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Editorial note

Climate change impacts, adaptation, and mitigation in global agriculture

Impactos del cambio climático, adaptación y mitigación en la agricultura mundial

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ABSTRACT

Climate change has become an immediate and systemic stressor on global agrifood systems, with agriculture being both highly vulnerable to climate impacts and a major source of greenhouse gas emissions. Rising temperatures, water instability, soil degradation, and shifting pest and disease pressures are already reducing crop and livestock productivity, especially for smallholder farmers in Latin America, Sub-Saharan Africa, and South Asia. Using the Climate-Smart Agriculture framework, this editorial note highlights integrated responses that combine digital agriculture, agroecology, advanced breeding, and modeling for adaptation and mitigation. It emphasizes that technology alone is inadequate without strong institutions, inclusive knowledge systems, coherent policies, and green economy investments. Addressing persistent research gaps and moving beyond incremental change toward transformative and equitable transitions is essential to safeguard food security, livelihoods, and ecosystems while meeting climate goals.

Keywords: Climate services, crop physiology, regional hotspots, soil degradation, water resources

RESUMEN

El cambio climático se ha convertido en una presión sistémica inmediata para los sistemas agroalimentarios globales, siendo la agricultura altamente vulnerable a los impactos climáticos y una fuente importante de emisiones de gases de efecto invernadero. El aumento de las temperaturas, la inestabilidad hídrica, la degradación del suelo y la presión cambiante de plagas y enfermedades ya están reduciendo la productividad agrícola y ganadera, especialmente para los pequeños agricultores de América Latina, África subsahariana y el sur de Asia. Utilizando el marco de la Agricultura Climáticamente Inteligente, esta nota editorial destaca respuestas integradas que combinan la agricultura digital, la agroecología, el mejoramiento genético avanzado y la modelización para la adaptación y la mitigación. Enfatiza que la tecnología por sí sola es insuficiente sin instituciones sólidas, sistemas de conocimiento inclusivos, políticas coherentes e inversiones en la economía verde. Abordar las brechas persistentes en la investigación y avanzar más allá del cambio gradual hacia transiciones transformadoras y equitativas es esencial para salvaguardar la seguridad alimentaria, los medios de vida y los ecosistemas, a la vez que se cumplen los objetivos climáticos.

Palabras clave: degradación del suelo, fisiología de cultivos, puntos críticos regionales, recursos hídricos, servicios climáticos

Introduction

Climate change has moved from a distant theoretical concern to the defining operating environment for global agriculture. The Earth's atmosphere is now approximately 1.09 °C warmer than pre-industrial levels, and the past decade has been the hottest on record (Psistaki et al., 2024). This warming is fundamentally disrupting the biological and hydrological processes underpinning agricultural production. Agriculture occupies a paradoxical position: it is both a major contributor to climate change and the sector most vulnerable to its impacts. The stakes are exceptionally high, as global population growth toward nearly 9 billion by 2050 is expected to drive an approximate 85% increase in food demand (O'Sullivan, 2023). At the same time, climate change threatens to reduce the productive capacity of the very systems expected to meet this demand. Staple crop yields in climate-vulnerable regions are projected to decline by 10–20% by mid-century, while annual global economic losses from climate-related agricultural impacts may reach USD 23 billion by 2050 (Fei et al., 2023). This editorial examines the multifaceted impacts of climate change on agriculture, evaluates adaptation and mitigation strategies, particularly through Climate-Smart Agriculture (CSA), and assesses the technological, institutional, and policy pathways required to secure a resilient global food future.

Biophysical impacts of climate change on agricultural systems

The effects of climate change on agriculture are neither consistent nor linear. They differ depending on land use, production systems, and climate regimes, and result from interacting physiological, hydrological, edaphic, and biotic processes.

