Climate-Resilient Irrigation Pathways: A Systematic Review of Global Hydrological Modeling, Vulnerabilities, and Adaptation Strategies

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(Received: May 17, 2026; Revised: June 05, 2026; Accepted: June 13, 2026; Published: Jun 30, 2026)

Abstract Irrigation is the largest user of freshwater globally and is increasingly exposed to climate variability, groundwater depletion, and growing competition from domestic, industrial, and environmental sectors (FAO, 2017; IWMI, 2019). This review synthesizes evidence from peer-reviewed studies published between 2010 and 2025 to examine how climate change is influencing irrigation water demand, hydrological processes, regional vulnerability, and adaptation responses (Page et al., 2021). The literature indicates that altered precipitation regimes, increasing evaporative demand, groundwater stress, and more frequent hydrological extremes are intensifying irrigation-related risks, particularly in already water-scarce regions (IPCC, 2021; Green et al., 2011). The review further shows that climate-resilient irrigation depends on integrated adaptation pathways that combine technological improvements, demand management, groundwater governance, crop adjustment, and institutional reform (Wada et al., 2014; Darko et al., 2025). Particular vulnerabilities are evident in semi-arid areas, smallholder systems, transboundary basins, and regions with weak monitoring and governance capacity (Müller et al., 2017; Wada et al., 2013). The principal contribution of this review lies in linking hydrological modeling, regional vulnerability, and adaptation planning within a single analytical framework that is directly relevant to researchers, irrigation managers, and policymakers. The review concludes by identifying major research gaps in integrated modeling, groundwater sustainability, adaptation performance, and equity-centred implementation.

Keywords: climate change; irrigation water demand; hydrological modeling; groundwater depletion; climate adaptation; water management

I Introduction

Freshwater resources are under increasing pressure from population growth, agricultural intensification, urban expansion, and climate change, while irrigation continues to account for the largest share of global freshwater withdrawals (FAO, 2017; IWMI, 2019). In many agricultural regions, irrigation is central to crop stability, food production, and rural livelihoods; consequently, any decline in water reliability has implications that extend beyond farm-level productivity to regional food systems and economic resilience (World Bank, 2016). These concerns are particularly acute in arid, semi-arid, and monsoon-dependent regions, where rainfall variability and groundwater dependence already constrain agricultural planning.

Climate change is altering irrigation systems through several interrelated pathways. Changes in precipitation amount, timing, and intensity affect runoff, recharge, and storage, while rising temperatures increase evaporative demand and crop water requirements (Barnett et al., 2005; Kaser et al., 2010; Arnell & Lloyd-Hughes, 2014). Groundwater, which functions as a strategic buffer against seasonal and interannual rainfall variability, is becoming more vulnerable because of declining recharge and continued over-extraction in many irrigated regions (Döll, 2009; Wada et al., 2010). These pressures are compounded by competition among agricultural, urban, industrial, and environmental water uses, making long-term irrigation sustainability increasingly uncertain (Wada et al., 2014).

Recent review literature has shown that research on climate change and irrigation water demand is expanding rapidly, with growing attention to integrated modeling, adaptive irrigation systems, and water-productivity-oriented responses (Darko et al., 2025; Muharomah et al., 2025). However, much of the available literature remains fragmented across hydrology, crop-water analysis, groundwater assessment, and policy studies. A more integrated review is therefore needed to explain how hydrological change, regional vulnerability, and adaptation pathways interact in practice. The revised FAO56 guidelines further strengthen crop-water estimation by incorporating updated data sources, calculation procedures, and climate-change-relevant considerations for irrigation planning (Pereira et al., 2026).

The present review addresses that need by examining three linked themes: hydrological and crop-water modeling under climate change, regional vulnerability in irrigation-dependent systems, and adaptation strategies for climate-resilient water management. This review is intended to benefit both researchers and policymakers. For researchers, it identifies knowledge gaps in modeling, groundwater sustainability, and adaptation performance. For policymakers and irrigation planners, it synthesizes evidence on the types of interventions and governance approaches most relevant for improving resilience under future climatic uncertainty. The review therefore provides an interdisciplinary evidence base for designing more effective irrigation adaptation strategies.

