



Sustainable Agricultural Practices and Technological Innovations for Climate Change Mitigation in Dryland Farming Systems

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Abstract

Climate change poses significant challenges to agricultural productivity, particularly in dryland regions, where water scarcity and soil degradation are exacerbated by altered precipitation patterns and extreme weather events. This review examines recent advancements in sustainable agricultural practices aimed at mitigating these impacts. A primary focus is on conservation tillage systems, such as no-tillage and reduced tillage, which are proven to enhance soil water retention, improve organic carbon sequestration, and ultimately increase crop yield by minimizing soil disturbance and protecting surface residues. Complementing these mechanical approaches, nature-based solutions like mulching and intercropping are explored for their synergistic role in building robust agro-ecosystems. Mulching conserves soil moisture and suppress weeds, while intercropping enhances biodiversity, improves soil structure, and optimizes nutrient and water use efficiency. The integration of precision agriculture, powered by remote sensing and IoT-based technologies, acts as a force multiplier for these practices. It enables real-time, data-driven decision-making by allowing for the precise monitoring of soil moisture, crop health, and environmental stressors. Collectively, these strategies form a holistic framework for enhancing agricultural resilience. By moving beyond conventional methods, they work in concert to build healthier soils, optimize every drop of water, and create more buffered production systems. This integrated approach is critical for improving resource use efficiency, ensuring food security, and safeguarding the livelihoods of communities within climate-vulnerable dryland ecosystems, thereby paving the way for a more sustainable and adaptive agricultural future.

1. Introduction

Climate change presents a profound threat to global agricultural systems, with dryland regions being particularly vulnerable due to their inherent water scarcity and susceptibility to soil degradation (Adil et al., 2025). These regions, which cover approximately 40% of the Earth's terrestrial surface, are facing heightened challenges due to altered precipitation patterns and an increased frequency of extreme weather events, directly compromising crop productivity and livelihoods (Adil, Lu, et al., 2024; Jain et al., 2024). The complexity of these challenges necessitates a multifaceted response that integrates sustainable agricultural practices with technological innovation (Ali et al., 2022; Malik et al., 2021; ul Abadin, 2021). In recent years, significant research has focused on developing strategies to enhance the resilience of dryland agriculture. These include

advanced conservation tillage systems and nature-based solutions to optimize water use and improve soil health, alongside the rapid emergence of digital agriculture technologies designed to enable precise, data-driven farm management (Adil, Lv, Cao, et al., 2024; Adil, Zhang, et al., 2022).

A critical line of inquiry involves understanding crop responses to changing climatic conditions (Adil, Zhang, et al., 2023; Hussain, 2021; Parveen, 2021). Recent research systematically assesses the adequacy of farmland productivity in combating climate change, revealing the complex interplay between CO₂ fertilization effects and extreme weather events. For instance, studies quantify yield fluctuations of staple cereals like wheat and maize under different warming scenarios, noting that elevated CO₂ can partially offset heat stress for C3 crops like wheat, while C4

crops like maize may demonstrate superior water use efficiency (Akhter, 2021; Arshad, 2021). Beyond crop physiology, building socio-economic resilience is equally crucial. Index-based livestock insurance (IBLI) has emerged as a key policy tool to support pastoralists in the drylands of Africa, protecting livelihoods against drought-induced livestock mortality. Such financial instruments have scaled dramatically, providing over \$100 million in coverage to hundreds of thousands of households by 2023, demonstrating the importance of risk-mitigation strategies in climate-vulnerable economies.

Concurrently, the digital transformation of agriculture offers unprecedented tools for adaptation. In Low and middle-income countries (LMICs), the adoption of Agriculture 4.0 technologies, such as the Internet of Things (IoT), artificial intelligence (AI), and big data, is a key focus (Mwanza et al., 2023). Contemporary literature reviews identify a complex web of influencing factors, from socioeconomic conditions like farmer education and income to technological aspects such as perceived usefulness and cost (Rizzo et al., 2024). However, the full potential of these digital tools is often hampered by barriers, including inadequate infrastructure, limited digital literacy, and insufficient institutional support. To address the core challenge of developing resilient crops, innovative breeding approaches are being developed. Model-aided enviro-typing, which categorizes environments into distinct types, is one such approach that accelerates "ideo-typing", the design of ideal crop traits. A novel framework integrating enviro-typing with genetic algorithms has successfully identified wheat ideotypes that can boost average yield by approximately 18% and enhance yield stability across diverse Australian environments, providing a scalable path toward climate-resilient cultivars (Abdel-salam et al., 2024).