Physiology and phenology of crops. Rising temperatures and elevated CO_2 directly affect plant growth and metabolism, with C3 crops being especially vulnerable. Although higher CO_2 can enhance photosynthesis, heat stress often negates these gains by shortening development and disrupting reproduction. Wheat yields in India have already declined by about 5.2% per decade due to warmer nights (Kuriachen et al., 2022). C4 crops, while more heat-tolerant, remain vulnerable when high temperatures coincide with water stress; maize yields in East Africa could fall by up to 40% by the century's end (Choi et al., 2023). In Latin America's tropical and semi-arid regions, warming is already causing yield losses in major crops and driving coffee production upslope in Brazil and Colombia, increasing pressure on forest ecosystems (Faraz et al., 2023).

Water resources and hydrological disruption. Climate change is disrupting water availability and the reliability of supplies, leaving rainfed and food-insecure farming systems highly vulnerable. Altered precipitation patterns such as shifting monsoons, delayed onsets, early cessations, and erratic rainfall are increasing drought and flood risks in Sub-Saharan Africa and South Asia, contributing to significant agricultural losses, including a 5–10% annual decline in Ethiopia's agricultural GDP (Asfew & Bedemom, 2022). In Latin America, growing rainfall variability destabilizes rainfed production, while prolonged droughts intensify surface- and groundwater depletion in arid and semi-arid regions. Conversely, more intense rainfall in the Andes and Central America increases flooding, erosion, and nutrient loss. Glacier retreat in the tropical Andes further aggravates water insecurity by reducing dry-season streamflow critical for irrigation (Gonzalez-Trujillo et al., 2024).

Soil degradation and feedback loops. Temperature and moisture have a significant impact on the functioning of soils, which are dynamic ecosystems. The decomposition of soil organic matter is accelerated by climate change, reducing the soil's ability to retain nutrients and water. Erosion is exacerbated by heavy rainfall, especially on sloping terrain that is typical of farming systems in the Andes and Central America (Arias Montevechio et al., 2023). Negative feedback loops are created by these processes: degraded soils increase yield instability by sequestering less carbon, helping to mitigate climate change, and becoming more susceptible to drought and heavy precipitation.

Weeds, pathogens, and pests. Agricultural pests and diseases are spreading their geographic ranges and seasonal persistence due to warming temperatures and changed humidity regimes. Species that were formerly restricted by cold winters are shifting upslope and poleward, exposing crop varieties that were previously unaffected to new biotic stresses. Higher elevation reports of pests affecting livestock, horticultural crops, beans, and maize are growing in Latin America (Angelotti et al., 2024). Increased CO_2 levels also change crop-weed competition, favoring C_4 weeds and decreasing the effectiveness of herbicides, making management plans more difficult.

Socioeconomic susceptibility. Socioeconomic systems that control exposure, sensitivity, and adaptive ability filter biophysical effects. Disproportionally harsh outcomes are experienced by areas with a high reliance on agriculture for employment and GDP, little institutional support, and deep-rooted poverty.

Smallholders and Unequal Burdens. Particularly in Sub-Saharan Africa, South Asia, and much of Latin America, smallholder farmers are at the forefront of climate vulnerability. These farmers usually depend on rainfed production, work on marginal lands, and have limited access to climate information, credit, insurance, and irrigation. Diversified crop-livestock systems may improve resilience, but adaptive responses are constrained by a lack of financial buffers. Research indicates that almost 60% of smallholders in Africa do not have access to technologies for climate adaptation (Ogundeji, 2022). Climate shocks often result in food insecurity, immediate income losses, and distressed asset sales, with longer-term effects on health and education. Prolonged droughts in Ethiopia have resulted in significant losses in the production of crops and livestock, leading to humanitarian crises that continue long after the initial shock to the climate.

Regional hotspots. Climate change impacts on agriculture are highly uneven across regions. Maize yields in Sub-Saharan Africa are projected to decline by 10–20% by 2050, while drought-prone regions could see crop production fall by up to 25% by 2080 (Dickerson et al., 2022). In South Asia, the Indo-Gangetic Plains face severe stress from heat and groundwater depletion, threatening wheat and rice systems that sustain 1.5 billion people (Kaur et al., 2022). The Mediterranean and Latin America are emerging as parallel hotspots due to aridification and water competition, with vulnerability in Latin America exacerbated by institutional and technological inequalities. Increasing drought and rainfall variability are intensifying food insecurity and migration in southern Mexico and Central America, while glacier retreat in the Andes reduces water availability and alters pest dynamics. In southern South America, heat waves and drought are disrupting major crops, affecting global markets, and in the Amazon basin, interactions among deforestation, fire, and climate change raise the risk of ecosystem tipping points that could profoundly alter regional rainfall (Gouveia et al., 2023).