II Review Methodology

This study adopted a systematic review approach guided by the PRISMA 2020 framework for evidence identification, screening, eligibility assessment, and final inclusion. The literature search was conducted in Scopus, Web of Science, and Google Scholar to capture peer-reviewed studies published between 2010 and 2025. The search strategy combined terms such as "climate change," "irrigation water demand," "hydrological modeling," "groundwater depletion," "adaptation," and "integrated water resource management."

The selected studies were screened for relevance to climate-related irrigation demand, hydrological or crop-water modeling, groundwater recharge and sustainability, regional irrigation vulnerability, and technological or institutional adaptation responses. Studies were included if they addressed one or more of the following themes: climate-induced changes in irrigation water demand, hydrological impacts on agricultural water availability, groundwater stress in irrigated systems, regional vulnerability to water scarcity, and adaptation strategies for climate-resilient irrigation.

Following screening and thematic classification, the studies were organized into three broad groups: climate and hydrological impacts, modeling approaches, and adaptation strategies. Information was extracted on study region, methodological approach, principal findings, adaptation measures, and reported knowledge gaps. This structure enabled a comparative synthesis that linked biophysical change with management implications rather than treating them as separate domains.

The study selection process is presented in the PRISMA 2020 flow diagram in Figure 1.

III Climate Change Impacts on Water Resources

Climate change is reshaping the hydrological conditions that support irrigation through its effects on precipitation, evapotranspiration, runoff timing, soil moisture, and groundwater recharge (IPCC, 2021; Green et al., 2011). These changes affect not only the quantity of water available for agriculture but also the timing and reliability of supply. The implications are especially significant for highly irrigated and water-stressed regions where crop production depends on seasonal water predictability.

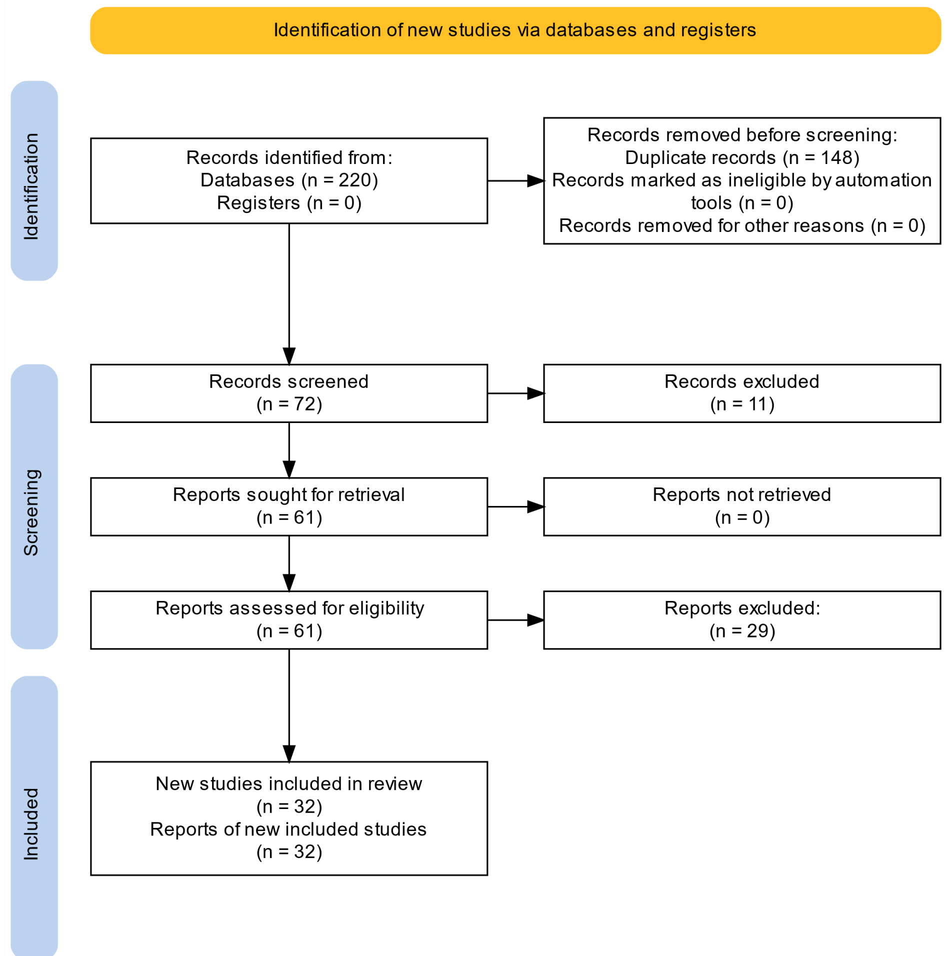

Figure 1: PRISMA 2020 flow diagram showing study identification, screening, eligibility assessment, and inclusion in the review.