This review synthesizes recent advancements in sustainable agricultural practices and technological innovations aimed at mitigating the impacts of climate change on dryland agriculture. It examines the effectiveness of conservation systems, nature-based solutions, and precision agriculture technologies in enhancing agricultural resilience, improving resource use efficiency, and ensuring food security in these climate-vulnerable ecosystems.

2. Impacts of Climate Change on Dryland Agriculture

Dryland regions, which constitute approximately 40% of the Earth's terrestrial surface, are on the front lines of the climate crisis. These ecosystems, characterized by low and erratic rainfall, high evaporation rates, and inherent water scarcity, are experiencing an acceleration of degradation processes due to anthropogenic climate change. Rising temperatures, altered precipitation patterns, and the increased frequency and intensity of extreme weather events are exerting unprecedented pressure on agricultural systems, leading to severe water scarcity, widespread soil degradation,

and diminished productivity that threatens global food security.

2.1. Drought and Water Scarcity

The hydrological stability of dryland regions is deteriorating rapidly due to climate change (Adil, Zhang, et al., 2022). A recent global analysis reveals a significant and ongoing depletion of terrestrial water storage, including soil moisture, lakes, and rivers, directly linked to global warming (Adil et al., 2025). This depletion critically undermines the foundation of rain-fed agriculture and places immense strain on irrigation resources.

The socio-economic consequences of this escalating water stress are profound (Javed et al., 2025). The United Nations Convention to Combat Desertification (UNCCD) reports that three out of every four people on Earth could be affected by drought by 2050 (Afroze, 2025). This is not a distant threat; currently, over three-quarters of the world's land area is already experiencing drier conditions, directly impacting agricultural output and water security for billions.

Regional studies further quantify this crisis. In North Africa, a region dominated by arid climates, GIS-based analyses show that 60% of the area within the Nile River's 10 km buffer zone faces an extremely high risk of water (Valjarević et al., 2025). This is exacerbated by a 45% population increase in these vulnerable riverside areas between 2000 and 2020, intensifying the competition between agricultural, industrial, and domestic water use (Jenerette, 2025). Furthermore, climate models project that if current temperature trends continue, the global extent of dryland conditions could expand to cover 24% to 32% of the world's total land surface, placing even more ecosystems and communities at risk.

2.2. Soil Degradation

Soil degradation in drylands is a multifaceted crisis, driven by the interplay of climate change and unsustainable land management practices. Key processes include salinization, erosion, and the loss of organic matter, all of which are intensified by a warming climate (Adil, Yao, et al., 2022).

Salinization has reached alarming levels globally (Adil, Bashir, et al., 2022; Adil, Shah, et al., 2023; Daud et al., 2025; Kamran et al., 2019). According to a landmark 2024 report by the UN Food and Agriculture Organization (FAO), a staggering 1.38 billion hectares of land, approximately 10% of the global land area—are already salt-affected (Mwesige, 2025). An additional 1 billion hectares are at risk, with climate change acting as a major accelerator through its causation of drought, freshwater shortage, and sea-level rise, which induces coastal saltwater intrusion (Ashrafuzzaman, 2025; Iqbal, Ma, et al., 2025; Iqbal, Wang, et al., 2025). In high-risk agricultural areas, stresses like salinity and drought can cause yields of staple crops like rice and pulses to fall by

up to **70%**, representing a direct threat to food production (Ahamad et al., 2024; Raza Altaf et al., 2021; Razzaq, Zhou, Adil, et al., 2024; Razzaq, Zhou, Ullah, et al., 2024).

Erosion and organic matter loss are equally critical. UNESCO has warned that without urgent action, 90% of the Earth's soils could be degraded by 2050, a catastrophic escalation from the current 75% that are already degraded (Reduction, 2025). This degradation is not merely a loss of physical soil; it represents a massive release of stored carbon into the atmosphere. Soils are the planet's second-largest carbon sink, and their degradation has already contributed an estimated 78 billion tons of carbon to the atmosphere, severely undermining global climate mitigation efforts. Furthermore, soil erosion is projected to cause a 10% reduction in global crop yields by 2050, coupled with the loss of 75 billion tons of soil (Teku & Derbib, 2025). This creates a vicious cycle: climate change degrades soils, which releases carbon and reduces their fertility, which in turn undermines agricultural resilience and food security.

