Research Journal of Agricultural Science, 58 (3), 2026; ISSN: 2668-926X;

http://doi.org/10.59463/RJAS.2026.3.52

CLIMATE CHANGE IMPACTS AND WATER RESOURCE MANAGEMENT STRATEGIES IN AGRICULTURE

Laura ȘMULEAC [1], Adrian ȘMULEAC [1], Raul PAȘCALĂU [1], Răzvan GUI-BACHNER [1], Mahfoud BAKLI [2], Rauf JURAKHON [3]

[1] University of Life Sciences "King Mihai I" from Timisoara, Romania

[2]Université de Ghardaia, Algeria

[3] Tajik Technical University named after M.S. Osimi

Corresponding author: adrian_smuleac@usvt.ro

Abstract. *Climate change is reshaping agricultural water systems through rising temperatures, altered rainfall patterns, glacier retreat, and more frequent droughts and floods. These pressures reduce surface water availability, accelerate groundwater depletion, degrade water quality, and increase crop evapotranspiration demands. Consequently, farmers face lower yields, higher production risks, and growing competition for limited freshwater among domestic, industrial, and ecological users. This abstract examines major climate change impacts on irrigation dependent and rainfed agriculture while evaluating practical water resource management strategies that improve resilience. Key adaptation measures include efficient irrigation technologies such as drip and sprinkler systems, deficit irrigation, soil moisture monitoring, rainwater harvesting, managed aquifer recharge, and on farm storage. Additional strategies involve conservation agriculture, mulching, drought tolerant crop varieties, revised planting calendars, crop diversification, and precision scheduling based on weather forecasts and remote sensing. Institutional responses are equally important including water pricing secure allocation rules farmer training participatory irrigation governance and climate information services Integrated watershed planning and reuse of treated wastewater can further expand reliable supplies while protecting ecosystems Effective implementation depends on financing data access extension support and policies tailored to local hydrology and social conditions Overall climate smart water management can reduce vulnerability sustain productivity and strengthen long term food security under increasing climate uncertainty. Research also shows that combining infrastructure upgrades with community institutions delivers stronger outcomes than isolated technical fixes because users coordinate withdrawals share maintenance costs and respond faster during emergencies Monitoring indicators such as irrigation efficiency groundwater levels salinity crop water productivity and equity helps managers adjust plans annually Public private partnerships can scale innovation through credit insurance digital advisory platforms and demonstration farms across vulnerable regions worldwide. Future priorities include stronger transboundary cooperation better seasonal forecasting open data standards gender responsive planning and youth engagement in governance processes everywhere today now soon ahead together globally.*

Keywords*: climate change, agriculture, water resources, irrigation management, resilience*

INTRODUCTION

Climate change has become one of the most significant challenges affecting global agriculture and the sustainable management of water resources. Agricultural production is strongly dependent on climatic conditions, particularly temperature, precipitation, solar radiation, and the temporal and spatial availability of water. Changes in these variables directly influence crop development, soil moisture, evapotranspiration, irrigation requirements, and ultimately agricultural productivity. At the same time, agriculture is the largest user of freshwater in many regions of the world, which makes the sector particularly vulnerable to increasing water scarcity and competition among different categories of users (CARETTA et al., 2022; MEKONNEN and HOEKSTRA, 2016).

Rising air temperatures are associated with higher potential evapotranspiration and increased crop water requirements. In regions where precipitation decreases or becomes more

irregular, the difference between crop water demand and naturally available soil moisture may increase considerably. Even where annual precipitation totals remain relatively stable, changes in rainfall distribution can have important consequences for agriculture. Longer dry periods interrupted by intense rainfall events can reduce effective water availability because a larger proportion of precipitation may be lost through surface runoff, erosion, or deep percolation rather than being stored in the root zone. Consequently, both rainfed and irrigated farming systems are exposed to increasing climatic uncertainty (ALLEN et al., 1998; CARETTA et al., 2022).

Drought represents one of the most important climate-related risks for agriculture. Prolonged periods of insufficient precipitation can reduce soil water reserves, decrease river flows and reservoir storage, and increase pressure on groundwater resources. Farmers frequently compensate for rainfall deficits by increasing groundwater abstraction, particularly in areas where surface water supplies are unreliable. However, excessive groundwater withdrawal may result in declining water tables, higher pumping costs, land subsidence, and deterioration of water quality. In coastal and intensively irrigated regions, overexploitation may also promote saline intrusion into freshwater aquifers (CARETTA et al., 2022; UNESCO, 2024).

