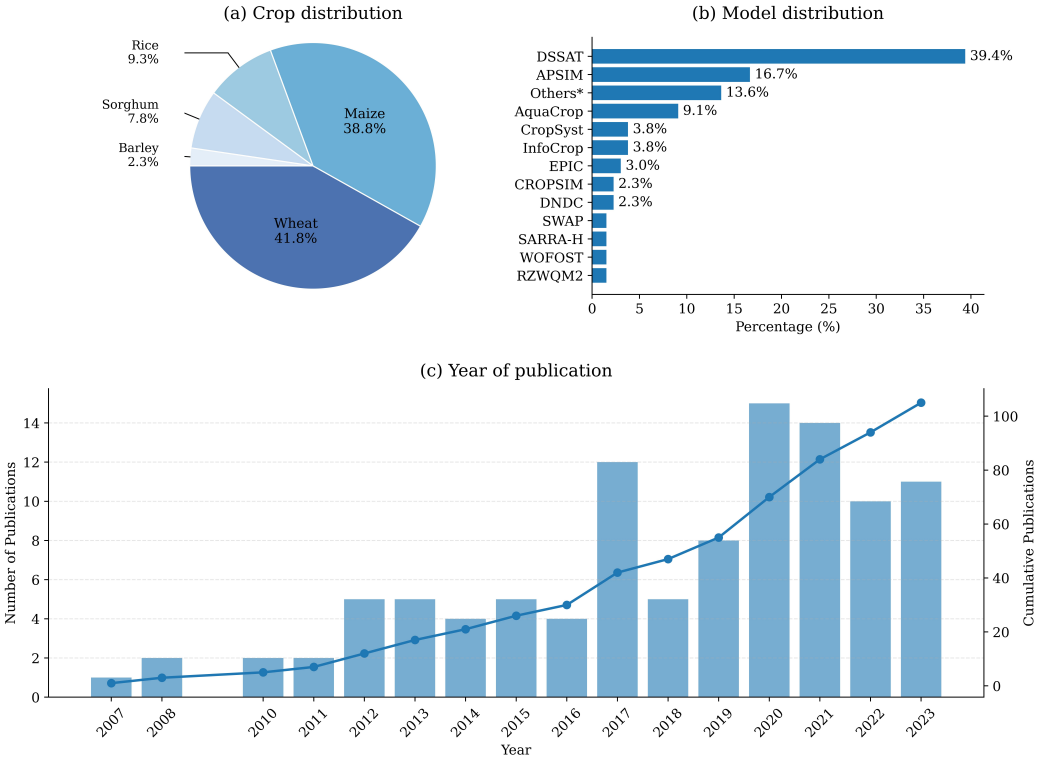


Figure 3. Percentage distribution of reviewed studies by (**a**) crops represented, (**b**) process-based crop models used, and (**c**) publication by year. * refers to crop models that individually appear in less than 2% of the reviewed studies and are grouped into a single category.

The Decision Support System for Agrotechnology Transfer (DSSAT) was the most widely used model, appearing in 39.4% of the reviewed articles (Figure 3b), followed by

the Agricultural Production Systems sIMulator (APSIM) at 16.7%. Their prominence likely reflects their versatility, relatively strong validation history, and broad capacity to simulate crop growth under varying climatic, soil, and management conditions. AquaCrop, which is particularly well suited for water-limited systems and water productivity analysis, was used in 9.1% of the studies. InfoCrop and CropSyst each accounted for 3.8%, indicating moderate use, while models such as EPIC, DNDC, CROPSIM, and SARRA-H were less common, generally ranging between 1.5% and 3%. Several other models, including Hybrid-Maize, WOFOST, CROPWAT, and SWAT, appeared only rarely (0.8%), suggesting more specialized or context-specific application. Overall, the dominance of DSSAT, APSIM, and AquaCrop indicates that most adaptation studies in arid and semi-arid regions rely on a relatively small set of well-established process-based tools.

3.2. Climate Change and Associated Impacts

3.2.1. Dominant Forms of Climate Impacts Across Arid and Semi-Arid Regions

Because climate variables interact strongly and often occur simultaneously, attributing crop responses to a single climatic driver is inherently difficult. To address this complexity, studies adopted both methods that effectively captured the joint influences of temperature variability and altered rainfall distribution, as well as a reductionist approach, where one or more climatic variables were isolated while holding others constant to evaluate their specific effects on crop growth and productivity. The most consistently represented forms of climate change were rising temperature, except for a few reported occurrences of cold stress [27]. Erratic precipitation patterns and elevated atmospheric CO_2 concentration were also among the frequently reported forms of climate change. Some studies highlighted specific and indirect yet consequential manifestations of these broader changes, such as intensified drought episodes, soil moisture deficiencies [28], altered solar radiation intensity [29–31], increased weed and pest populations [32], and increased risk windows for the occurrence of extreme temperatures [33].