3. Sustainable Agricultural Practices for Mitigation

3.1. Conservation Agriculture Systems

Conservation Agriculture (CA) is a holistic system built on three principles: minimizing soil disturbance, maintaining soil cover, and diversifying crop species. It is essential for enhancing soil health, improving water retention, and mitigating climate change in dryland farming systems (Figure 1). A recent meta-analysis clarifies that the central benefits for climate change mitigation and soil health are driven more by retaining crop residues on the soil surface than by the mere absence of tillage (Adil, Lv, Li, et al., 2024). While no-tillage alone may lead to a slight decline in crop yield, residue retention is a key driver for enhancing production.

The practice of retaining crop residues as a soil cover (mulch) significantly improves the soil's physical properties (Adil, Zhang, et al., 2022). It leads to a lower soil bulk density, a higher water infiltration rate, and protects the soil from erosion by the sun, rain, and wind. This improves soil moisture conservation, which is particularly critical in arid and semi-arid regions (Adil, Yao, et al., 2022). Furthermore, the increased soil organic carbon (SOC) and nutrient availability observed in CA systems are strongly linked to residue retention, which feeds soil microbial life (Adil, 2021; Arshad, 2021; Gul et al., 2024). Studies show that permanent bed planting combined with residue retention can significantly increase soil organic carbon and the availability of essential micronutrients like Zinc and Iron (Pradhan et al., 2025). These systems also reduce input costs for labor, seeds, and fertilizers, increasing net profits for farmers and building resilience against erratic rainfall and droughts.

3.2. Nature-Based Solutions (NBS)

Nature-Based Solutions (NBS), such as mulching, intercropping, agroforestry, and cover cropping, utilize natural processes to improve soil fertility, enhance biodiversity, and increase water retention. These practices are especially effective in dryland regions where water scarcity and soil degradation are exacerbated by climate change.

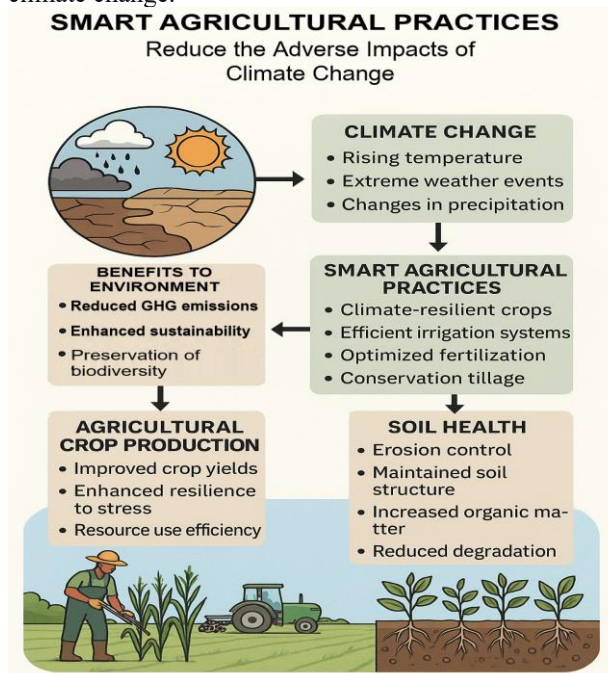


Figure 1. Smart Agricultural Practices: These practices help mitigate the adverse effects of climate change by promoting climate-resilient crops, efficient irrigation, optimized fertilization, and conservation tillage, resulting in improved crop production, enhanced soil health, and environmental sustainability.

Agroforestry: Integrating trees into farming systems provides a powerful adaptation strategy. Research from South Sudan and Senegal shows that farmers often integrate fruit trees like mango (*Mangifera indica*) and citrus (*Citrus sinensis*) for food and shade, while also using trees for windbreaks. These systems can improve soil fertility, control weeds naturally, and increase overall productivity and biodiversity. A key finding is that farmers' species selection is a deliberate climate adaptation strategy; for instance, they are more likely to plant fruit trees in response to perceived land degradation (Mvula et al., 2025).

