Journal of Aquatic and Terrestrial Ecosystems
Journal ISSN: 2960-1118
4(1)
Received: January 21, 2026
Accepted: April 11, 2026
Published: April 30, 2026

Biophysical Drivers and Spatiotemporal Dynamics of Maize Productivity Decline in Kenya: A Review of Climate Impacts and Environmental Planning Responses

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Abstract

Maize (*Zea mays L.*) is the cornerstone of Kenya's food security and agricultural economy, yet productivity across the country's diverse agro-ecological zones is declining under the compounding pressures of climate change. This integrative review synthesizes evidence from 36 studies published between 2015 and 2026 to examine the biophysical drivers and spatiotemporal dynamics of maize productivity decline in Kenya, and to critically evaluate the alignment between these biophysical realities and existing environmental planning responses. The analysis identifies three primary biophysical pathways underpinning productivity decline: phenological compression, driven by rising temperatures that shorten the growing cycle by 34–38 days in highland zones; thermal stress and pollen sterility, with each 1°C above optimal thresholds reducing yields by approximately 5%; and soil-climate synergism, wherein declining soil organic carbon amplifies moisture stress and nutrient deficiency, with productivity losses of 20–50% in unfertilized systems. These pathways interact across a stark agro-ecological gradient that is being progressively flattened by climate change, as high-potential western highland regions contributing over 80% of national output experience accelerated degradation while arid and semi-arid lands face intensified climatic extremes. Temporal dynamics reveal a shift from predictable seasonality toward heightened inter-annual and intra-seasonal variability, undermining traditional farming calendars and amplifying production uncertainty. Despite an elaborate environmental planning architecture including the Climate Change Act (2016), National Adaptation Plan (2015–2030), and Kenya Climate Smart Agriculture Strategy (2017–2026) planning responses remain structurally decoupled from mechanistic biophysical realities. Critical disconnects persist in spatial targeting, temporal horizon alignment, monitoring and evaluation capacity, and institutional coordination between national and county levels. County plans are structured around administrative wards rather than agro-ecological zones, are constrained by five-year political cycles that mismatch decadal biophysical trends and rely on climate information too coarse to capture farm-level variability. The review concludes that addressing these disconnects requires planning frameworks restructured around agro-ecological realities, nested across multiple temporal scales, grounded in high-resolution biophysical monitoring, and coordinated through unified institutional mechanisms. Without such reorientation, substantial investments in climate adaptation risk being misdirected toward interventions that fail to protect the most nationally significant production zones, undermining Kenya's food security in an era of accelerating climate change.

Keywords: Maize Productivity, Climate Variability, Biophysical Mechanisms, Spatiotemporal Analysis, Environmental Planning, Kenya, Food Security

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Funding: The author received no financial support for the research, authorship and/or publication of this article

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials or upon reasonable request.

Competing interests: The authors declare no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

Introduction

Background Information

Maize (*Zea mays* L.) is one of the most important cereal crops globally, serving as a staple food for millions of people, particularly in developing countries (Amanjyoti et al., 2024; Kaushal et al., 2023; Suganya et al., 2020). It is highly adaptable, cultivated across temperate to tropical zones, and versatile in its uses providing food, animal feed, and raw materials for industrial products including biofuels (Dabija et al., 2021; Visković et al., 2024). Nutritionally, maize is rich in carbohydrates and essential vitamins and minerals, playing a crucial role in global food security, particularly in sub-Saharan Africa and Latin America where it forms a significant part of the daily diet (Galani et al., 2022; Goredema-Matongera et al., 2021; Grote et al., 2021). The crop is also economically significant, contributing to both smallholder agriculture and large-scale commercial farming (Santpoort, 2020).

Global maize production has expanded significantly over recent decades, driven by advances in agricultural technologies, improved crop varieties, and increased demand for food and non-food uses. The United States, China, and Brazil are the largest producers, collectively accounting for more than 60% of global output. Global corn production in 2023 reached 1.15 billion metric tons, with the International Grains Council forecasting a record 1.233 billion metric tons for the 2024–2025 season (Development Aid, 2024). Despite these advancements, maize production faces significant challenges including climate variability, pest infestations, and market fluctuations that impact global supply and demand dynamics (FAO, 2020).

In Kenya, maize is the main staple food crop and is of vital concern to agricultural policy decisions, food security, and overall economic development (Njora & Yılmaz, 2021). The crop is grown in nearly all regions, but the Rift Valley, Western, and Nyanza regions are the major producing areas, accounting for over 80% of national output (Ochola et al., 2024). Maize contributes over 3% to gross domestic product and 12% to agricultural GDP and is consumed by 85% of the population (Ngeno, 2024). Total maize yield in Kenya ranged from 1.43 to 1.82 tons per hectare from 2010 to 2018 (FAO, 2018). Most production comes from smallholder rural farms, where over 75% of maize is grown by resource-constrained farmers with limited access to agricultural inputs such as fertilizers, improved seeds, and pesticides (Aguk et al., 2021; Njagi et al., 2019). These farmers cultivate maize in diverse agroecological zones ranging from high-potential regions with adequate rainfall to semi-arid areas prone to drought (Njeru et al., 2023).

Despite its socio-economic significance, maize productivity in Kenya has stagnated and declined across many regions due to persistent biophysical and climatic stresses (Kipkulei et al., 2025). There is an increasing gap between production and consumption, with growing frequency of supply shortages. Kenya's maize production systems operate within diverse agroecological zones ranging from humid highlands to semi-arid lowlands, experiencing varying rainfall patterns, soil conditions, temperature regimes, and environmental pressures that directly influence growth and yields. Historically, high-potential areas such as Trans Nzoia, Uasin Gishu, Nakuru, and Bungoma counties supported stable production due to favorable climatic conditions and fertile soils. However, changing climatic patterns, land degradation, and ecological stressors have increasingly disrupted these systems (Kogo et al., 2019; Kipkulei et al., 2025).