Overall, three broad approaches were used to represent climate impacts in crop models. The most common approach, adopted by approximately 77.8% of studies, derived weather inputs from general circulation models (GCM) or regional climate models (RCM), which are standardized greenhouse gas emission and concentration scenarios designed to represent alternative future climate pathways [34]. Projected changes in temperature, precipitation, radiation, and related variables were translated into the daily weather data required by crop models, either by applying statistically downscaled and bias-corrected climate data directly or by adjusting historical weather records with projected seasonal or monthly changes. Studies using GCM-based projections mostly relied on scenarios from the IPCC Special Report on Emissions Scenarios (SRES) or the Representative Concentration Pathways (RCPs) from IPCC's fifth assessment report, while only a few recent papers adopted Shared Socioeconomic Pathways (SSPs) from the sixth assessment report. Because the Sixth Assessment Report was released more recently than the time frame covered by the literature search, most studies reviewed relied on either the RCPs or the earlier SRES scenarios. Scenarios derived from these reports ranged from lower-emission futures, such as RCP2.6 and B1, to intermediate pathways, such as RCP4.5, SSP2-4.5, and A1B, and higher-emission futures, such as RCP8.5, SSP5-8.5, and A2. RCP 4.5 and 8.5 were the most common scenarios used to assess the climate change impact on agricultural production in the reviewed literature, with 36% of the studies reporting these scenarios; a small percentage reported RCP 2.6 (3.7%). The most common SRES scenarios utilized were the A2 and B1, reported by 15.7% and 8.3% of studies. Other series scenarios were A1B, B2, utilized by 6.5% and 4.6% of studies, while the A1, A1F1, A1T, and A2a were used by < 1% of studies. SSP2-4.5 and SSP5-8.5 were used by 3% of studies.

The second approach adopted by approximately 12% of the studies involved generating synthetic climate data from historically observed records by modifying temperature and precipitation with fixed increments. For example, Sultana et al. [35] analyzed wheat responses by increasing observed temperatures by uniform increments, while Briak and Kebede [14] utilized a multilevel mixed-effects model to generate climate data. The third approach, also common in historical studies, used observed weather records directly as model inputs without further modification [36–38].

3.2.2. Climate-Driven Variations in Crop Yield and Phenology

Yield losses due to climate warming trends were consistently projected for all four crops across most studies (~90%). A comprehensive summary of these climate-driven impacts on crop yield, growing season length (GSL), and water-related variables is provided in Table 1. Maize showed the highest average yield reduction (Figure 4a), ranging from 0.4 to 63.0%, with a mean reduction of 20.32%. Wheat followed with a mean loss of 14.99% and reported reductions ranging from 0.05 to 64.0%. Rice showed a somewhat narrower distribution, with yield declines ranging from 4.0% to 37.0% and a mean reduction of 14.72%. Sorghum also exhibited an overall negative response, with a mean decline of 14.54% and a reported range from 1.0% to 36.0%. These results confirm that climate change is projected to reduce cereal productivity across arid and semi-arid regions, but the magnitude of impact varies substantially among crops and locations. The wider distributions observed for maize and wheat likely reflect their greater sensitivity to differences in climate scenarios. Although model assumptions, management assumptions, and geographic conditions likely contributed to the variations as well. This broader variability may also be partly explained by the larger number of studies available for maize and wheat, which captured a wider range of agro-climatic environments than the more limited rice and sorghum literature. Overall, the findings point to a clear need for location-specific interpretation of climate impacts rather than broad generalization across dryland cereal systems.

Table 1. Summary of climate change impacts on crop yield, growing season length (GSL), and other related variables. Values represent percentage change.

Crop	Impact Driver	Variable	Range	Mean ± SD	References
Maize					
	CO_2	Yield	−6.85 to 30.00	11.16 ± 15.28	[39–41]
	Temperature	Yield	−52.81 to −7.78	−26.80 ± 17.52	[39,41–49]
	Temperature	GSL	−14.00 to −2.00	−6.80 ± 4.71	[45,50–53]
	Precipitation	Yield	−30.00 to 1.00	−14.50 ± 21.92	[39,46]
	Precipitation	Water Use	5.00	5.00	[54]
	Temp + CO_2	Yield	−55.00 to 12.50	−16.21 ± 21.50	[38,55,56]
	Temp + Precip	Yield	−63.00 to 68.00	−13.93 ± 21.45	[29,33,39–42,54,57–72]
	Temp + Precip	GSL	−32.00 to −3.00	−12.50 ± 8.82	[29,39,50,59–61,64,68,71,73]
	Temp + Precip	WUE	23.55	23.55	[50]
Rice					
	CO_2	Yield	16.90 to 27.10	22.00 ± 7.21	[74]
	Temperature	Yield	−14.90 to 8.85	−4.35 ± 12.09	[37,74]
	Temperature	GSL	−4.20 to −3.50	−3.85 ± 0.49	[37,51]
	Precipitation	Yield	−27.00 to −7.30	−19.77 ± 10.84	[75,76]
Sorghum					
	Temperature	Yield	−36.00 to −7.00	−20.00 ± 12.52	[77]
	Temp + Precip	Yield	−18.00 to −3.00	−10.93 ± 5.10	[77–82]
Wheat					
	CO_2	Yield	−25.00 to 237.00	20.30 ± 73.66	[30,35,83–86]
	Temperature	Yield	−54.60 to 20.00	−12.27 ± 17.16	[35,49,65,83,87–90]
	Temp + Precip	Yield	−64.00 to 135.00	1.02 ± 35.06	[20,30,36,60,66,87,91–104]