Mulching and Cover Crops: As a core component of Conservation Agriculture, maintaining a layer of crop residues on the soil surface is a foundational NBS practice. This mulch conserves moisture, moderates soil temperature, and adds organic matter back to the soil. In olive orchards, for example, mulching has been used to successfully rejuvenate trees and maintain soil moisture, with studies showing it helps prevent up to 70% of water loss from runoff (Adil et al., 2025).

Synergistic Benefits: The FAO emphasizes that agroecological approaches like these optimize renewable resources and enhance ecosystem services such as pest control, pollination, and soil health, which are vital for sustainable agriculture. By mimicking natural ecosystems, NBS restore ecological balance, enhance nutrient cycling, and help mitigate the adverse effects of drought, thereby improving land productivity and enhancing a wide range of ecosystem services (Kiribou et al., 2025).

4. Precision Agriculture and Remote Sensing for Dryland Agriculture

The integration of precision agriculture and remote sensing technologies provides innovative and critical solutions for managing dryland agriculture under changing climatic conditions. These technologies enable real-time monitoring of soil moisture, crop health, and land use patterns, empowering farmers to make data-driven decisions on irrigation, fertilization, and pest management. The adoption of these systems in dryland farming can significantly enhance resource use efficiency, boost productivity, and mitigate environmental impacts, which is particularly vital in water-scarce regions.

4.1. Remote Sensing for Monitoring Soil Moisture and Crop Health

Remote sensing tools, including satellites, drones, and ground-based sensors, are pivotal for large-scale assessment of soil moisture, crop vigor, and health. For instance, the Crop Water Stress Index (CWSI) can be derived from satellite-based land surface temperature data to support irrigation scheduling. Recent research demonstrates that machine learning models, particularly Random Forest (RF), can effectively correct biases in satellite-derived CWSI, enhancing its accuracy for optimizing water use in arid regions (Lamichhane et al., 2025; Lu et al., 2022).

Drone technology, especially UAV multispectral remote sensing, offers high-resolution, high-frequency monitoring. Drones equipped with multispectral sensors can quantify key physiological parameters like leaf area index and chlorophyll content. Vegetation indices such as the Normalized Difference Vegetation Index (NDVI) are widely used, though newer indices like the Green NDVI (GNDVI) and the Soil-Adjusted Vegetation Index (Verma, #77) offer improved performance by reducing saturation effects in dense or sparse vegetation (Tian et al., 2025). This capability allows for precise monitoring of drought or salinity stress, enabling targeted interventions.

4.2. Variable Rate Irrigation and Nutrient Management

Precision technologies enable the variable application of water and nutrients, which is fundamental to improving efficiency in dryland farming. Variable Rate Irrigation (VRI) systems, guided by real-time remote sensing data, adjust water application based on field variability,

minimizing waste. Similarly, precision nutrient management optimizes fertilizer application by aligning it with specific soil conditions and crop needs. For example, the TCARI/OSAVI index combination has been successfully used for corn nitrogen estimation. Fusing multi-spectral data with machine learning models (e.g., XGBoost, Random Forest) has achieved high prediction accuracy for nitrogen accumulation, allowing for more efficient fertilization and reduced environmental runoff (Zhao et al., 2025).

The practical application of these principles is exemplified by the "Digital Twin Irrigation Zone Water Management Platform." This platform uses multi-source remote sensing and machine learning for crop water perception, demand forecasting, and irrigation decision-making. Its implementation has led to water savings of over 5% in field irrigation, demonstrating significant economic and environmental benefits (Yang et al., 2025).

4.3. Advancements in Data Integration and Intelligent Algorithms

Recent advancements lie in the sophisticated integration of remote sensing data with intelligent algorithms. High-resolution satellites from programs like Landsat and Sentinel-2 provide invaluable data, but the true revolution is powered by Artificial Intelligence (AI) and Machine Learning (ML).

ML algorithms are proving highly effective in various agricultural tasks. Random Forest (RF) and Support Vector Machine (SVM) excel in crop disease classification, while deep learning models like U-Net and Mask R-CNN achieve superior precision (over 96%) in segmenting and locating disease lesions, such as wheat stripe rust (Salka et al., 2025). These AI-driven systems can analyze vast datasets to predict crop performance, optimize irrigation schedules, and facilitate early disease detection, ultimately leading to more efficient resource management (Figure 2).