Climate change has emerged as a major driver of agricultural instability in sub-Saharan Africa, with maize identified among the most climate-sensitive crops. In Kenya, rainfall variability and increasing temperatures have altered planting seasons, shortened growing periods, and intensified crop moisture stress (Kerich et al., 2025). Climate models project continued warming and increased frequency of extreme weather events including droughts and floods, threatening the sustainability of rain-fed maize farming systems (Kogo et al., 2022; Omoyo et al., 2015). Temperature increases during critical growth stages such as flowering and grain filling have been linked to significant yield reductions, as high temperatures accelerate evapotranspiration, reduce soil moisture availability, and impair physiological processes such as pollination and grain development (Bhattacharya, 2022). Counties in arid and semi-arid lands face more severe challenges due to water scarcity and fragile ecological conditions. Research indicates that future climate scenarios could reduce maize yields in Kenya by between 7% and 41% depending on emission pathways, geographic location, and adaptation capacity (Kipkulei et al., 2025).

Beyond climate variability, several biophysical factors contribute to productivity decline. Soil degradation, driven by nutrient mining, erosion, and continuous cultivation without adequate replenishment, has severely limited the yield potential of Kenyan soils (Naik et al., 2025). Furthermore, the heavy reliance on rain-fed systems leaves the crop acutely vulnerable to moisture deficits during germination and thermal stress during reproductive stages (Salat & Swallow, 2018; Bhattacharya, 2022). As these spatiotemporal dynamics evolve, the integration of remote sensing and crop simulation models has become indispensable for predicting productivity trends and identifying vulnerable regions (Kipkulei et al., 2025). Addressing these challenges necessitates a robust environmental planning approach, incorporating climate-smart agriculture (CSA), integrated soil fertility management (ISFM), and evidence-based land-use policies to secure the future of maize-based livelihoods in Kenya (Imran, 2024; Oluoch et al., 2022).

Statement of the Problem

Despite extensive research on climate change and Kenyan agriculture, a critical knowledge gap exists regarding the convergence of biophysical mechanisms, spatiotemporal variability, and environmental planning frameworks. Existing studies frequently treats climatic variables in isolation or focuses on localized case studies, failing to synthesize how multi-dimensional stressors such as soil moisture deficits during sowing, reproductive heat stress, and pest range expansion manifest differentially across Kenya's diverse agro-ecological zones (AEZs). While process-based models (e.g., Bwambale & Mourad, 2025) and remote sensing analyses (Ondiek et al., 2024) have documented historical and projected yield declines, there is no comprehensive review that integrates these biophysical realities with the spatial efficacy of the planning responses intended to mitigate them. The current landscape of environmental planning in Kenya is characterized by a significant spatial and structural mismatch. Adaptation strategies, including the National Adaptation Plan and the Climate Smart Agriculture Strategy, emphasize irrigation and technological interventions; however, evidence suggests these are often not spatially targeted to the counties experiencing the most severe biophysical stress (Kamiri et al., 2026). Furthermore, the devolution of authority under the 2010 Constitution has resulted in a fragmented institutional environment. Multiple, uncoordinated instruments ranging from County Integrated Development Plans (CIDPs) to County Spatial Plans (CSPs) operate with varying temporal horizons and distinct mandates, leading to inconsistencies in how climate-risk prioritization is applied to the maize sector across jurisdictions (Government of Kenya, 2022). This institutional fragmentation is compounded by a fundamental temporal disconnect. Biophysical degradation, such as soil organic carbon depletion and the progressive loss of thermal suitability in highland grains baskets operates on decadal timescales. In contrast, Kenyan planning processes are largely driven by five-year political and budgetary cycles. This mismatch often results in reactive planning that addresses immediate climate shocks such as emergency drought relief rather than tackling the underlying structural vulnerabilities of the maize system (Mnukwa et al., 2025; Government of Kenya, 2022). Additionally, the continued reliance on top-down climate projections in formal planning often marginalizes indigenous ecological knowledge and micro-climatic nuances that are essential for effective local adaptation. Consequently, there is an urgent need to determine the extent to which Kenya's environmental planning frameworks are structurally and spatially aligned with the mechanistic realities of climate-driven maize productivity decline. This review addresses this gap by synthesizing literature on biophysical stressors, spatial yield dynamics, and policy frameworks to identify where planning interventions fail to bridge the divide between crop science, climate modeling, and regional spatial planning.

Methodology

Study Design and Approach

This study employed an integrative review methodology to synthesize evidence on the biophysical drivers and spatiotemporal dynamics of maize productivity decline in Kenya and to critically evaluate the alignment between these biophysical realities and existing environmental planning responses. An integrative review was selected because it permits the inclusion of diverse methodological traditions such as including experimental crop science, spatial modeling, policy analysis, and institutional assessment thereby enabling a comprehensive understanding of the climate-maize-planning nexus (Whittemore & Knafl, 2005). This approach was particularly suited to the study's objective of bridging biophysical and social-science literatures, which are typically siloed in separate disciplinary domains. The review was structured according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency, replicability, and rigor in the identification, screening, and synthesis of literature (Page et al., 2021).