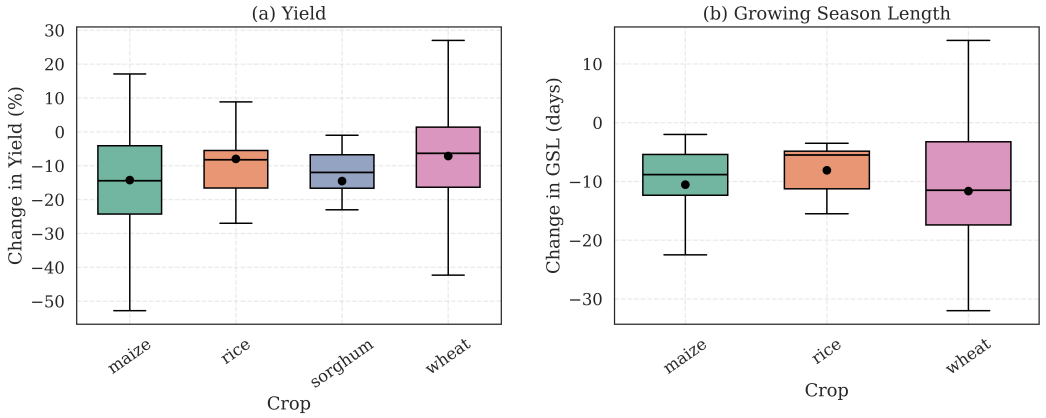


Figure 4. Climate-driven impacts on (**a**) crop yield and (**b**) growing season length (GSL) without adaptation. Negative values represent a reduction in yield, while positive values represent beneficial effects. Beneficial impacts were associated with increased CO_2.

A similar frequently reported mechanism through which warming affects crop production is the acceleration of crop development, which shortens individual phenological stages and reduces total growing season length (GSL) [105]. From the reviewed studies, wheat experienced the largest average shortening (Figure 4b), with a mean reduction of approximately 15.2 days. This was followed by maize, with an average reduction of 10.5 days, while rice showed the smallest mean shortening of about 8 days. Comparable GSL information was not reported for sorghum and was therefore excluded from the results. Shorter growing seasons help crops avoid terminal heat stress during flowering and water deficits during grain filling. However, they limit the time available for canopy expansion, biomass accumulation, and grain filling, thereby constraining final yield. In arid and semi-arid environments, this effect is especially important because accelerated development often occurs alongside water deficits and terminal heat stress, further compounding productivity losses. Thus, reduced GSL should be understood not only as a phenological consequence of warming, but also as one of the main pathways through which climate change lowers crop yield.

Although the dominant climate-driven impacts on crops across the reviewed studies were negative, a notable subset of the literature reported positive crop responses under specific environmental conditions. Approximately 31.5% of the simulation studies indicated some degree of yield improvement relative to the historical baseline. However, these benefits were conditional and typically associated with particular combinations of moderate warming, increased or adequate rainfall with increased CO_2 intake. Several studies suggested that moderate warming may improve crop productivity in higher-latitude regions by lengthening the effective growing season [36,86,102] or shifting temperatures toward a more favorable range [20,45]. For example, global wheat simulations showed increased productivity in higher-latitude regions [36], while some regional studies reported that warming improved maize performance where historical temperatures were below the crop's optimum range [45]. In other cases, positive yield responses were linked primarily to elevated CO_2 [39,41,86,101], which can improve radiation-use efficiency and water-use efficiency, particularly in C_3 crops, especially in controlled environments [106], and thereby partly offset climatic stress. In the extracted dataset, elevated CO_2 was identified as the main explanation for positive yield responses in all rice studies reporting gains, and in 60% and 52.6% of the maize and wheat studies, respectively. Nevertheless, these benefits should be interpreted cautiously, because CO_2 fertilization effects can be overestimated depending on how individual crop models represent photosynthesis and stomatal response [87]. Positive responses were also associated with improved rainfall conditions or relatively

modest warming in some locations. For instance, projected maize yield gains in parts of Uganda [55] and Argentina [66] were attributed largely to increased precipitation or more favorable rainfall distribution. However, even where water availability was improved through rainfall or irrigation drove such gains, an occurrence of severe heat stress could still override the benefits, especially for Wheat [100]. Overall, the literature suggests that positive responses to climate change are possible, but they are highly context-dependent and often insufficient to offset the dominant negative effects of warming and water stress in already warm and dry environments. Studies reporting yield gains rarely documented corresponding increases in GSL for maize and rice, although about 5% of the wheat studies reported increases of approximately 10 days.