4.4. Future Prospects and Challenges

Despite the proven advantages, widespread adoption in dryland areas faces hurdles, including high technology costs, lack of infrastructure, and a need for technical expertise. Future development should focus on:

Algorithm Optimization and Model Generalization: Addressing data scarcity and improving model robustness across different regions and crops through transfer learning and lightweight model design.

Multi-Modal Data Fusion: Combining satellite, drone, and ground sensor data to create a more comprehensive picture of field conditions.

Policy Support and Accessibility: Government initiatives, such as the "Digital Agriculture Innovation Application Base" project in China, which offers subsidies for smart agricultural equipment, are crucial to lower financial barriers and encourage adoption. Continued research into low-cost

sensors and user-friendly cloud-based platforms will also be key to making these technologies accessible to smallholder farmers.

5 Conclusion

This review affirms that enhancing the resilience of dryland agriculture to climate change is achievable through

supportive policy frameworks that incentivize adoption, invest in rural digital infrastructure, and foster participatory research to co-develop locally tailored solutions. Capacity building through farmer education and accessible decision-

support tools are equally critical to bridge the implementation

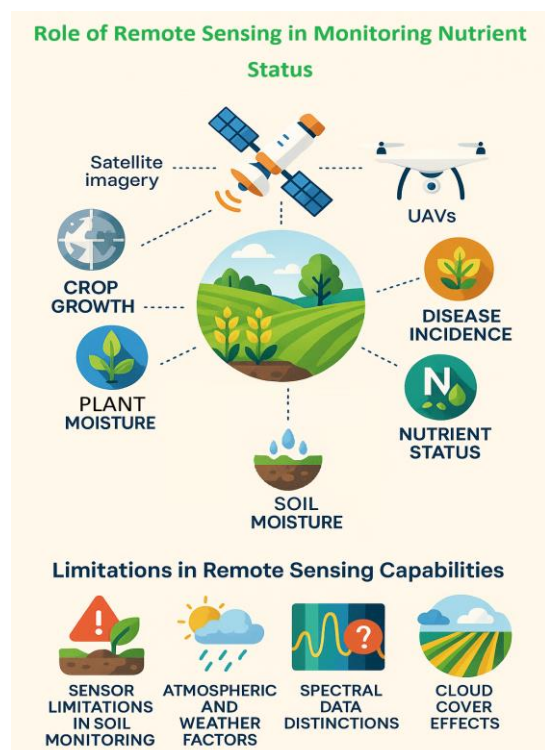


Figure 2 Remote Sensing in Monitoring Nutrient Status: Remote sensing technologies such as satellite imagery and UAVs play a crucial role in monitoring plant growth, soil moisture, and nutrient levels, though limitations such as sensor constraints, atmospheric conditions, spectral data challenges, and cloud cover effects must be addressed for improved accuracy

the synergistic integration of sustainable land management and digital technologies. The evidence demonstrates that conservation tillage systems, particularly no-tillage with residue retention, are foundational for improving soil water storage, sequestering organic carbon, and stabilizing yields. Complementarily, nature-based solutions like mulching and intercropping leverage ecological processes to optimize resource use, enhance biodiversity, and build systemic resilience. Furthermore, precision agriculture, powered by remote sensing and AI, provides unprecedented capabilities for data-driven irrigation and nutrient management, significantly boosting water use efficiency. The convergence of these approaches offers a robust paradigm shift from conventional practices towards a more adaptive and productive dryland farming system. However, widespread adoption faces barriers, including high initial costs, a need for technical knowledge, and context-specific variability in effectiveness. Future efforts must, therefore, prioritize

gap. By championing this integrated strategy—merging proven agroecological principles with technological innovation—we can transform vulnerable dryland regions into bastions of sustainability, ensuring food security and improved livelihoods for millions in the face of an increasingly variable climate.

Declarations

6 Author contributions

M.A. perceived the review and draft and finalized the manuscript.

7 Funding

N/A

8 Competing financial interests:

The author declares no competing financial interests.

8 Ethics approval

Not applicable

9 Data Availability

N/A

10 SDGs Addressed

These sustainable agricultural practices directly support SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land).

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