Search Strategy and Information Sources

A systematic literature search was conducted across multiple electronic databases to identify peer-reviewed articles, gray literature, and policy documents published between 2015 and 2025. The databases searched included Web of Science, Scopus, PubMed, Google Scholar, and the Directory of Open Access Journals. Gray literature and policy documents were retrieved from institutional repositories including the Kenya National Bureau of Statistics, the Ministry of Agriculture, Livestock, Fisheries and Cooperatives, the National Environment Management Authority, the United Nations Development Programme, and the World Bank Open Knowledge Repository. The search strategy employed a combination of controlled vocabulary and free-text terms organized into three conceptual clusters: (1) climate and biophysical drivers; (2) maize production and productivity; and (3) environmental planning and policy. Search strings were adapted to the syntax of each database and included terms such as "climate variability," "drought," "heat stress," "soil degradation," "maize yield," "productivity decline," "Kenya," "environmental planning," "spatial planning," "climate adaptation policy," "county climate change action plan," and "agro-ecological zones." Boolean operators (AND, OR) were used to combine terms within and across clusters. The search was conducted in English, reflecting the dominant language of scientific and policy discourse in Kenya. Reference lists of included studies were manually screened to identify additional relevant sources, and forward citation tracking was performed using Google Scholar to capture recent publications citing seminal works.

Eligibility Criteria and Study Selection

Inclusion and exclusion criteria were established prior to the search to guide study selection. Studies were included if they: (1) examined biophysical drivers of maize productivity change in Kenya, including but not limited to drought, temperature stress, soil degradation, and pest or disease pressure; (2) analyzed spatiotemporal patterns of maize yield or production at sub-national scales, including county, agro-ecological zone, or farm-level analyses; (3) evaluated environmental planning, climate adaptation policy, or spatial planning instruments relevant to Kenyan agriculture; or (4) integrated biophysical and planning dimensions to assess climate adaptation in maize systems. Studies were excluded if they: (1) focused exclusively on crops other than maize; (2) were conducted outside Kenya without comparative relevance to Kenyan contexts; (3) were purely methodological papers on crop modeling or remote sensing without application to Kenyan maize systems; or (4) addressed climate change education or curriculum design, as these fell outside the scope of the present review. The study selection process involved two stages. First, titles and abstracts of all retrieved records were independently screened by the lead author against the eligibility criteria. Second, full texts of potentially relevant studies were retrieved and assessed for final inclusion. Disagreements were resolved through discussion and consensus. The selection process was documented using a PRISMA flow diagram, recording the number of records identified, screened, assessed for eligibility, and included in the final review (Page et al., 2021).

Data Extraction and Synthesis

A standardized data extraction form was developed and piloted on a subset of five studies to ensure consistency and comprehensiveness. The form captured bibliographic information, study objectives, methodological approach, geographic focus, temporal scope, biophysical variables examined, yield or productivity metrics, planning or policy instruments assessed, key findings, and limitations. For studies employing quantitative methods, data on effect sizes, statistical significance, and spatial or temporal trends were extracted. For qualitative policy analyses, data on institutional arrangements, implementation challenges, and stakeholder perspectives were recorded. Data extraction was performed by the lead author and verified by a second reviewer to minimize error and bias. The synthesis of extracted data followed a two-stage analytical framework. In the first stage, studies were grouped according to their primary focus: biophysical mechanisms, spatiotemporal dynamics, or environmental planning responses. Within each group, thematic analysis was conducted to identify recurrent patterns, convergent findings, and divergent evidence. In the second stage, cross-cutting synthesis was performed to examine intersections between biophysical and planning literatures, identifying alignments, gaps, and contradictions. This integrative synthesis drew on the framework synthesis method, which combines inductive identification of themes from primary studies with deductive application of a priori concepts from planning theory and climate adaptation studies (Barnett-Page & Thomas, 2009).

Quality Appraisal

The quality of included studies was assessed using standardized critical appraisal tools appropriate to each study design. Quantitative experimental and observational studies were evaluated using adapted versions of the Cochrane Risk of Bias tool and the Newcastle-Ottawa Scale, respectively (Higgins et al., 2011; Wells et al., 2014). Qualitative studies and policy analyses were appraised using the Critical Appraisal Skills Programme qualitative checklist (CASP, 2018). Mixed-methods studies were assessed using the Mixed Methods Appraisal Tool (Hong et al., 2018). Quality appraisal was conducted independently by two reviewers, with disagreements resolved through discussion. The results of quality appraisal were used to weight the contribution of individual studies to the synthesis, with higher-quality studies given greater evidentiary weight in the formulation of conclusions. However, no studies were excluded solely on the basis of quality, as the review aimed to capture the breadth of available evidence, including emerging or policy-oriented literature that may not meet strict methodological criteria but provides essential contextual insight (Whittemore & Knafl, 2005).

Analytical Framework

The analytical framework guiding this review was developed through an iterative process combining deductive and inductive reasoning. The deductive component drew on established conceptual frameworks in climate adaptation and environmental planning, including the socio-ecological systems framework (Berkes & Folke, 1998), the climate vulnerability framework (Turner et al., 2003), and the adaptive governance literature (Folke et al., 2005). These frameworks informed the identification of key analytical categories, including exposure, sensitivity, adaptive capacity, institutional fit, and scale mismatch. The inductive component allowed emergent themes from the primary literature to refine and extend these categories, ensuring that the synthesis remained grounded in the empirical evidence rather than forcing data into predetermined conceptual boxes. The final analytical framework organized the review around three interconnected dimensions: (1) biophysical drivers; (2) spatiotemporal dynamics and (3) environmental planning responses, covering national policy frameworks, county spatial plans, institutional arrangements, and implementation gaps.

Limitations of the Methodological Approach

Several limitations of this methodological approach were acknowledged. First, the reliance on English-language sources may have excluded relevant literature published in Swahili or local languages, potentially biasing the review toward externally generated research and policy analysis. Second, the heterogeneity of study designs, spatial scales, and temporal periods across the included literature precluded formal meta-analysis of effect sizes, limiting the quantitative precision of conclusions regarding the magnitude of climate impacts on maize yields. Third, the integrative nature of the review, while enabling cross-disciplinary synthesis, required interpretive judgments about the relevance and weighting of diverse evidence types, introducing subjectivity that was mitigated but not eliminated through structured appraisal and dual-reviewer verification.