3.3. Prominent Adaptation Measures and Their Applications

Adaptation strategies in the reviewed literature were generally defined as crop, soil, water, or management interventions that depart from existing practice in order to reduce climate-related yield losses or improve resilience. Although a wide variety of adaptation measures were reported, most clustered around a relatively small number of recurring strategies (Table 2). Common adaptation strategies included adjustments in planting or sowing date, cultivar or trait selection, irrigation management, nutrient management, planting density, cropping pattern modification, and soil moisture conservation practices. Across all the reported adaptation strategies, planting date adjustments, which included early or delayed planting or sowing depending on the crop and region [35,76,88,90,92,107–113], were the most frequently reported strategy. This strategy was typically intended to influence the crop phenology in such a way as to avoid temperature extremes at critical growth stages, which might otherwise negatively impact the yield. Genetically modified cultivars constituted another key strategy which was aimed at enhancing resilience to specific climatic conditions which cannot be avoided. These included heat-tolerant cultivars [68,84], drought tolerant cultivars [14,63,69,94], high-yielding cultivars [71,81,114], early-maturing cultivars [59,86,115], medium-maturing cultivars [74] and late-maturing cultivars [36,93,116]. For instance, early maturing varieties may escape terminal drought, while late-maturing ones may utilize extended wet periods. In some studies, root-related traits such as deeper or more proliferative root systems were also considered because of their potential to improve water extraction from deeper soil layers [47,81,102], while several other studies demonstrated synergistic benefits by combining one or more of these different genotypic traits, as well as with other management-based strategies to enhance resilience [48,53,54,77,101,117,118]. Irrigation management, which is often critical across arid and semi-arid regions [8], was also commonly implemented, often as supplemental irrigation or deficit irrigation [28,59,62,78,83,119,120], revised irrigation timing to enhance how water is scheduled and how much non-productive evaporation can be reduced, and conversion from rainfed to irrigated management to ensure crop survival during critical periods of water stress. Nutrient management, particularly increased or optimized nitrogen application [44,70,80,89,99,121–124], was also implemented in several studies to partially offset climate-related yield reductions and support optimal growth. Other strategies included increased planting density [31,45,75,87,95,104,121,124], alternative cropping patterns such as crop diversification or rotation to reduce dependency on a single crop and distribute climate risk [27,32,125–127], as well as soil residue and organic matter management through reduced-tillage [128], and addition of mulch or biochar [37,49,55,119,127,129], were also reported with the aim of improving soil moisture retention and moderating soil temperature. A few studies also reported the benefits of leveraging CO_2 enrichment from changing climatic patterns to mitigate losses, due to its effects on photosynthetic efficiency and water use dynamics [28,85,115].

Table 2. Summary of adaptation strategies and their effects on crop yield, growing season length (GSL), and other related variables for selected crops.