III.a Hydrological responses to climate change

Changes in precipitation patterns are among the most important drivers of irrigation stress under climate change. Several studies indicate that parts of South Asia, the Middle East, and southern Africa are likely to experience declining rainfall, greater interannual variability, and more frequent drought conditions by mid-century (IPCC, 2021). Even where annual rainfall totals remain relatively stable, shifts in rainfall timing and intensity may reduce effective water availability for crops and complicate irrigation scheduling.

Snow-fed and mountain river systems face an additional layer of vulnerability. Earlier snowmelt and altered seasonal runoff timing reduce water availability during the peak irrigation period, particularly in basins that depend on delayed meltwater contributions (Barnett et al., 2005; Kaser et al., 2010). Rising temperatures also increase atmospheric evaporative demand, which can lower soil moisture and increase irrigation requirements.

III.b Aquifer recharge and groundwater dynamics

Groundwater plays a critical role in sustaining irrigated agriculture, particularly where rainfall is unreliable or surface-water systems are insufficient. Climate change can influence groundwater systems through reduced infiltration, altered soil-moisture dynamics, increased evapotranspiration losses, and changes in recharge timing and location (Green et al., 2011; Döll, 2009). Studies on global water availability and future food-production requirements further indicate that regional water scarcity can constrain agricultural output when water supply is limited and demand increases (Gerten et al., 2011). In semi-arid environments, even modest declines in effective precipitation can substantially reduce recharge.

This is particularly concerning because many irrigation-dependent regions are already experiencing extraction rates that exceed recharge. Falling groundwater levels, salinity intrusion, and declining water quality increase vulnerability further and reduce the long-term reliability of aquifers for agricultural use (Siebert et al., 2010; Wada et al., 2010). Groundwater sustainability must therefore be treated as a core component of climate-resilient irrigation planning rather than a secondary issue.

III.c Evapotranspiration and irrigation demand

Rising temperatures increase atmospheric water demand and crop evapotranspiration, thereby increasing irrigation requirements across many cropping systems and climate zones (Siebert & Döll, 2010). The scale of change depends on crop type, soil characteristics, effective rainfall, and management conditions, but the overall pattern is clear: under warmer climates, more irrigation water is often required to maintain existing yield levels. This effect becomes more severe when warming coincides with declining rainfall reliability.

These dynamics highlight the need to integrate climatic projections with crop-water and hydrological modeling. Future irrigation planning cannot rely solely on historical water use patterns because the underlying hydroclimatic context is already changing in many regions (Wada et al., 2013; IPCC, 2021).

IV Regional Vulnerabilities and Hotspots

The impacts of climate change on irrigation are spatially uneven. Regional vulnerability is shaped by hydroclimatic exposure, dependence on irrigation, groundwater reliance, infrastructure quality, institutional capacity, and the adaptive ability of farming systems (World Bank, 2016; Lipper et al., 2014). Regions facing existing water scarcity and governance constraints are likely to experience the most severe irrigation stress.

IV.a South Asia

South Asia is one of the most vulnerable irrigation regions because of its high population density, extensive irrigated area, dependence on monsoon rainfall, and heavy reliance on groundwater (IPCC, 2021; Siebert et al., 2010). In the Indo-Gangetic Plain, groundwater depletion in Punjab, Haryana, and Uttar Pradesh is becoming a major constraint on long-term irrigation sustainability. Monsoon variability, recurrent drought, and competition from non-agricultural sectors further intensify stress on agricultural water systems.

The significance of this vulnerability extends beyond irrigation management alone. Because irrigated agriculture underpins staple food production across the region, water stress also creates risks for food security, rural employment, and broader economic stability (World Bank, 2016).

IV.b Sub-Saharan Africa

Sub-Saharan Africa presents a different, but equally severe, profile of irrigation vulnerability. In many countries, irrigation coverage remains limited and large areas of agriculture continue to depend on highly variable rainfall (Müller et al., 2017). Weak infrastructure, low investment capacity, and limited monitoring systems constrain the ability of farmers to adapt to drought and water variability.