Results and Discussion

Overview of the Reviewed Studies

This review synthesized evidence from 36 studies published between 2015 and 2026, organized across three thematic areas: biophysical drivers of maize productivity decline (9 studies, 25%), spatiotemporal dynamics of maize productivity (12 studies, 33%), and environmental planning responses and their alignment with biophysical realities (10 studies, 28%), with 5 studies (14%) spanning multiple thematic areas. The reviewed studies employed diverse methodological approaches, including crop simulation modeling (8 studies), spatial analysis and GIS (7 studies), field experiments (6 studies), policy and document analysis (5 studies), meta-analyses and scoping reviews (4 studies), survey research (3 studies), ecological niche modeling (2 studies), and integrated assessment modeling (1 study). Geographically, 14 studies examined national-level patterns in Kenya, 10 focused on multi-county or regional analyses, 8 presented single-county case studies, and 4 adopted an East Africa regional perspective incorporating Kenya. The evidence base was dominated by recent publications, with over 70% of studies published between 2022 and 2026, reflecting the rapidly evolving research attention to climate-maize interactions and adaptation planning in Kenya.

Biophysical Drivers of Maize Productivity Decline

The synthesis of literature revealed that maize productivity decline in Kenya was driven by a complex interplay of abiotic and biotic stressors operating through three primary biophysical pathways. These pathways such as phenological compression, thermal stress and pollen sterility, and soil-climate synergism interacted across multiple spatial and temporal scales to undermine maize physiology, with each pathway exhibiting distinct mechanistic signatures and differential severity across Kenya's agro-ecological zones.

Phenological compression represented an emerging and intensifying threat in highland production zones. Mnukwa et al. (2025) applied crop simulation modeling using DSSAT and downscaled climate projections for Nakuru and surrounding highland counties, demonstrating that rising mean temperatures accelerated plant development and effectively "rushed" the crop to maturity. Their analysis projected a reduction in growing duration by 34 to 38 days by the 2050s, leading to biomass accumulation deficits and yield reductions ranging from 2.7% to 26.5% depending on cultivar type and emission scenario. Early maturing cultivars showed relatively higher resilience than late-maturing varieties, suggesting that thermal acceleration of crop development significantly reduced grain filling duration and compromised the crop's ability to accumulate sufficient photosynthate for grain formation. The mechanistic basis for this decline resided in the temperature-driven acceleration of developmental rates; as thermal time accumulation increased, the vegetative and reproductive phases were truncated, reducing the duration of light interception and assimilate deposition into harvestable grain. Kipkulei et al. (2025) extended this understanding through county-scale modeling, projecting substantial maize productivity declines in several counties due to rising temperatures and rainfall variability, with some counties experiencing yield reductions exceeding 30% under severe warming scenarios. Their analysis concluded that climate change would significantly alter maize suitability patterns and increase spatial inequality in agricultural productivity across Kenya, revealing that future productivity trajectories would be characterized not merely by uniform decline but by spatial restructuring, with some counties potentially becoming unsuitable for maize production while others experienced intensified production pressure.

Thermal stress and pollen sterility operated across multiple agro-ecological zones but with intensifying severity as warming progressed. Maize is highly sensitive to temperatures exceeding 30–35°C during reproductive stages, with physiological damage manifesting through desiccation of silks, reduced pollen viability, and impaired fertilization. Gachathi and Nzengya (2026) confirmed in their meta-analysis of tropical maize systems that each 1°C of warming above the optimal threshold resulted in an average 5% yield loss due to these reproductive failures. Bwambale and Mourad (2025) provided complementary process-based evidence, projecting yield declines of 7.9% under RCP4.5 and up to 25% under RCP8.5 by mid-century, escalating to 36% by end-of-century under high-emission scenarios. Their modeling established that elevated temperatures above 30°C accelerated plant senescence and reduced kernel formation, with each degree above 30°C decreasing grain yield by 1% under optimal rain-fed conditions and 1.7% under drought conditions. Heat stress impaired pollen viability, germination rates, and silk receptivity, with temperatures exceeding 32°C causing irreversible damage to male gamete development and subsequent kernel abortion.

Qasim (2025) demonstrated that increasing consecutive dry days and rising temperatures significantly reduced simulated maize yields across Kenya from 1983 to 2016, with pronounced negative correlations between yield and both mean temperature and hot day frequency in eastern and southern lowland regions. The geographic extent of this thermal stress was expanding; as temperatures rose in historically cooler highland zones, areas previously considered thermally optimal were approaching or exceeding critical thresholds, while already warm ASAL regions experienced more frequent and sustained episodes of heat stress during the sensitive reproductive window. The soil-climate synergism represented a foundational and spatially pervasive pathway that amplified the effects of both phenological compression and thermal stress. Cirad (2026) investigated the combined effects of soil organic carbon depletion and climate variability on maize productivity in East African farming systems including Kenya, using long-term soil fertility simulations and integrated nutrient management scenarios. Their findings showed that declining soil organic carbon significantly reduced soil moisture retention and nutrient availability, creating a biophysical feedback loop in which climate stress and soil degradation reinforced one another. In scenarios lacking integrated fertilization, maize productivity declined by 20–50% over future decades, demonstrating that soil degradation interacted synergistically with climate stress to intensify yield decline. Laub et al. (2024) modeled the effects of integrated soil fertility management on maize production and soil carbon dynamics in Kenya using the DayCent simulation model calibrated with Kenyan field data, finding that integrated soil fertility management improved maize yields substantially compared to unfertilized systems and that soil organic carbon increased under integrated nutrient management, improving moisture retention and nutrient cycling. Their analysis underscored that restoring soil fertility was central to reducing maize productivity decline under changing climatic conditions.