Crop	Adaptation	Variable	Range	Mean ±SD	References
Maize					
	Planting date	Yield	−40.00 to 118.00	16.67 ± 19.99	[29,38–41,45,46,49,52,54,56,58,60,61,64,66–68,72,76,128,130]
	Planting date	GSL	15.00 to 15.00	15.00	[46]
	Planting date	WUE	28.00 to 44.00	36.00 ± 11.31	[46,60]
	Irrigation	Yield	−6.47 to 48.29	17.95 ± 12.85	[40,42,49,51,59,60,64,67,72,130]
	Irrigation	WUE	17.00 to 17.00	17.00	[60]
	Nutrient management	Yield	2.90 to 84.20	43.58 ± 34.87	[39,49,55,57,59,72,130]
	Drought-tolerant cultivar	Yield	2.00 to 38.50	11.80 ± 12.79	[48,49,63,69]
	Heat-tolerant cultivar	Yield	1.00 to 84.00	28.04 ± 23.35	[43,46,48,60,68]
	Heat-tolerant cultivar	GSL	5.50 to 9.00	7.25 ± 2.47	[68]
	Cropping patterns	Yield	−10.00 to 15.90	3.17 ± 12.96	[58,73,128]
	Reduced tillage	Yield	3.40 to 77.50	28.17 ± 42.72	[49,73,128]
	Multi-strategy	Yield	−14.80 to 100.00	22.17 ± 27.41	[42,45,49,50,52–55,57,59–61,65,70–72,125,128,130]
	Multi-strategy	GSL	7.00 to 27.00	17.00 ± 11.55	[50,52]
	Multi-strategy	WUE	23.55 to 23.55	23.55	[50]
Rice					
	Planting date	Yield	−15.00 to 33.00	7.27 ± 13.66	[27,74–76,87,123,124,131]
	Nutrient management	Yield	7.00 to 27.13	19.58 ± 10.96	[37,123,131]
	Irrigation	Yield	2.00 to 20.00	11.00 ± 12.73	[51,131]
Sorghum					
	Planting date	Yield	−50.00 to 17.00	−1.20 ± 28.39	[79,80,82,132]
	Irrigation	Yield	4.50 to 50.00	28.78 ± 13.34	[42,78,79,82]
	Heat-tolerant cultivar	Yield	2.90 to 12.00	6.95 ± 3.17	[77,81]
	Multi-strategy	Yield	−6.75 to 50.00	13.26 ± 21.56	[79,81,132]
Wheat					
	Planting date	Yield	−52.00 to 138.50	12.40 ± 40.61	[20,49,52,60,66,84,87–89,93,95,96,98,104,116,133,134]
	Irrigation	Yield	−15.00 to 130.00	31.64 ± 42.44	[49,51,60,83,85,92,97,103,120,134,135]
	Irrigation	WUE	4.00 to 44.30	29.50 ± 22.18	[103,120,135]
	Nutrient management	Yield	−3.61 to 46.85	12.37 ± 18.85	[49,83,90,135]
	Multi-strategy	Yield	−37.80 to 40.00	5.80 ± 15.05	[30,36,42,49,60,83,85,86,91,100,102,120,136]

Overall Effectiveness of Adaptation Strategies on Crop Yield

Of the 563 yield simulations compiled in this review, approximately 65% evaluated adaptation practices. Maize accounted for about 51% of these simulations, followed by wheat (34%), sorghum (9%), and rice (6%), indicating that current evidence on adaptation effectiveness is concentrated mainly in maize- and wheat-based systems. Across all four crops, the results show that adaptation can substantially reduce climate-related yield losses, but its effectiveness is highly uneven across crops, practices, and environments.

For wheat and maize, nutrient management produced the largest mean yield gains among the major adaptation categories considered. In wheat, average yield increases were 15.1%, 36.6%, 43.0%, and 12.5% for cultivar-based strategies, irrigation management, nutrient management, and planting date adjustment, respectively (Figure 5d). For maize, the corresponding gains were 21.7%, 17.5%, 43.3%, and 15.7% (Figure 5a). Notably, some unusually high responses were reported under improved soil fertility. For example, Shahid et al. [137] reported wheat yield increases from 127.61% to 140.04% in Pakistan, while Akumaga et al. [122] simulated maize yield increases ranging from 120% to 182.9% in West Africa, and 127.4% to 203.6%, respectively, under near-optimal and optimal fertility conditions. These large responses highlight the critical importance of soil fertility in shaping adaptation outcomes.

Planting date adjustment was also one of the most widely tested strategies, but its effects were more variable. Across the compiled studies, early planting increased crop yield by 17.2% on average, compared with 7.1% for delayed planting (Figure 5), suggesting that earlier sowing is generally more effective. This likely reflects better alignment of sensitive

stages such as anthesis and grain filling with favorable temperature conditions, whereas delayed sowing often exposes crops to heat or cold stress during critical periods [105]. However, the data also show that sowing-date adaptation is highly context dependent. Naresh Kumar et al. [84] reported wheat yield declines of 45% and 52% in India under very late sowing in 2050 and 2080, respectively, while Srivastava et al. [41] found that delaying maize sowing by 10–20 days reduced yield by 30–50% under rainfed conditions in eastern India. In sorghum, the mean yield response to planting date adjustment was negative (−5.1%), and Kouressy et al. [132] reported yield declines of up to 50% even under optimal planting dates. These findings suggest that sowing-date adaptation is effective only when it successfully matches crop phenology to local rainfall and temperature patterns.