Technological frontiers and integrated adaptation–mitigation pathways

Integrating technological innovation with systems-based adaptation and mitigation strategies is becoming increasingly important for effective responses to climate change.

Innovation in crops and livestock. The pace of climate change is frequently too slow for conventional breeding. Heat-, drought-, and disease-tolerant crops can be developed more quickly and precisely thanks to pan-genomics, genomic-assisted breeding, and gene-editing technologies such as CRISPR-Cas9 (Syeda, 2025). In diverse agroecological settings, regional germplasm conservation and participatory breeding are particularly important. Improved pasture management, silvopastoral systems, and heat-tolerant breeds all increase productivity in livestock systems while lowering vulnerability.

Climate services and digital agriculture. Climate uncertainty requires adaptive management supported by real-time data. Mobile extension services, satellite-based crop monitoring, and seasonal climate forecasts enable more informed decisions regarding planting dates, varietal selection, and input management. Digital climate services can significantly improve resource-use efficiency and adaptive capacity in areas with inadequate traditional extension systems (Warner et al., 2022).

Co-benefits of mitigation and agroecology. When incorporated into agroecological and landscape-based methods, technological advancements work best. Integrated crop-livestock systems, diversified rotations, conservation agriculture, and agroforestry all enhance soil structure, control microclimates, and maintain yields (Sun et al., 2023). By reducing deforestation pressure, improving pasture management, and sequestering carbon in the soil, these practices also provide mitigation co-benefits that align productivity with biodiversity and climate goals.

Integrated assessment and systems modeling. There is still a significant gap in the integration of the economic and biophysical aspects of climate change. Numerous studies focus on the effects on yield while ignoring the ways that growing input costs, water, fertilizer, and energy impact production choices and profitability (Wang et al., 2022). To assess the long-term costs, benefits, trade-offs, and synergies of adaptation and mitigation strategies, integrated assessment models are crucial.

Policy, institutions, knowledge systems, and the green economy

Climate-resilient agriculture cannot be achieved through technology alone; scaling climate-smart agriculture requires coherent policies, strong institutions, and inclusive knowledge systems. Key barriers include insecure land tenure, weak extension services, misaligned subsidies, and limited access to credit. Aligning agricultural, climate, land-use, and food security policies is essential to avoid maladaptation, as poorly designed incentives can worsen food prices and emissions. Evidence from Sub-Saharan Africa and Latin America shows that investments in green economies such as renewable energy, energy efficiency, and sustainable land management can improve food security while reducing emissions, especially when integrated with adaptation strategies. Decentralized renewable energy, including solar-powered irrigation, is therefore critical for agricultural development. Effective adaptation also depends on participatory and locally tailored knowledge systems that combine scientific and indigenous knowledge, supported by digital tools within inclusive governance frameworks that ensure equitable access.

Future research directions and concluding remarks

Despite progress, major gaps remain in climate change adaptation for agriculture. Evidence is limited by the lack of long-term studies, insufficient understanding of how combined adaptation practices interact, and major knowledge deficits regarding climate impacts on fisheries, aquaculture, and livestock systems. Climate change is already eroding decades of agricultural productivity, making incremental adjustments inadequate.

Transformational changes are required in genetics, agronomy, and policy, including scaling climate-smart agriculture, advancing genomic plant breeding, and removing institutional barriers to information and technology. Equity is central, as smallholder farmers in South Asia, Latin America, and Sub-Saharan Africa, who contribute least to emissions, bear the greatest impacts. The core challenge is not knowledge generation but effective delivery, requiring expanded adaptation finance, technology transfer, and a shift from short-term, donor-led projects to nationally owned, system-wide programs to prevent worsening hunger, poverty, and inequality.

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