Climate change can simultaneously increase the frequency and intensity of extreme rainfall and flooding. Agricultural land affected by floods may experience crop losses, soil erosion, nutrient leaching, infrastructure damage, and contamination of water sources. Thus, agricultural water management must address both water scarcity and excess water. The challenge is no longer limited to supplying sufficient irrigation water during dry periods; it also involves storing water when it is abundant, improving soil infiltration, controlling runoff, protecting water quality, and increasing the overall resilience of farming systems.

The relationship between climate change, agriculture, and water resources is particularly relevant in regions characterized by strong interannual climatic variability. European agriculture, including agricultural systems in Romania, is increasingly exposed to heat waves, seasonal drought, irregular precipitation, and episodes of intense rainfall. These conditions underline the importance of integrated water management strategies capable of combining technological, agronomic, environmental, and institutional measures (CARETTA et al., 2022; UNESCO, 2023).

Improving irrigation efficiency is an important component of adaptation. Traditional irrigation systems can generate considerable losses through evaporation, runoff, and inefficient application. Drip irrigation, appropriately designed sprinkler systems, soil moisture sensors, automated control technologies, and precision irrigation can improve the relationship between the quantity of water applied and crop production. However, irrigation efficiency alone cannot ensure sustainable water management. Improvements at field level need to be combined with appropriate allocation policies, monitoring of groundwater and surface water resources, maintenance of irrigation infrastructure, and measures designed to conserve water within agricultural landscapes.

Soil management is equally important because soil represents a major temporary reservoir of water available to plants. Conservation tillage, crop residues, cover crops, organic amendments, and mulching can improve soil structure, reduce evaporation, increase infiltration, and limit erosion. Crop selection and diversification also provide important opportunities for adaptation. Drought-tolerant varieties, crops with lower water requirements, and adjustments in sowing dates can reduce exposure to periods of high temperature and water deficit.

Therefore, effective adaptation requires an integrated approach that considers water availability, irrigation technology, soil characteristics, crop requirements, climate information, and socioeconomic conditions. The objective of this paper is to analyse the principal impacts of

climate change on agricultural water resources and to discuss management strategies that can improve water-use efficiency, agricultural resilience, and the long-term sustainability of crop production.

MATERIAL AND METHODS

The study was developed as a qualitative and comparative synthesis of the main relationships between climate change, agricultural water availability, and water resource management. The methodological approach focused on identifying the principal climatic pressures affecting agricultural water systems and evaluating adaptation measures applicable to both rainfed and irrigated agriculture.

The analysis was organized around four major components: climate-related pressures, impacts on water resources, consequences for agricultural production, and adaptation and management responses. Climatic pressures considered included increasing temperature, changes in precipitation distribution, drought frequency, extreme rainfall, and increasing climatic variability. Their potential effects on surface water, groundwater, soil moisture, water quality, and crop evapotranspiration were subsequently assessed (SMULEAC et al., 2025; FAO, 2025).

Table 1

Framework for assessing climate-related pressures and agricultural water management responses

Climate-related pressure	**Main effect on water resources**	**Agricultural consequence**	**Main management response**
Rising temperature	Increased evapotranspiration and soil moisture depletion	Higher crop water requirements	Improved irrigation scheduling and precision irrigation
Irregular precipitation	Reduced effective rainfall and soil-water availability	Increased crop water stress	Rainwater harvesting and supplementary irrigation
Drought	Reduced surface water and groundwater recharge	Yield reduction and increased groundwater abstraction	Deficit irrigation, storage and drought monitoring
Extreme rainfall	Increased runoff, erosion and nutrient losses	Crop damage and reduced water-use efficiency	Drainage, water storage and infiltration measures
Groundwater decline	Reduced long-term water availability	Lower reliability of irrigation supply	Managed aquifer recharge and abstraction control
Water-quality deterioration	Increased salinity and contamination risks	Soil degradation and crop limitations	Water-quality monitoring and appropriate irrigation management

Source: Authors' synthesis based on CARETTA et al. (2022), PEREIRA et al. (2012), FAO (2025), and UNESCO (2024).