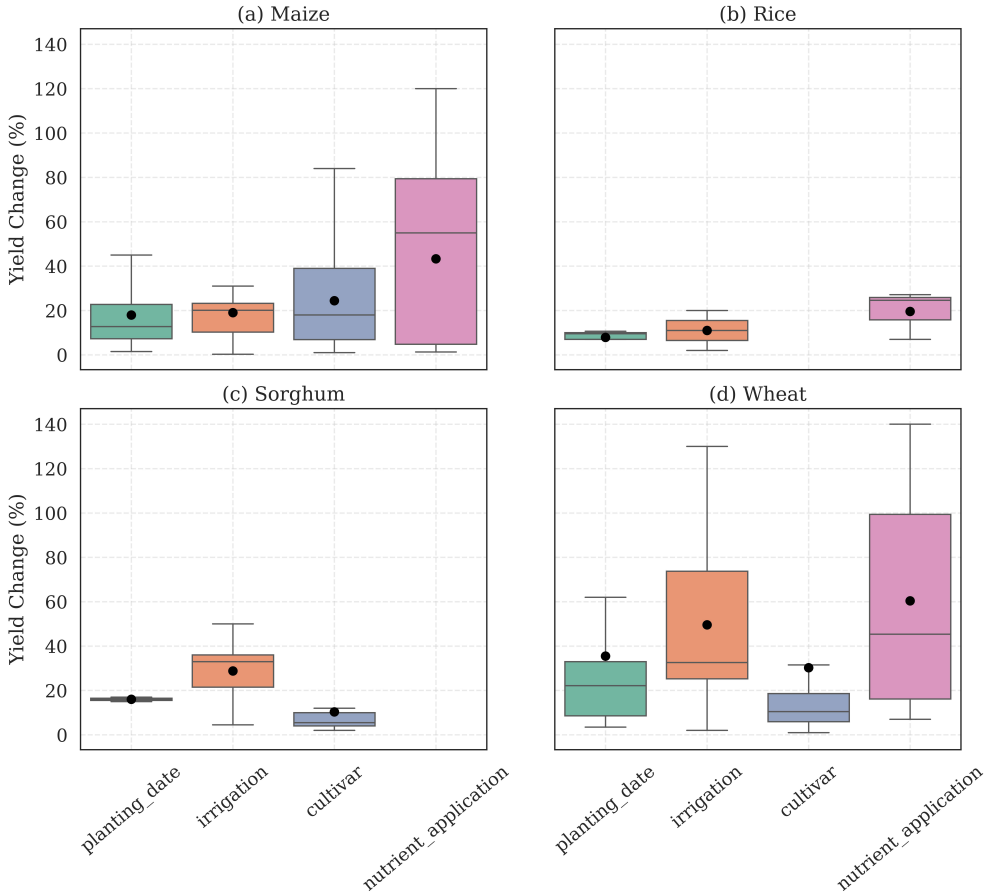


Figure 5. Effectiveness of adaptation strategies on (**a**) maize (**b**) rice (**c**) sorghum and (**d**) wheat yields. Nutrient management and irrigation consistently yielded the highest potential benefits, especially for maize and wheat.

Cultivar-based adaptation also showed mixed but generally positive effects. Across the dataset, heat-tolerant cultivars increased mean yield by 13.3%, and late-maturing cultivars by 16.0%, whereas early-maturing cultivars showed a slight mean decline of 0.2%. This contrast highlights that cultivar performance depends not simply on maturity class, but on how crop traits interact with local stress patterns. In some environments, early maturity may help escape terminal drought, but in others it may reduce the time available for biomass accumulation. Tahmasebi et al. [138], for example, reported a 19.6% variation in wheat yield associated with quantitative trait loci under flooding, drought, and heat stress, reinforcing the importance of trait-by-environment interactions in adaptation assessment.

Rice showed smaller and less consistent responses than wheat and maize. Mean yield gains were 0.7% for planting date adjustment, 11.0% for irrigation management, and 19.6% for nutrient management (Figure 5b). Deb et al. [123] reported that doubling fertilizer

application in Vietnam increased simulated rice yield by 32.11% for the 2025s, 14.56% for the 2055s, and 11.76% for the 2085s under the A2 scenario, suggesting that nutrient-related benefits may weaken under stronger future climate stress. Likewise, Wang et al. [27] showed that optimized planting dates increased annual caloric yield in rice-wheat rotation systems by 10% under RCP 4.5 but reduced it by 15% under RCP 8.5, indicating that the effectiveness of calendar-based adaptation may diminish under more severe warming.

Although the evidence base is smaller and more diverse, the evaluated research also demonstrated that adaptation effects are often stronger when multiple practices are combined. On average, combined adaptation strategies increased yield by 12.3% for maize, 20.3% for rice, and 41.9% for wheat, compared with 21.9%, 5.9%, and 20.4%, respectively, for single strategies. While this pattern suggests that integrated management practices can generate synergistic benefits, especially in wheat and rice, the comparison lacks robustness, as relatively few studies evaluated multiple adaptations, and the combinations tested differed substantially among studies. Even so, the overall trend supports the view that no single adaptation practice is universally effective. This is also consistent with the earlier meta-analysis reported by the IPCC Working Group II [139], which found mean yield gains of 15–18% from management-based adaptation in wheat, rice, and maize, but also emphasized that outcomes range from negative to strongly positive.

