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Agronomic approaches to mitigate climate change effects on crop production: Recent developments

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Abstract
Climate change has emerged as a major threat to global crop production through rising temperatures, altered precipitation patterns, increased frequency of droughts and floods, and enhanced pest and disease pressure. Agronomic management plays a critical role in reducing crop vulnerability and improving resilience under changing climatic conditions. This review examines recent developments in agronomic approaches designed to mitigate climate change impacts on crop production. Key strategies include conservation agriculture, crop diversification, climate-resilient varieties, integrated nutrient management, precision agriculture, water-saving irrigation, agroforestry, and digital decision-support systems. These practices contribute to improved soil health, enhanced water-use efficiency, reduced greenhouse gas emissions, and greater adaptation to climatic stresses. Recent technological advances such as remote sensing, Internet of Things (IoT)-based monitoring, artificial intelligence-assisted crop management, and carbon-smart farming are also discussed. Although significant progress has been made, challenges related to cost, technical expertise, policy support, and adoption by smallholder farmers remain substantial. The review highlights that integrating multiple agronomic strategies within climate-smart farming systems offers the most promising pathway for sustaining crop productivity and food security under future climate scenarios.

Keywords: Climate-smart agriculture, conservation agriculture, precision farming, drought adaptation, integrated nutrient management, agroforestry, sustainable crop production, climate resilience

Introduction
Climate change has become one of the most significant challenges confronting global agriculture in the twenty-first century. Rising atmospheric temperatures, increasing concentrations of greenhouse gases, irregular precipitation patterns, prolonged droughts, intense rainfall events, and the growing frequency of extreme weather conditions are affecting crop growth and productivity across diverse agroecological regions. These climatic changes have disrupted traditional farming calendars, altered pest and disease dynamics, reduced soil moisture availability, and increased the vulnerability of agricultural systems to environmental stress. As the global population continues to expand, the demand for food is expected to rise substantially, placing additional pressure on already stressed agricultural resources [1]. Agriculture is particularly sensitive to climate variability because crop development depends heavily on temperature, water availability, solar radiation, and soil conditions. Even small changes in these factors can influence germination, flowering, grain filling, and overall yield. Heat stress during reproductive stages can reduce pollen viability and seed set, while drought conditions can limit nutrient uptake and photosynthesis. Flooding and waterlogging may damage root systems and reduce oxygen availability in the soil. In many regions, climate change is also contributing to the expansion of insect pests, weeds, and plant pathogens, further threatening crop productivity [2, 5]. Conventional agricultural practices have often intensified these challenges. Intensive tillage, monocropping, excessive use of chemical fertilizers and pesticides, inefficient irrigation, and poor residue management have contributed to soil degradation, declining organic matter, biodiversity loss, and increased greenhouse gas emissions. Such practices may provide short-term productivity gains but frequently compromise the long-term resilience of farming systems. Consequently, there is an urgent need to develop and adopt agronomic approaches that can sustain crop production while minimizing environmental impacts and enhancing adaptation to climate change [6, 8]. Recent developments in climate-smart agronomy offer promising solutions to these challenges. Strategies such as conservation agriculture, crop diversification, integrated nutrient management, precision farming, water-saving irrigation, agroforestry, and the use of climate-resilient crop varieties have demonstrated considerable potential for improving productivity under adverse climatic conditions. Advances in digital agriculture, remote sensing, artificial intelligence, and sensor-based monitoring have further strengthened the ability of farmers to make informed management decisions. This review examines recent agronomic developments aimed at mitigating climate change effects on crop production and highlights their role in promoting sustainable and resilient agricultural systems.

Conservation Agriculture
Conservation agriculture has emerged as a cornerstone of climate-smart crop production due to its capacity to improve soil health, conserve water, and enhance resilience to climatic stress. The system is based on three fundamental principles: minimal soil disturbance through reduced or no tillage, permanent soil cover using crop residues or cover crops, and diversified crop rotations. By reducing mechanical disturbance, conservation agriculture helps preserve soil structure and maintains the integrity of soil biological communities [9, 12]. One of the most important recent developments in conservation agriculture is the increased understanding of its role in soil carbon sequestration. Crop residues retained on the soil surface

gradually decompose and contribute to the accumulation of soil organic matter. Higher organic carbon levels improve soil aggregation, increase microbial activity, and enhance nutrient retention. These improvements not only support crop productivity but also help mitigate climate change by storing carbon in the soil for extended periods.