Water management strategies were grouped into several categories: irrigation technologies, soil and crop management practices, alternative water sources and storage, digital and precision agriculture, and institutional or governance measures. This classification allowed technical solutions to be analysed together with agronomic and organizational approaches rather than treating irrigation as an isolated intervention (PEREIRA et al., 2012; FAO, 2025).

The effectiveness of irrigation management was considered through the concept of crop water productivity, which can be expressed as:

$$CWP = Y / W$$

where CWP represents crop water productivity, Y is crop yield or biomass production, and W represents the quantity of water consumed or supplied during the production process. Increasing CWP implies obtaining greater agricultural output per unit of water used and is therefore an important objective in water-scarce agricultural systems (PEREIRA et al., 2012; KANG et al., 2017).

The assessment also considered indicators relevant to long-term water sustainability, including irrigation efficiency, groundwater level trends, soil salinity, soil moisture, water storage capacity, crop yield stability, and vulnerability to drought. Particular attention was given to the distinction between improving application efficiency at field level and achieving actual water savings at watershed or basin scale (PEREIRA et al., 2012).

Adaptation measures were evaluated according to their potential contribution to five objectives: reducing water losses, increasing water availability, improving soil water retention, reducing crop vulnerability, and strengthening institutional capacity.

This integrated framework (table 1) reflects the fact that climate-resilient agricultural water management depends on interactions among environmental, technological, economic, and social factors (CARETTA et al., 2022; UNESCO, 2023).

RESULTS AND DISCUSSIONS

The analysis indicates that climate change affects agricultural water resources through several interconnected mechanisms. Increasing temperatures represent a fundamental pressure because they increase atmospheric evaporative demand. Higher evapotranspiration can accelerate the depletion of soil moisture and increase irrigation requirements, especially during critical crop development stages. Under such conditions, crops may experience water stress even when seasonal precipitation totals do not change substantially (ALLEN et al., 1998; CARETTA et al., 2022).

Changes in rainfall distribution further intensify these effects. Agricultural production benefits not only from the total quantity of rainfall but also from its timing and intensity. Moderate rainfall distributed throughout the growing season generally contributes more effectively to crop water requirements than a similar quantity concentrated in a few intense events. Heavy rainfall can exceed soil infiltration capacity, producing runoff, erosion, nutrient transport, and localized flooding. Consequently, an increase in extreme precipitation does not necessarily translate into improved agricultural (Figure 1) water availability (CARETTA et al., 2022; ROCKSTRÖM et al., 2009).

Water scarcity can significantly affect crop yields. Water stress during flowering, pollination, or grain filling may produce substantial yield reductions, while repeated drought can also influence soil biological activity and nutrient availability. Irrigated agriculture can partially compensate for precipitation deficits, but this advantage depends on reliable water supplies. Where irrigation is based primarily on groundwater, increasing drought frequency can create a feedback mechanism in which declining rainfall causes higher pumping, which in turn accelerates groundwater depletion (MEKONNEN and HOEKSTRA, 2016; UNESCO, 2024).

Improving irrigation systems is therefore a major adaptation strategy. Drip irrigation delivers water close to the root zone and can substantially reduce evaporation and non-beneficial water application when properly designed and managed. Sprinkler irrigation can provide relatively uniform application and greater operational flexibility than traditional surface systems. Nevertheless, the effectiveness of any irrigation technology depends on correct scheduling, maintenance, crop characteristics, soil conditions, and farmer knowledge. Installing efficient

http://doi.org/10.59463/RJAS.2026.3.52

equipment without appropriate management may produce smaller benefits than expected (PEREIRA et al., 2012; KANG et al., 2017).