3.4. Spatial Patterns in Adaptation Effectiveness and Limiting Factors

We assessed how adaptation effectiveness varies spatially by comparing each location's realized benefit to the global mean potential for the same adaptation category. The resulting adaptation effectiveness gap is negative when a location outperforms the global mean and positive when it underperforms. The global mean gap across all locations was 7.33%, indicating that most study locations achieved slightly higher benefits than the global average for their respective adaptation strategies. Many locations in East Asia, South Asia, and Eastern Africa exhibit positive gaps (underperformance relative to global mean potential), while parts of Europe and North America show negative gaps (overperformance), suggesting that adaptation measures in these regions frequently exceeded global mean performance (Figure 6). Across the reviewed studies, the reported limiting factors that influenced adaptation effectiveness were grouped into four categories: modeling, data, methodological, and resource-related limitations. Modeling limitations were the most frequently reported and included cases where the model could not fully represent processes such as extreme events like heatwaves and heavy rainfall, as well as the effects of pest and disease pressure, water stress, elevated CO_2, photoperiod effects, or complex multi-cropping systems. Data limitations were associated with challenges like coarse soil information, limited cultivar-specific parameterization, and weak local calibration datasets. Resource limitations included constraints such as water scarcity, limited irrigation expansion, fertilizer shortages, and restricted access to improved crop varieties. Methodological limitations generally consisted of challenges arising from simplifying assumptions in scenario design or management, including uniform warming, constant prices or input costs, and the omission of socio-economic factors. Notably, the spatial distribution of dominant limitations showed clear regional clustering. Modeling limitations, despite being frequently reported, were associated with the most negative gaps (–29.46%), meaning that locations reporting these limitations actually outperformed the global mean by a wide margin. These limitations were most common in East Asia and Eastern Europe. Methodological limitations also corresponded to better-than-average performance (−11.32%), particularly in South Asia. In contrast, data limitations were associated with slightly worse performance (+1.64 percentage points above baseline) and were concentrated in Sub-Saharan Africa, reflecting persistent challenges in observational and experimental datasets. Error-propagation

limitations were the only category associated with clear underperformance (+5.68), suggesting that uncertainty-related constraints may meaningfully suppress adaptation benefits in some regions.

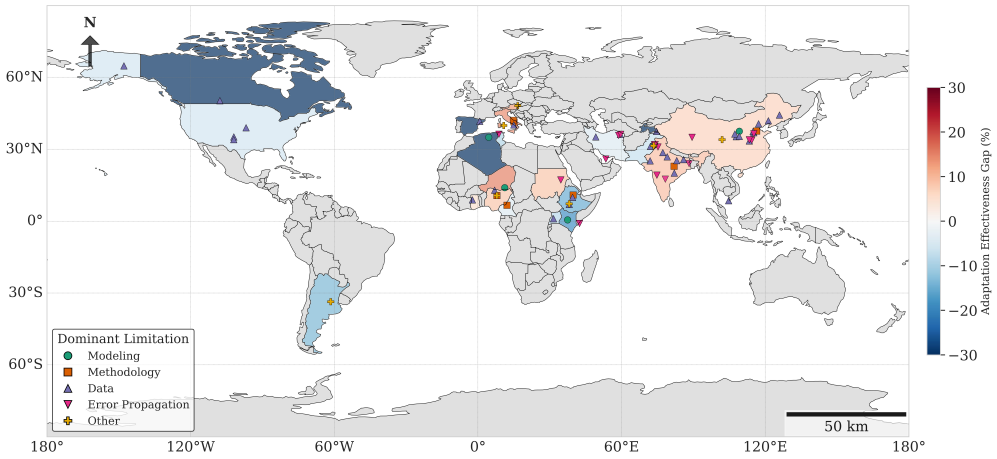


Figure 6. Spatial distribution of adaptation effectiveness gaps and limiting factors. Negative values indicate that a location performs better than the global mean, while positive values indicate underperformance. Marker shapes indicate the dominant limitation reported in each study.

3.5. Critical Gaps and Potential Future Pathways for Enhancing Resilience of Crops and Cropping Systems

Although the literature demonstrates that adaptation can offset a portion of climate-induced yield losses, several critical gaps limit the robustness, scalability, and contextual relevance of current adaptation assessments. A central insight from this review is that adaptation effectiveness is highly context-dependent, such that the same strategy can overperform in one environment yet underperform in another with similar climatic conditions. This reflects the importance of local interactions among genotype, environment, and management. Across these three sections, several methodological gaps emerge. First, adaptation studies remain heavily concentrated in maize and wheat, with far fewer analyses for rice, sorghum, and barley, especially in Africa and parts of South Asia. This imbalance constrains the ability to generalize adaptation outcomes across cereal systems and to design strategies for underrepresented crops that are critical to regional food security. For researchers and modelers, the results point to the need for greater emphasis on underrepresented crops, as well as multi-crop assessments, especially in data-scarce regions, to allow comparison of adaptation performance across cereals within the target agro-ecological zone.