Bowers et al. (2024) assessed the effectiveness of zai pits and manure application in semi-arid southern Kenya through experimental field trials, finding that zai pits combined with manure significantly improved maize growth, moisture retention, and productivity compared to conventional surface planting, with maize performance improving most in manure-treated zai systems. Miriam et al. (2025) examined organic and inorganic soil fertility inputs in semi-arid Kenyan farming systems, finding that combining farmyard manure with inorganic fertilizers improved soil fertility and increased crop productivity substantially compared to untreated controls, with yield increases reaching up to 383% relative to non-fertilized systems. These findings demonstrated that soil restoration was central to reducing maize productivity decline, but that the spatial feasibility and economic viability of such restoration varied markedly across Kenya's agro-ecological gradient. This pathway was not uniformly distributed; intensively cultivated highland areas with historically high production exhibited more severe soil degradation due to sustained nutrient mining and limited organic matter replenishment, while ASAL regions faced inherently poor soils further depleted by erratic rainfall and limited biomass inputs. The spatial pattern of soil degradation thus partially inverted the apparent productivity gradient, with the highest-yielding zones experiencing the most rapid erosion of their biophysical foundation.

The interaction among these three pathways created compounding effects that exceeded the additive impacts of individual stressors. Phenological compression reduced the temporal window during which the crop could accumulate biomass, while thermal stress damaged the reproductive organs responsible for converting that biomass into grain. Simultaneously, soil degradation reduced the plant's capacity to access water and nutrients, diminishing its ability to withstand either thermal or temporal stress. Drought stress operated synergistically with heat stress to compound yield losses; prolonged dry spells during the critical flowering and grain-filling stages reduced photosynthetic efficiency and restricted assimilate allocation to developing kernels, while elevated temperatures increased evaporative demand and accelerated soil moisture depletion.

Biotic stressors represented an increasingly significant dimension of the biophysical driver complex, with climate change expanding the geographic range and seasonal activity of key pests and diseases. Warmer and more humid conditions facilitated the spread of fall armyworm (*Spodoptera frugiperda*), maize lethal necrosis, and maize streak virus, causing yield losses ranging from 20 to 40% in affected areas (Kabara et al., 2026; Wambugu et al., 2023). The interaction between abiotic and biotic stressors created feedback loops that diminished adaptive capacity; water-stressed plants exhibited reduced vigor and heightened susceptibility to pest infestation and disease pressure, while pest damage further compromised the plant's ability to withstand subsequent climatic stress (Wambugu et al., 2023). These biotic stressors were not independent of the three primary pathways but were mechanistically linked to them; phenological compression reduced the duration of vegetative resistance, thermal stress weakened plant immune responses, and soil degradation reduced the metabolic resources available for defense.

Spatiotemporal Dynamics of Maize Productivity

Kenya's maize productivity is shaped by a stark agro-ecological gradient that is being progressively flattened by climate change. Ondiek et al. (2024) documented this gradient, with the Lake Victoria basin and Highlands East of the Rift Valley maintaining yields of 7.93 to 46.40 metric tons per hectare, while ASAL regions in the North Eastern and South Eastern lowlands experienced chronically low yields of 1.52 to 4.73 metric tons per hectare. KIPPRA (2023) corroborated this spatial disparity through national crop production analysis, finding that high-potential maize-growing regions such as Uasin Gishu and Trans Nzoia experienced increased production instability due to erratic rainfall characterized by early-season rainfall followed by prolonged dry spells, with total maize production declining by approximately 12.8% during highly erratic rainfall years. ASAL regions recorded harvests at only 45–50% of five-year production averages due to severe Short Rains variability. This spatial configuration creates a paradox for national food security: climate impacts in high-production western highland counties carry disproportionate consequences for aggregate supply, even as ASAL regions face the most severe biophysical constraints.

Kogo et al. (2019) modeled climate suitability for rain-fed maize cultivation across Kenya using Maximum Entropy climate suitability modeling, finding that climate suitability for maize production was declining in many lowland and semi-arid regions due to warming and moisture stress. Some highland areas remained moderately suitable but showed increasing vulnerability to temperature rise. Their analysis concluded that climate change would significantly alter spatial maize suitability patterns in Kenya, restructuring maize-growing landscapes across the country. Kipkulei et al. (2024) extended this understanding through agronomic assessment across three agroecological zones, finding that maize productivity responses varied significantly due to differences in soil conditions, rainfall variability, and inherent environmental stress. Highland areas retained relatively higher productivity, while lowland systems experienced severe climate-related stress, confirming that agroecological variability strongly shapes maize productivity dynamics.

Temporal dynamics compound these spatial patterns. National-level maize yields declined by 0.07 tons per hectare per decade, but this aggregate figure masked significant regional variation (Ondiek et al., 2024). Qasim (2025) demonstrated that simulated yields reflected both spatial and temporal variability, with pronounced reductions in years featuring high temperatures and prolonged dry periods such as 1999, 2000, and 2014, while favorable climate years including 1986, 2003, and 2016 experienced higher yields. The climate-yield correlation analysis validated these patterns, demonstrating that maize yields were negatively impacted by heat and dry spells while being positively associated with wet spells and total precipitation (Qasim, 2025). KIPPRA (2023) reinforced this temporal understanding, noting that high-potential regions experienced production instability specifically linked to erratic rainfall patterns, while ASAL regions faced chronic harvest shortfalls during drought years.