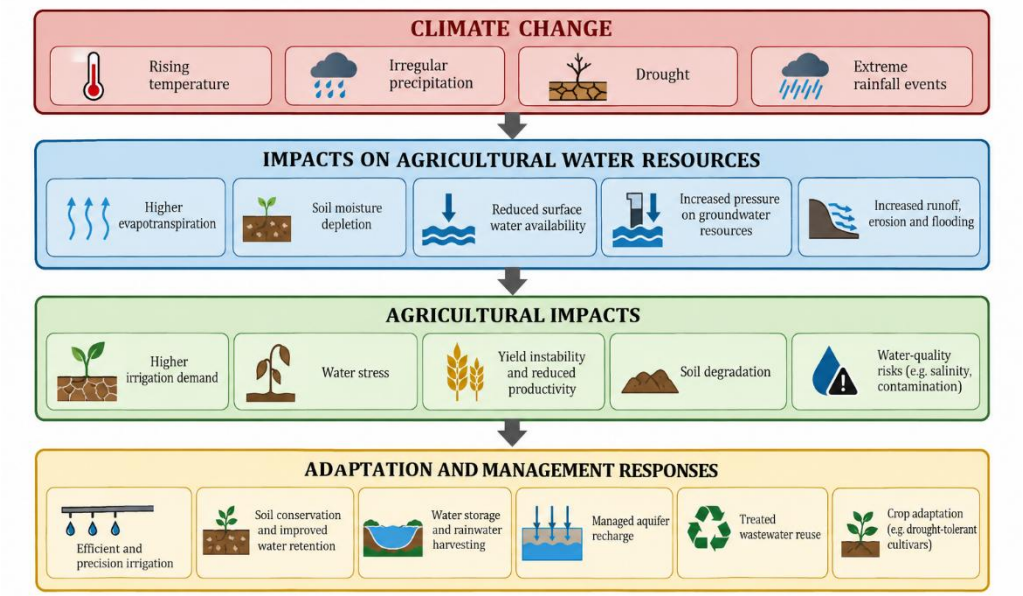


Figure 1. Pathways linking climate change, agricultural water resources and adaptation responses. Source: Authors' conceptualization based on CARETTA et al. (2022), FAO (2025), and UNESCO (2024).

Precision irrigation provides additional opportunities to improve water management. Soil moisture sensors can indicate whether irrigation is necessary and help determine the appropriate quantity of water to apply. Weather information and estimates of reference evapotranspiration can be combined with crop coefficients to estimate crop water requirements. Remote sensing can identify spatial differences in crop development, vegetation stress, and soil moisture conditions. Together, these technologies support irrigation decisions based on actual field conditions rather than fixed calendars (FERERES et al., 2007; KANG et al., 2017).

Deficit irrigation can also be useful where water supplies are limited. Under this strategy, irrigation volumes are deliberately maintained below maximum crop evapotranspiration requirements during selected growth periods. The objective is not necessarily to maximize yield per hectare but to maximize economic return or crop production per unit of available water. Its success depends strongly on crop type and growth stage because some crops can tolerate moderate water deficits during particular developmental periods better than others (FERERES and SORIANO, 2007; GEERTS and RAES, 2009; CHAI et al., 2016).

At the same time, technological improvements should be accompanied by soil conservation practices. Mulching reduces direct evaporation from the soil surface and can suppress weeds that compete with crops for water. Conservation tillage and residue retention can improve soil structure and infiltration while reducing erosion. Increasing soil organic matter may improve aggregate stability and water-holding characteristics. Cover crops can provide additional benefits by protecting soil from erosion and improving soil structure, although their

http://doi.org/10.59463/RJAS.2026.3.52

water consumption must be carefully considered in dry environments (ROCKSTRÖM et al., 2009; FAO, 2025).

Rainwater harvesting and on-farm water storage can reduce dependence on external water supplies. Water collected from roofs, farm structures, drainage systems, or controlled surface runoff may be stored for later use. Small reservoirs and farm ponds can capture water (ROCKSTRÖM et al., 2009; FAO, 2025) during wet periods and provide supplementary irrigation during short drought episodes. However, storage systems require appropriate design because evaporation losses can become significant under high-temperature conditions (FAO, 2025; ROCKSTRÖM et al., 2009).

Table 2

Comparative assessment of climate-resilient agricultural water management strategies

Strategy	Main advantage	Main limitation	Recommended application
Drip irrigation	High application efficiency and reduced evaporation	Initial cost and maintenance requirements	Water-scarce areas and high-value crops
Precision irrigation	Water application according to actual crop needs	Requires sensors, data and technical expertise	Modern irrigated farms
Deficit irrigation	Improves crop production per unit of available water	Possible yield reduction if poorly scheduled	Areas with limited water availability
Soil conservation	Improves infiltration and soil water retention	Benefits vary with soil and climatic conditions	Rainfed and irrigated agriculture
Rainwater harvesting	Reduces dependence on external water supplies	Storage capacity and evaporation losses	Areas with seasonal rainfall
Managed aquifer recharge	Supports groundwater recovery and seasonal storage	Requires suitable hydrogeological conditions	Regions affected by groundwater decline
Treated wastewater reuse	Provides a relatively stable alternative water source	Water-quality, salinity and health risks	Agriculture near urban areas
Crop adaptation	Reduces vulnerability to drought and heat	Depends on suitable crops and varieties	Climate-sensitive agricultural regions

Source: Authors' synthesis based on FERERES and SORIANO (2007), GEERTS and RAES (2009), PEREIRA et al. (2012), HASHEM and QI (2021), and LEVINTAL et al. (2022).