Secondly, most studies examined climate change as an isolated mean change in a single factor such as shifts in temperature and precipitation, while compound extremes, such as concurrent heat and drought, erratic rainfall patterns, and extreme event timing, remain insufficiently explored, despite their growing relevance under climate change. Also, regions with sparse observational networks and limited experimental datasets (e.g., parts of Sub-Saharan Africa and South Asia) tend to show larger adaptation effectiveness gaps and greater data-related limitations. In contrast, locations reporting mainly methodological or modeling constraints often achieve above-average adaptation benefits, likely reflecting stronger analytical capacity and data availability. Addressing these structural inequities requires coordinated field trials, improved long-term monitoring of climate and crop responses, and open data initiatives that support calibration and validation of process-based models in data-poor regions.

Farmer management decisions and resource constraints also strongly shape adaptation outcomes and can be complex based on individual needs. However, many model-based assessments simplify these management decisions to fixed quantities, such as fertilizer doses, uniform irrigation schedules, or single cultivar choices, which can overestimate or understate reality. This simplification partly explains why simulated adaptation sometimes performs better than what is observed in practice, particularly in regions with limited input access or infrastructure. Studies should therefore represent realistic management heterogeneity, including input constraints, adoption barriers, and risk preferences, and link crop models more explicitly with socio-economic and decision frameworks.

Overall, the findings highlight a need to transition from isolated, single-factor adaptation experiments to integrated assessments that explicitly consider genotype, environment, and management interactions under compound stress. Such assessments should leverage higher-resolution climate inputs, multi-model ensembles, and robust uncertainty analysis, while also incorporating realistic management and socio-economic constraints. Addressing these modeling gaps is critical for enhancing climate adaptation to not only be technically effective in simulations, but also implementable and scalable in the diverse production landscapes of arid and semi-arid regions. Although these limitations highlight the critical gaps, a risk of study bias exists. The use of strict search filters, including the word 'adapt ', may exclude relevant studies that describe interventions using alternative terminology. Future evidence syntheses should consider a broader set of search terms to improve the coverage of literature. Additionally, because several studies contributed multiple simulation outcomes, either through different climate scenarios or adaptation strategies, the synthesized observations are not fully independent. As a result, the descriptive statistics here should be interpreted as summaries of the available simulation evidence rather than statistically independent estimates of adaptation effects. Future reviews should therefore consider formal meta-analytic approaches, together with explicit quantification of uncertainties, to improve inference from heterogeneous simulation studies. Another important limitation is the uneven geographic distribution of the reviewed literature. The concentration of studies in a few countries may influence the overall conclusions and limit the generalization of the findings to underrepresented regions. The strong increase in publications over time also reflects broader developments in climate change research, including the expansion of crop modeling applications and the growing influence of successive IPCC assessment reports in shaping adaptation-oriented research efforts. In addition, the evidence base was limited due to inaccessibility of some full texts. Broader institutional access and greater use of open-access repositories are encouraged to reduce retrieval bias and improve the completeness of the evidence base.

Finally, future studies would benefit from greater use of ensemble crop modeling to better represent structural uncertainty across models and to improve confidence in projected climate impacts and adaptation benefits. Improved model calibration and validation using long-term field data are also needed, particularly in data-scarce regions where model performance is more uncertain. In addition, the wider adoption of Shared Socioeconomic Pathway (SSP) scenarios would help align crop impact assessments with more recent climate projections and socio-economic futures.

4. Conclusions

This review shows that climate change continues to pose a persistent threat to cereal production in arid and semi-arid regions primarily through yield reductions and shortened growing seasons under warming and altered precipitation patterns. At the same time, the evidence demonstrates that well-targeted adaptation can offset a meaningful share of these losses, particularly when strategies are tailored to local conditions. These findings

imply that the effectiveness of adaptation outcomes is driven less by the choice of strategy alone and more by how that practice interacts with local genotype, environment, and management conditions. Earlier sowing, cultivar choice, irrigation scheduling, and nutrient management all produced positive results, but only when they matched the timing and intensity of local stress. This explains why the same strategy can succeed in one environment and fail in another that appears similar. Finally, an analysis of where adaptation potential is being realized and where it is not revealed that regions with strong data and modeling capacity frequently exceed global mean adaptation benefits whereas data-poor regions with higher uncertainty often underperform, even when similar adaptation types are implemented. Combining improved data, robust modeling, and locally grounded management interventions enhances the capability of agriculture to move toward more systematic, scalable climate resilience across arid and semi-arid regions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land15081449/s1, Table S1. Database-specific search strings used for the systematic review; PRISMA_2020_abstract_checklist; PRISMA_2020_checklist.

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