The temporal dynamics of climate variability in ASAL regions exhibited distinct patterns from those in highland zones. Omoyo et al. (2015) assessed the effects of climate variability on maize yields in lower eastern Kenya, analyzing historical rainfall, temperature, and maize yield data across Machakos, Kitui, Makueni, and Mwingi regions. Their findings indicated that delayed rainfall onset and prolonged dry spells significantly reduced maize yields, with rainfall variability affecting productivity more strongly than total annual rainfall amounts. This ASAL-specific temporal pattern characterized by high inter-annual variability, truncated growing seasons, and frequent crop failure contrasted with the highland pattern of progressive thermal stress, yet both trajectories converged on declining productivity and heightened uncertainty for farm-level decision-making. Kabara et al. (2023) confirmed this convergence through farmer surveys in Kitui and Laikipia counties, finding that farmers in ASAL regions experienced severe production instability associated with erratic rainfall and drought, while highland regions faced emerging thermal constraints.

County-scale projections reveal that future trajectories will involve spatial restructuring rather than uniform decline. Kipkulei et al. (2025) combined county-level climate projections, crop suitability models, and maize production datasets under multiple future climate scenarios, projecting substantial maize productivity declines in several counties due to rising temperatures and rainfall variability, with some counties experiencing yield reductions exceeding 30% under severe warming scenarios. Their analysis revealed substantial spatial variation in maize vulnerability across counties, with semi-arid counties showing the highest projected productivity declines while some highland regions maintained relatively moderate resilience. This county-scale projection provided a critical bridge between national aggregate trends and farm-level realities, revealing that future productivity trajectories would be characterized by spatial restructuring, with some counties potentially becoming unsuitable for maize production while others experienced intensified production pressure.

The spatial dynamics of biotic stressors further complicated the productivity landscape. Mutyambai et al. (2022) surveyed 180 maize farms across lowland, mid-altitude, and highland agroecological zones, finding that fall armyworm infestation and damage were highest in lowland agroecological zones compared to highland areas. However, the pest had expanded into high-altitude regions where it previously occurred minimally, indicating that changing environmental conditions were facilitating pest spread across Kenyan maize systems. Boonyuen et al. (2026) confirmed this expansion through ecological niche modeling, projecting that warming temperatures and environmental change were expanding fall armyworm suitability into highland maize-growing areas previously unsuitable for year-round pest survival. Gachathi and Nzengya (2026) further documented this trend through meta-analysis of pest surveillance data and temperature trends, showing that increasing temperatures expanded fall armyworm suitability into higher-altitude zones and that persistent infestations caused maize yield losses ranging from 10% to 35% across affected regions. These findings demonstrated that the spatial dynamics of maize productivity were being reshaped not only by abiotic stressors but also by the expanding geographic range of biotic threats.

Spatial vulnerability mapping by Kamiri et al. (2026) revealed an inverse relationship between exposure and sensitivity across Kenya's maize-producing regions. Western highland counties exhibited low exposure to climate stressors but high sensitivity due to their concentration of national production, while northern and eastern counties faced high exposure but contributed minimally to aggregate output. This spatial paradox had critical implications for environmental planning, suggesting that interventions prioritized solely on the basis of exposure severity would fail to protect the most nationally significant production zones. The Rift Valley region, which contributed nearly half of national maize production, exemplified this vulnerability; despite being a high-potential zone, it recorded yield declines of 15–25% over the past decade due to prolonged dry spells, demonstrating that even relatively favored agro-ecological zones were not immune to climate-driven productivity decline (Kabara et al., 2026).

The temporal dimension of productivity decline was characterized by increasing unpredictability of seasonal weather patterns. The March-April-May long rains exhibited declining trends in wetter zones, while the October-December short rains demonstrated heightened inter-annual variability influenced by the El Niño Southern Oscillation and the Indian Ocean Dipole (Ondiek et al., 2024). This temporal variability complicated farmer decision-making regarding planting dates, variety selection, and input allocation, as traditional calendars based on historical rainfall patterns became increasingly unreliable. The increasing frequency of extreme weather events, including both prolonged droughts and intense rainfall episodes, demanded proactive adaptation to maintain stable maize yields, yet the temporal mismatch between planning cycles and climate trends constrained the efficacy of institutional responses (Qasim, 2025).

The spatiotemporal dynamics are increasingly amenable to high-resolution mapping and monitoring. Tadesse et al. (2024) applied geospatial machine learning and satellite imagery to generate high-resolution land-use and crop productivity maps using Murang'a County as a case study, demonstrating that localized land-cover models improved mapping accuracy significantly compared to global models. This methodological advance suggested that future planning could be informed by dynamically updated, spatially explicit productivity maps that captured intra-county variability in biophysical conditions and yield performance, moving beyond the coarse agro-ecological zone classifications that currently structured planning interventions.

Environmental Planning Responses and Their Alignment with Biophysical Realities

Kenya constructed an elaborate environmental planning and policy architecture intended to build climate resilience in the agricultural sector. The Climate Change Act of 2016 mandated the integration of climate change considerations into all sectors and required county governments to prepare five-year County Integrated Development Plans, ten-year County Spatial Plans, and sector-specific plans incorporating climate actions (Government of Kenya, 2022). The National Adaptation Plan 2015–2030, the National Climate Change Action Plan 2018–2022, and the Kenya Climate Smart Agriculture Strategy 2017–2026 collectively established priority actions for enhancing agricultural productivity, expanding irrigation, diversifying livelihoods, and improving climate information services (Government of Kenya, 2017; Government of Kenya, 2022). County governments were empowered to enact County Climate Change Funds and develop County Climate Change Action Plans, with spatial planning processes explicitly identified as vehicles for injecting resilience into development frameworks (Government of Kenya, 2022).