Managed aquifer recharge represents another potential strategy. During periods when surface water is relatively abundant, suitable water can be directed toward infiltration areas or recharge structures to replenish groundwater reserves. This approach can contribute to balancing seasonal differences between water availability and demand. Its implementation requires detailed knowledge of hydrogeological conditions and careful water-quality monitoring to avoid groundwater contamination (NISWONGER et al., 2017; LEVINTAL et al., 2022; SHOUSHTARI et al., 2021).

The reuse of treated wastewater can diversify water supplies, particularly near urban areas (Table 2). Properly treated wastewater may provide a relatively stable source for agricultural irrigation while simultaneously reducing pressure on freshwater resources. However, its use requires strict monitoring of microbiological quality, salinity, nutrients, trace elements, and potential contaminants. Appropriate regulations and irrigation practices are essential to protect soil quality, crops, groundwater, farmers, and consumers (HASHEM and QI, 2021; URBANO et al., 2021).

Crop adaptation represents another major component of climate-resilient water management. Drought-tolerant cultivars can maintain production under moderate water stress,

while shorter-season varieties may avoid periods of severe summer drought. Adjusting planting dates can help synchronize sensitive crop stages with periods of more favourable temperature and water availability. Crop diversification reduces dependence on a single crop and can distribute climate risk across species with different rooting depths, growing seasons, and water requirements.

An important result of the integrated analysis is that water efficiency should not be considered exclusively at field scale. A reduction in water applied to an individual field does not automatically produce an equivalent reduction in total basin water consumption. Some water traditionally considered an irrigation "loss" may return to rivers or recharge groundwater and subsequently become available to other users. Consequently, water-saving programmes should evaluate consumptive use and return flows at watershed level (PEREIRA et al., 2012).

Institutional measures are therefore essential. Clear water allocation rules can reduce conflicts during drought, while monitoring systems can prevent unsustainable groundwater abstraction. Water pricing may encourage conservation when designed appropriately, but pricing mechanisms should consider farm size, production systems, affordability, and food-security objectives. Excessively high costs may disadvantage small farmers without necessarily creating effective water savings.

Participatory irrigation management can improve cooperation among farmers, irrigation associations, water authorities, and other stakeholders. Collective management is particularly important where multiple farms depend on shared canals, reservoirs, or groundwater systems. Participation can facilitate infrastructure maintenance, improve compliance with allocation rules, and promote faster responses during drought emergencies.

Climate information services also have considerable potential. Seasonal forecasts, short-term weather forecasts, drought indicators, and early-warning systems can help farmers decide when to irrigate, plant, harvest, or implement protective measures. Digital advisory systems can combine weather information, satellite observations, crop models, and field sensors to generate site-specific recommendations. However, technological sophistication alone does not guarantee adoption. Information must be timely, understandable, affordable, and relevant to farmers' decisions (UNESCO, 2023; FAO, 2025).

Economic constraints remain a major barrier to adaptation. Modern irrigation equipment, sensors, reservoirs, and renewable-energy pumping systems require initial investment that may exceed the financial capacity of small and medium-sized farms. Credit programmes, subsidies, insurance, farmer cooperatives, demonstration projects, and public-private partnerships can support wider adoption. Nevertheless, financial incentives should be connected to measurable sustainability outcomes to avoid encouraging expansion of irrigation in already overexploited water systems.

For Romania and other countries in Central and Eastern Europe, adaptation should integrate irrigation rehabilitation with soil-water conservation, drought monitoring, drainage management, and improved water storage. Agricultural areas exposed to increasingly variable rainfall may benefit from combining irrigation infrastructure with precision technologies and practices that increase the capacity of soils to retain water. Local solutions should reflect regional differences in soil properties, groundwater availability, crop structure, farm size, and climatic exposure (PRĂVĂLIE et al., 2020; CARETTA et al., 2022).