Where groundwater resources exist, high pumping costs and weak institutional support often limit their use by smallholder farmers. As a result, adaptation in this region requires both water-management improvements and broader investment in infrastructure, climate services, and institutional capacity.

IV.c Middle East and Central Asia

The Middle East and Central Asia contain some of the most water-stressed irrigation systems globally. Many basins in these regions already experience chronic scarcity, high evaporative demand, and intensive competition over shared water resources (Wada et al., 2014; IPCC, 2021). Climate change is expected to intensify these pressures through declining river flows, more frequent drought, and reduced recharge in already stressed aquifers.

Central Asia also illustrates the ecological consequences of long-term over-expansion of irrigation, particularly in the Aral Sea basin. These regional cases highlight the need to connect irrigation efficiency with environmental safeguards, transboundary governance, and long-term basin-scale planning.

V Hydrological Modeling Approaches

Hydrological modeling is central to understanding how climate change may affect irrigation water demand, water availability, and groundwater sustainability (Alcamo et al., 2003; Wada et al., 2013). These models provide a basis for estimating how changes in rainfall, temperature, evapotranspiration, runoff, and human withdrawals may alter agricultural water systems under present and future conditions.

V.a Global hydrological models

Global hydrological models simulate water movement, storage, and allocation across large spatial scales by integrating climate inputs, runoff generation, soil-water processes, and sectoral demand (Alcamo et al., 2003; Hanasaki et al., 2008). Their main strength lies in comparative assessment across regions and scenarios, allowing researchers to evaluate irrigation stress and water scarcity under changing climatic conditions.

However, their operational usefulness depends on how well they represent local irrigation practices, land use, allocation rules, and management conditions. Simplified assumptions can reduce their realism at smaller scales, which means that regional calibration remains important when models are used for planning purposes (Wada et al., 2013; Oki & Kanae, 2006).

V.b Crop water requirement modeling

Crop water requirement models estimate irrigation needs based on crop evapotranspiration, effective rainfall, soil-water storage, and irrigation efficiency (Allen et al., 1998; Siebert & Döll, 2010). Recent updates to the FAO56 framework have improved meteorological data handling, crop coefficient estimation, and climate-sensitive crop water calculations, making it more relevant for irrigation planning under water scarcity and climate change (Pereira et al., 2026). These models are especially relevant for analysing how warming may alter crop water demand and for identifying changes in irrigation requirements under future climate scenarios. Their value lies in direct applicability to farm- and command-area planning. Nevertheless, their performance depends on reliable climate data, realistic crop coefficients, and local calibration of management assumptions. Without such calibration, model outputs may diverge substantially from actual field conditions.

V.c Groundwater sustainability assessment

Groundwater sustainability assessments compare recharge, abstraction, and environmental water needs in order to determine whether aquifer use remains within sustainable limits (Wada et al., 2010; Siebert et al., 2010). This is particularly important in irrigation-dependent regions where groundwater acts as the principal source of water during dry periods or when surface supplies are unreliable.

Where abstraction persistently exceeds recharge, irrigation systems become increasingly vulnerable to declining water tables, rising pumping costs, and quality deterioration. These assessments are therefore essential for identifying regions where current irrigation practices may be unsustainable under future climate conditions.

V.d Limitations and future needs

Despite their importance, current modeling approaches still face important limitations. Many models do not adequately incorporate farmer behavior, local institutional constraints, informal groundwater use, or rapid shifts in cropping systems (Green et al., 2011; Wada et al., 2013). Uncertainty in climate projections and data limitations also affect the reliability of model outputs, especially in data-scarce regions.

Future research should prioritize integrated frameworks that connect hydrology, groundwater, agronomy, and socioeconomic factors more explicitly. Improved monitoring networks, stronger regional calibration, and better linkage between modeling outputs and decision-support tools are essential research priorities.

VI Adaptation Strategies and Technologies

The reviewed literature indicates that climate-resilient irrigation depends on combinations of supply-side, demand-side, and institutional responses rather than isolated technical measures (Howden et al., 2007; Lipper et al., 2014). The effectiveness of adaptation depends on local hydrological conditions, crop systems, infrastructure, governance, and implementation capacity.