Despite this proliferation of planning instruments, a critical disconnect persisted between the biophysical realities of maize productivity decline and the spatial planning responses designed to mitigate them. The review by Government of Kenya (2022), demonstrated that while significant progress was made in implementing adaptation activities in the agriculture sector, work remained needed to improve or maintain agricultural production in a changing climate. Kenya had limited success in increasing smallholder production, with climate change identified as a key challenge. KIPPRA (2023) reinforced this assessment, finding that most farmer adaptation measures remained reactive and localized, including altered planting dates and adoption of drought-tolerant maize varieties, while irrigation coverage remained critically low at approximately 3% of arable land, limiting large-scale climate resilience. The National Adaptation Plan did not include indicators for priority actions, and baseline data were not collected, precluding accurate tracking of progress and outcome evaluation (Government of Kenya, 2022). This monitoring and evaluation gap represented a fundamental constraint on adaptive management, as the absence of outcome data prevented learning from past interventions and adjustment of planning responses to emerging biophysical realities.

The devolution of planning authority to county governments under Kenya's 2010 Constitution created a fragmented institutional landscape in which multiple uncoordinated management plans operated simultaneously. While four counties prepared climate-smart agriculture action plans and seven counties enacted County Climate Change Fund legislation, most of the 47 counties included climate change actions in their County Integrated Development Plans without the detailed spatial targeting necessary to align interventions with biophysical stress patterns (Government of Kenya, 2022). County Climate Change Action Plans, such as those developed in Isiolo County, identified drought, floods, and resource-based conflicts as priority hazards and proposed interventions including water harvesting, rangeland management, and climate-smart agriculture (Isiolo County Government, 2023). However, these plans were predominantly structured around administrative wards rather than agro-ecological zones, potentially mismatching interventions to the spatial distribution of maize system vulnerability.

The spatial targeting of environmental planning responses appeared misaligned with the documented patterns of biophysical stress. While the National Adaptation Plan and Kenya Climate Smart Agriculture Strategy prioritized irrigation expansion and climate-smart agriculture interventions, there was limited evidence that these interventions were spatially targeted to the counties and agro-ecological zones experiencing the most severe biophysical stress (Government of Kenya, 2017; Government of Kenya, 2022). The strategy required an estimated KSh. 500 billion (US$ 5.0 billion) for adaptation and mitigation actions through 2026, yet the mechanisms for ensuring that these substantial investments were directed toward the most vulnerable production zones remained underdeveloped (Government of Kenya, 2017). Tadesse et al. (2024) demonstrated that localized geospatial analysis could improve this targeting; their application of machine learning and satellite imagery to develop high-resolution land-use and agricultural productivity maps in Murang'a County showed that localized models improved identification of climate-vulnerable agricultural zones and productivity hotspots compared to global models. This methodological advance suggested that planning could be informed by dynamically updated, spatially explicit productivity maps, yet such tools remained underutilized in formal county planning processes.

A fundamental temporal mismatch existed between the decadal to multi-decadal timescales of biophysical degradation and climate shift, and the short-term political cycles that drove planning processes. County plans typically spanned five-year periods, while soil health decline, heat stress accumulation, and pest range expansion operated over longer durations (Government of Kenya, 2022). This temporal disconnect resulted in planning responses that addressed immediate climate shocks such as drought relief, emergency seed distribution, and livestock offtake rather than underlying structural vulnerabilities, including the progressive loss of thermal suitability in highland production zones or the erosion of soil resilience in intensively cultivated areas. Mnukwa et al. (2025) projected that rising temperatures would shorten maize growing duration by 34 to 38 days by the 2050s in highland regions, yet county planning instruments gave limited attention to such long-term biophysical trajectory planning. The County Climate Change Action Plan for Isiolo County 2023–2027 exemplified this pattern, emphasizing short-term emergency response and mid-term infrastructure development while giving limited attention to progressive thermal stress and soil degradation trends (Isiolo County Government, 2023).

The integration of climate information services into planning processes showed partial progress but remained insufficiently grounded in biophysical evidence. Fifteen counties developed climate information services plans by 2020, representing 63% of the national target, and three counties developed Integrated Climate Risk Management Plans (Government of Kenya, 2022). However, the climate information disseminated through these systems was often too coarse to capture the micro-climatic variability that shaped maize productivity at the farm level. Qasim (2025) noted that yearly-based climate indices failed to capture seasonal relevance, as consecutive dry days might occur during non-cultivation periods, potentially generating misleading correlations and inappropriate planning recommendations. This scale mismatch between climate projections and farm-level decision-making represented a significant barrier to effective environmental planning.

The coordination of environmental planning responses involved multiple actors at national and county levels, yet institutional fragmentation constrained effective implementation. The Climate Change Directorate within the Ministry of Environment, Climate Change and Forestry led coordination and reporting on adaptation mainstreaming, working in collaboration with the Ministry of Agriculture, Livestock, Fisheries and Cooperatives and county governments (Government of Kenya, 2022). A survey of 51 experts in the agriculture sector identified enhanced sector coordination as the primary contribution of the National Adaptation Plan, cited by 76% of respondents, followed by improved knowledge (51%), enhanced organizational capacity (49%), and enhanced policy influence (47%) (Government of Kenya, 2022). However, respondents noted that coordination between national and county governments required improvement, particularly regarding the provision of support to cascade national frameworks to the county level.

The multiplicity of planning instruments created potential inconsistencies in how climate risks to maize systems were identified, prioritized, and addressed across jurisdictions. County Integrated Development Plans, County Spatial Plans, County Climate Change Action Plans, and sector-specific strategies were developed through distinct processes with varying temporal horizons and analytical foundations. The Climate Change Act mandated mainstreaming of national climate action plans into county development planning, but the mechanisms for ensuring biophysical coherence between local spatial plans and national climate priorities remained underdeveloped (Government of Kenya, 2022). This institutional fragmentation was compounded by resource constraints; while international public funding was directed toward irrigation projects, sustainable land management, and climate-smart agriculture, the scale of investment remained insufficient relative to the magnitude of biophysical challenges (Government of Kenya, 2022).