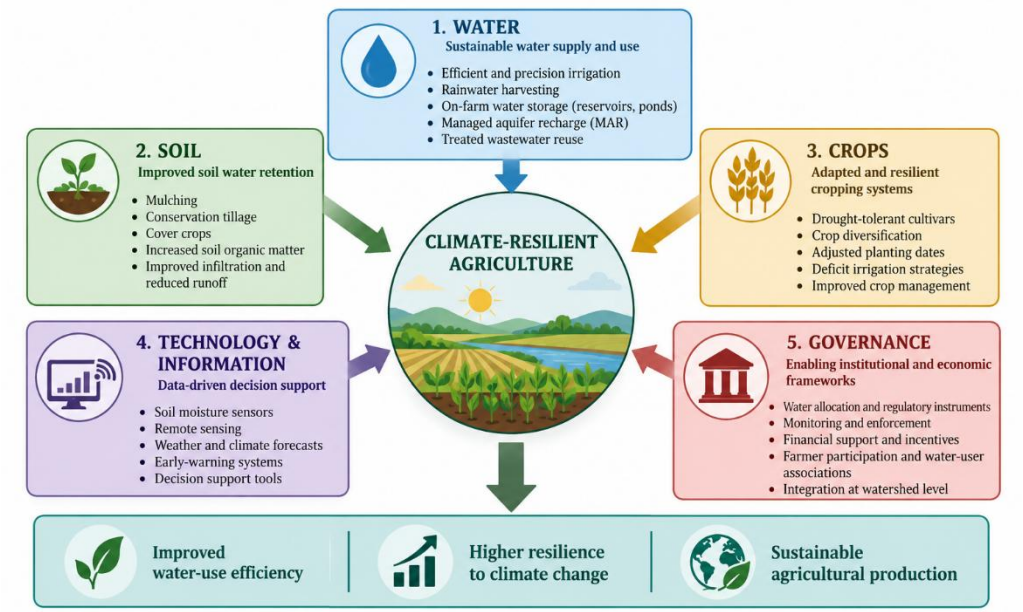


Figure 2. Integrated framework for climate-resilient agricultural water management
Source: Authors' conceptualization.

Overall, the results suggest that no single measure can adequately address climate-related agricultural water risks. The greatest resilience is achieved through combinations of interventions. Efficient irrigation can reduce unnecessary application, soil conservation can retain more precipitation within the root zone, crop adaptation can reduce water demand and vulnerability, while storage and alternative sources can improve supply reliability. Institutional arrangements and climate information provide the framework (figure 2) necessary to coordinate these measures over time (CARETTA et al., 2022; FAO, 2025; UNESCO, 2023).

CONCLUSIONS

Climate change is increasing the complexity of agricultural water management by altering precipitation patterns, increasing temperatures and evapotranspiration, intensifying droughts, and contributing to more frequent extreme hydrological events. These processes affect both the quantity and quality of available water and increase uncertainty for rainfed and irrigated agricultural systems.

Sustainable adaptation requires a transition from conventional water-supply management toward integrated and climate-resilient approaches. Efficient irrigation systems, soil moisture monitoring, precision scheduling, deficit irrigation, rainwater harvesting, water storage, managed aquifer recharge, and safe wastewater reuse can contribute to improved water security. At the same time, conservation agriculture, mulching, increased soil organic matter, drought-tolerant crops, crop diversification, and adjusted planting calendars can reduce agricultural water demand and improve resilience.

Technical measures should be integrated with effective governance. Monitoring groundwater levels, irrigation efficiency, crop water productivity, salinity, and water quality is essential for identifying unsustainable trends and adjusting management strategies. Farmer

participation, training, climate information services, appropriate financing mechanisms, and transparent water allocation policies can significantly increase the effectiveness of adaptation programmes.

Future agricultural water management should focus not only on producing more food with less applied water but also on protecting the long-term functioning of watersheds, aquifers, soils, and aquatic ecosystems. Water-saving technologies should therefore be evaluated at both farm and basin levels, taking into account consumptive use, return flows, environmental requirements, and social equity.

In conclusion, climate-resilient agriculture depends on the coordinated management of water, soil, crops, infrastructure, information, and institutions. Combining technological innovation with ecosystem-based practices and participatory governance offers the strongest opportunity to maintain agricultural productivity under increasing climatic uncertainty. Such an integrated approach can improve water-use efficiency, reduce vulnerability to drought and floods, protect natural resources, and contribute to sustainable food production and long-term water security.

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