VI.a Supply-side adaptation

Supply-side measures seek to improve the availability, storage, or reliability of irrigation water. Common options include rainwater harvesting, managed aquifer recharge, reservoir rehabilitation, conjunctive use of surface water and groundwater, wastewater reuse, and in specific contexts, desalination (Wada et al., 2014; UNEP, 2012). These measures are particularly relevant in regions where rainfall is seasonal, surface-water flows are declining, or groundwater is under severe pressure.

VI.b Demand-side adaptation

Demand-side adaptation focuses on improving water-use efficiency while maintaining agricultural productivity. Frequently discussed measures include drip and sprinkler irrigation, improved irrigation scheduling, deficit irrigation, soil-moisture conservation, crop diversification, and drought-tolerant crop varieties (Burt et al., 1997; Burt et al., 1999; Challinor et al., 2014). Recent review evidence suggests that adaptive irrigation systems linked to water productivity and evapotranspiration monitoring may play an increasingly important role in future irrigation management (Muharomah et al., 2025).

However, the success of these approaches depends not only on technical efficiency but also on affordability, maintenance requirements, farmer acceptance, and extension support. This is especially important in smallholder systems where adoption barriers remain substantial.

VI.c Water management approaches

Broader water-management strategies are also essential. These include integrated water resource management, canal rehabilitation, water accounting, improved allocation systems, and conjunctive management of different water sources (UNEP, 2012; Wada et al., 2014). These approaches can reduce system losses, improve drought resilience, and help balance competing demands across sectors.

VI.d Policy and institutional frameworks

Policy and institutional support strongly influence whether adaptation measures are adopted and sustained over time. Water laws, allocation mechanisms, farmer organizations, extension services, climate information systems, and groundwater regulation all affect the practical performance of irrigation adaptation (Lipper et al., 2014; World Bank, 2016). The literature suggests that the most effective pathways are those that combine technical improvements with governance reform, financing support, and local capacity development.

Table 1 summarizes the main climate-resilient irrigation adaptation strategies discussed in this review, grouping them into supply-side, demand-side, and institutional responses.

Table 1: Synthesis of climate-resilient irrigation adaptation strategies.

Strategy Type	Examples	Primary Challenge	Enabling Condition
Supply-Side	Reservoir rehabilitation, Managed Aquifer Recharge (MAR)	High capital cost, land availability	Stable hydrological data, basin-level planning
Demand-Side	Drip irrigation, Deficit irrigation, Crop diversification	High maintenance, farmer behaviour adoption	Strong extension services, subsidies
Institutional	Groundwater regulation, Water Allocation Laws	Political friction, enforcement gaps	Transboundary cooperation, transparent governance

VII Discussion

The literature reviewed in this study demonstrates that climate-related irrigation stress arises from the interaction of multiple forces rather than from a single hydrological trend. Changing precipitation, rising evapotranspiration, altered runoff timing, groundwater decline, and competing sectoral demands together create complex pressures on agricultural water systems (IPCC, 2021; Wada et al., 2014). This means that climate-resilient irrigation must be understood as a systems issue that spans hydrology, agronomy, infrastructure, governance, and social equity.

A recurring finding across the reviewed studies is that integrated adaptation performs better than isolated interventions. Technological measures such as drip irrigation, water-saving practices, and recharge enhancement can be highly effective, but their outcomes depend on institutional support, affordability, and implementation context (IWMI, 2019; Howden et al., 2007). This is one reason why adaptation success varies sharply across regions and farming systems.

The literature also reveals important unresolved issues. Many models still rely on simplified assumptions about irrigation behavior, groundwater abstraction, and farmer decision-making. Long-term evidence on the economic durability and social equity of adaptation measures remains limited. Similarly, many regional studies focus on technical performance while giving less attention to governance failures, implementation constraints, and cross-sector competition.

VIII Case Studies

Case studies illustrate how broad climate-related irrigation challenges unfold in practice and how adaptation strategies differ according to regional conditions.

VIII.a Punjab, India

Punjab demonstrates the risks associated with long-term dependence on groundwater-intensive irrigation. Declining groundwater levels, water-intensive crop systems, and pressure on aquifers have created major sustainability concerns in the region (CGWB, 2018). Responses such as micro-irrigation, crop diversification, and revised pumping practices show the importance of linking technological change with incentive structures and institutional support.