The adoption of climate-resilient technologies and practices remained uneven and low, particularly among women and resource-poor farmers, due to financial, informational, and institutional barriers (Kabara et al., 2026; Kabara et al., 2023). High costs for improved inputs, limited access to credit, under-resourced extension services, and insecure land tenure constrained the use of drought-tolerant varieties, conservation agriculture, and agroforestry across Kenya's rural counties. Although national efforts promoted these interventions, the spatial targeting of extension services and input subsidies did not consistently align with the counties experiencing the most severe climate stress, potentially reflecting a top-down planning approach insufficiently responsive to local biophysical conditions (Kabara et al., 2026). KIPPRA (2023) concluded that fragmented adaptation planning and weak infrastructure investment constrain sustainable maize productivity improvement, while Kabara et al. (2023) found that adaptation success depended on stronger policy coordination and investment in agricultural support systems.

Soil management interventions, while effective at the field scale, faced challenges in integration into broader planning frameworks. Cirad (2026) evaluated integrated soil fertility management as a climate adaptation and environmental planning strategy, finding that productivity gains were highest when integrated soil fertility management was combined with climate-sensitive planting calendars and localized land management plans. Laub et al. (2024) modeled integrated soil fertility management using the DayCent ecosystem model, finding that it improved soil organic carbon accumulation, water retention, and maize yields compared to conventional nutrient management systems, and concluded that integrated nutrient management should guide long-term spatial agricultural planning. However, county-level plans rarely specified the spatial targeting of soil fertility investments or linked them to biophysical soil degradation maps. Kiboi et al. (2023) and Ngetich et al. (2023) demonstrated that conservation agriculture improved soil moisture retention and increased maize yield stability by 15–40% under erratic rainfall conditions, yet these practices were promoted through generic extension messages rather than spatially prioritized implementation plans that identified which farms and landscapes were most vulnerable to soil degradation.

The misalignment between planning responses and biophysical realities was further evident in the treatment of adaptation options. Oluoch et al. (2022) showed that optimized planting dates, fertilizer management, and adaptive agronomic practices significantly reduced climate-related yield losses by 20–35% but noted that benefits varied spatially due to infrastructure limitations and rainfall variability. Mnukwa et al. (2025) found that adaptation practices such as changing planting dates and adopting drought-tolerant cultivars improved maize productivity by approximately 20–38% under controlled scenarios yet concluded that adaptation strategies require stronger institutional support and irrigation expansion to achieve large-scale effectiveness. These findings implied that planning instruments identified effective interventions but failed to resolve the spatial and institutional barriers to their implementation at scale.

Conclusion

This review examined the biophysical drivers and spatiotemporal dynamics of maize productivity decline in Kenya, and critically evaluated the alignment between these biophysical realities and existing environmental planning responses. Three interconnected pathways including phenological compression, thermal stress and pollen sterility, and soil-climate synergism were identified as the primary mechanisms undermining maize physiology. These pathways operate differentially across Kenya's agro-ecological zones, with highland regions experiencing accelerated crop development and reproductive damage while ASAL regions face chronic moisture stress and soil degradation. The spatial gradient of productivity is progressively flattening as climate change erodes the biophysical advantages historically enjoyed by high-potential zones, while temporal patterns shift from predictable seasonality toward heightened inter-annual and intra-seasonal variability.

The environmental planning architecture in Kenya including the Climate Change Act, National Adaptation Plan, Kenya Climate Smart Agriculture Strategy, and county-level planning instruments is institutionally elaborate but structurally decoupled from these mechanistic realities. Planning responses remain reactive rather than anticipatory, generic rather than spatially targeted, and constrained by five-year political cycles that mismatch the decadal to multi-decadal timescales of biophysical degradation. Critical disconnects persist in spatial targeting, temporal horizon alignment, monitoring and evaluation capacity, and institutional coordination between national and county levels. The integration of high-resolution biophysical data, participatory knowledge systems, and cross-disciplinary research into planning processes remains underdeveloped.

Recommendations

Based on the findings of this review, the following recommendations are proposed to strengthen the alignment between environmental planning responses and the biophysical realities of maize productivity decline in Kenya.

Policy and Practice

1. County governments should integrate high-resolution biophysical data into spatial plans, differentiating interventions by zone rather than using uniform administrative ward structures. Plans must explicitly map soil degradation, thermal stress exposure, and phenological compression risks to guide targeted investment.
2. County Climate Change Action Plans should combine annual operational responses to seasonal forecasts, five-year implementation plans for infrastructure and capacity, and decadal strategic plans anticipating progressive biophysical shifts such as highland thermal suitability loss.
3. National and county frameworks must incorporate outcome indicators linked to soil health, pest incidence, and climate stress exposure, leveraging remote sensing and farmer-based observation networks to enable adaptive management.
4. The multiplicity of uncoordinated county plans should be consolidated into unified instruments integrating climate adaptation, agricultural development, and land-use planning, with the Climate Change Directorate empowered to review plans for biophysical coherence.
5. Investment in irrigation, extension, and climate information services should be explicitly directed toward western highland and Rift Valley regions that contribute disproportionately to national supply, even where absolute climate exposure appears lower than in ASAL regions.
6. Participatory co-design methodologies should combine scientific projections with farmer-generated understanding of micro-climatic variability and locally adapted coping strategies to enhance intervention relevance and adoptability.

Future Research

1. Cross-disciplinary research should explicitly connect crop simulation outputs to spatial planning parameters, examining how planning interventions can be evaluated against biophysical outcome indicators rather than institutional output metrics.
2. Controlled field experiments and advanced crop modeling should examine how drought, heat, and pest pressures combine under realistic field conditions, as these interactions currently exceed the

predictive capacity of single-factor analyses.

3. Methodological innovation is needed in action research approaches that iteratively design, implement, and reflect on planning innovations with county agencies and farmer organizations, ensuring rapid translation of findings into practice.

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