Conservation agriculture also plays a crucial role in water management. Residue cover reduces evaporation losses and protects the soil surface from the direct impact of rainfall, thereby improving infiltration and reducing runoff. During drought periods, soils under conservation management generally retain more moisture than conventionally tilled soils, allowing crops to withstand water stress more effectively.

In addition, reduced tillage decreases fuel consumption and labor requirements, lowering production costs and greenhouse gas emissions associated with field operations [13, 15]. Recent research has demonstrated that conservation agriculture can significantly improve the stability of crop yields under variable climatic conditions. Long-term studies in cereals, legumes, and oilseed crops have shown enhanced resilience to both drought and heavy rainfall events. However, successful adoption often requires appropriate residue management, weed control strategies, and access to suitable seeding equipment. Despite these challenges, conservation agriculture remains one of the most effective agronomic approaches for building climate-resilient production systems.

Table 1: Major Agronomic Approaches for Mitigating Climate Change Effects

Agronomic Approach	Primary Objective	Climate Benefit
Conservation agriculture	Reduce soil disturbance	Carbon sequestration and moisture conservation
Crop diversification	Increase cropping diversity	Reduced climate-related production risk
Climate-resilient varieties	Enhance stress tolerance	Improved adaptation to drought and heat
Integrated nutrient management	Optimize nutrient supply	Lower emissions and improved soil fertility
Water-saving irrigation	Increase water-use efficiency	Drought resilience and water conservation
Precision agriculture	Site-specific input management	Reduced resource wastage
Agroforestry	Integrate trees with crops	Carbon storage and microclimate regulation

Table 2: Climate Stresses and Corresponding Agronomic Interventions

Climate Stress	Agronomic Intervention
Drought	Drip irrigation, mulching, drought-tolerant varieties
Heat stress	Heat-tolerant cultivars, agroforestry shade systems
Flooding	Raised beds, flood-tolerant varieties
Soil salinity	Salt-tolerant varieties, improved drainage
Nutrient loss	Integrated nutrient management
Soil erosion	Conservation tillage and cover cropping
Pest and disease pressure	Crop rotation and diversified cropping systems

Table 3: Recent Technological Developments in Climate-Smart Agronomy

Technology	Application	Expected Outcome
Remote sensing	Crop stress monitoring	Early detection of drought and nutrient stress
Drones	Field variability assessment	Improved management precision
IoT soil sensors	Moisture monitoring	Optimized irrigation scheduling
AI decision support	Input management	Enhanced resource-use efficiency
Variable-rate technology	Fertilizer and water application	Reduced input wastage
Climate forecasting tools	Crop planning	Improved adaptation strategies

Table 4: Benefits of Integrated Agronomic Mitigation Strategies

Benefit Category	Observed Impact
Crop productivity	Higher and more stable yields
Water management	Improved water-use efficiency
Soil fertility	Increased organic matter and nutrient availability
Climate adaptation	Greater resilience to drought and heat
Climate mitigation	Reduced greenhouse gas emissions
Biodiversity	Enhanced ecosystem stability
Farm economics	Lower input costs and diversified income

Table 5: Major Constraints to Adoption of Climate-Smart Agronomic Practices

Constraint	Impact on Adoption
High initial investment	Limits adoption of precision technologies
Limited technical knowledge	Reduces effective implementation
Inadequate extension services	Slows technology dissemination
Small landholdings	Restricts mechanization and automation
Poor access to credit	Reduces investment capacity
Weak policy support	Insufficient incentives for sustainable farming
Climate variability	Inconsistent performance of some practices

Crop Diversification and Rotation

Crop diversification and rotation are increasingly recognized as essential strategies for mitigating climate-related risks in agriculture. Diversification involves cultivating multiple crop species within a farming system, while rotation refers to the planned sequence of different crops grown on the same field over successive seasons. These practices reduce dependence on a single crop and create more stable and resilient agroecosystems [16, 19]. Recent developments in diversified cropping systems include intercropping, relay cropping, strip cropping, and the integration of legumes into cereal-based systems. Such approaches improve resource utilization by allowing different crops to exploit water, nutrients, and light at varying depths and times. Leguminous crops contribute biological nitrogen fixation, reducing the need for synthetic nitrogen fertilizers and improving soil fertility. Diversified systems also interrupt pest and disease cycles, lowering the incidence of certain pathogens and reducing pesticide dependence.