VIII.b Nile Basin

The Nile Basin illustrates the complexity of adaptation in a shared river system. Climate change, irrigation expansion, and population growth increase pressure on a politically sensitive basin, making cooperation, allocation, and transboundary governance essential to any effective adaptation strategy (IWMI, 2019).

VIII.c Central Asia

Central Asia, particularly the Aral Sea basin, provides a strong example of the ecological consequences of unsustainable irrigation expansion. The case underscores the importance of integrating irrigation adaptation with environmental restoration, water-quality management, and long-term ecosystem protection (Wada et al., 2014).

Table 2 summarizes the three regional case studies by comparing their primary water source, core climate threat, adaptation focus, and main implementation barrier.

IX Synthesis of Effective Adaptation Pathways

The reviewed studies suggest that effective adaptation pathways can be grouped into three broad categories. First, integrated high-impact measures such as improved irrigation technology, conjunctive management, canal rehabilitation, crop adjustment, and groundwater governance often produce the strongest resilience outcomes. Second, supportive operational measures such as rainwater harvesting, wastewater reuse, local storage enhancement, and farmer training can strengthen adaptive capacity, particularly in resource-constrained settings. Third, enabling conditions such as climate information services, monitoring systems, groundwater regulation, and farmer institutions determine whether technical measures can be implemented effectively over time.

This synthesis indicates that climate-resilient irrigation cannot be achieved through infrastructure alone. It depends on coordinated improvements in technology, management, institutions, and information systems.

Table 2: Synthesis of regional case studies on irrigation vulnerability.

Region	Primary Water Source	Core Climate Threat	Recommended Adaptation Focus	Main Implementation Barrier
Punjab, India	Groundwater (over-extracted)	Declining water tables, rising pumping costs	Micro-irrigation, crop diversification, groundwater governance	Political will, farmer incentives
Nile Basin	Transboundary Surface Water (River Nile)	Flow reduction, population growth	Transboundary treaties, water allocation, improving efficiency	Political friction, enforcement
Central Asia	Snow-fed surface water (Amu Darya/Syr Darya)	Ecological collapse (Aral Sea), desertification	Water quality restoration, ecosystem flow, regional cooperation	Transboundary disputes, funding

X Policy Implications

Several policy implications emerge from this review. First, irrigation planning must move beyond reliance on historical averages and incorporate future climate risk, groundwater conditions, and hydrological uncertainty into planning and allocation decisions (IPCC, 2021; World Bank, 2016). Second, adaptation policy should support combined packages of supply-side, demand-side, and institutional measures rather than isolated interventions. Third, irrigation adaptation must address equity, since smallholders and resource-poor farmers often face the greatest barriers to adopting new technologies despite being among the most climate-vulnerable groups (Lipper et al., 2014).

For policymakers, the review highlights the need for stronger groundwater regulation, improved monitoring, investment in modern irrigation systems, and better integration of climate information into water governance. For researchers, it underscores the importance of interdisciplinary methods and more region-specific evidence on long-term adaptation performance.

XI Conclusion

This review shows that climate change is transforming irrigation systems through declining water reliability, rising evapotranspiration, groundwater stress, and growing competition among water users. These pressures are especially severe in regions already characterized by water scarcity and high dependence on irrigated agriculture.

The review also indicates that isolated technical interventions are insufficient to address these challenges. More effective adaptation emerges when engineering, hydrological, agronomic, and institutional responses are integrated within locally appropriate strategies. At the same time, several important research gaps remain.

The main research gaps identified by this review are: (i) limited integration of climate, hydrological, crop, and socioeconomic modeling; (ii) insufficient long-term evidence on the economic and social performance of adaptation strategies; (iii) weak understanding of groundwater–surface water interactions under future climate scenarios; (iv) limited attention to equity, governance, and implementation barriers in smallholder systems; and (v) inadequate regional evidence from highly vulnerable but data-scarce areas. Future research should therefore prioritize integrated modeling, groundwater monitoring, comparative evaluation of adaptation pathways, and policy-oriented studies that link technical performance with institutional feasibility. These areas deserve greater emphasis if irrigation systems are to remain productive, equitable, and resilient under future climate change.

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Conflict of interest: The Authors have no conflicts of interest to declare that they are relevant to the content of this article.

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