Climate resilience is one of the greatest advantages of crop diversification. Different crops respond differently to heat, drought, flooding, and other climatic stresses. When adverse weather affects one crop, other crops in the system may continue to perform well, thereby reducing the risk of total crop failure. This risk-spreading effect is particularly valuable for smallholder farmers who depend heavily on agricultural income and food production [20, 22]. Diversification also enhances biodiversity both above and below the soil surface. Greater plant diversity supports beneficial insects, pollinators, and natural enemies of pests, while diverse root systems stimulate microbial diversity and improve soil biological activity. Recent studies have shown that diversified cropping systems often exhibit higher ecosystem stability, better nutrient cycling, and improved long-term productivity compared with monoculture systems. Furthermore, crop rotation contributes to sustainable soil management by varying rooting patterns, residue characteristics, and nutrient demands. Deep-rooted crops can improve soil structure and access nutrients from deeper layers, while shallow-rooted crops may benefit from the improved soil conditions created by previous crops. As climate variability increases, integrating crop diversification and rotation into agricultural management offers a practical and cost-effective approach for enhancing productivity, reducing environmental risks, and strengthening the adaptive capacity of farming systems.

Climate-Resilient Crop Varieties

The development of climate-resilient crop varieties has become one of the most important recent advances in agronomic adaptation to climate change. Rising temperatures, drought stress, salinity, flooding, and other environmental stresses increasingly threaten crop productivity, making the identification and deployment of tolerant varieties a critical priority for agricultural research. Modern plant breeding programs are focusing on traits such as deep rooting, efficient water use, heat tolerance during flowering, salinity tolerance, and rapid recovery after flooding events [23]. Recent developments in molecular breeding, marker-assisted selection, genomic selection, and biotechnology have accelerated the production of stress-tolerant cultivars. Drought-tolerant maize varieties with improved root architecture, heat-tolerant wheat lines capable of maintaining grain filling under high temperatures, and submergence-tolerant rice varieties carrying the Sub1 gene are examples of successful breeding achievements. Similarly, salt-tolerant rice and barley cultivars have been developed for cultivation in saline soils where conventional varieties perform poorly.

Climate-resilient varieties contribute significantly to yield stability under variable weather conditions. They allow crops to maintain physiological functions such as photosynthesis, nutrient uptake, and reproductive development during periods of stress. The adoption of such varieties reduces the risk of crop failure and provides greater production reliability for farmers facing increasing climatic uncertainty [24, 27]. These varieties are most effective when integrated with complementary agronomic practices such as conservation agriculture, efficient irrigation, and balanced nutrient management. The combination of improved genetics and climate-smart management can substantially enhance the adaptive capacity of cropping systems. Continued investment in germplasm conservation, advanced breeding technologies, and region-specific varietal development will be essential for addressing future climate challenges.

Integrated Nutrient Management

Integrated Nutrient Management (INM) is a sustainable agronomic approach that combines organic manures, crop residues, biofertilizers, and inorganic fertilizers to provide balanced nutrition to crops while maintaining soil fertility. Under climate change conditions, efficient nutrient management has become increasingly important because nutrient losses through leaching, volatilization, and runoff can increase under extreme rainfall events and temperature fluctuations.

Recent developments in INM include the use of microbial biofertilizers, compost-enriched formulations, slow-release fertilizers, and nano-fertilizers. Biofertilizers containing beneficial microorganisms such as nitrogen-fixing bacteria and phosphorus-solubilizing microbes improve nutrient availability and promote root growth. Slow-release and nano-fertilizers enhance nutrient-use efficiency by supplying nutrients gradually according to crop demand, thereby reducing losses to the environment [28]. One of the major advantages of INM is the improvement of soil organic matter content. Organic amendments increase soil aggregation, water-holding capacity, and microbial activity, all of which enhance crop resilience during drought periods. Better soil structure also improves infiltration and reduces erosion during heavy rainfall events.

From a climate mitigation perspective, integrated nutrient management can reduce nitrous oxide emissions associated with excessive nitrogen fertilization. By optimizing nutrient application rates and improving nutrient recovery by crops, INM contributes to both environmental sustainability and economic efficiency. Long-term studies have shown that integrated nutrient management maintains productivity more effectively than sole reliance on chemical fertilizers.

Water-Saving Irrigation Strategies

Efficient irrigation management is a central component of climate adaptation in agriculture because water scarcity is expected to intensify in many regions. Recent agronomic developments focus on maximizing crop yield per unit of water used while minimizing losses through evaporation, runoff, and deep percolation [29] Drip irrigation has emerged as one of the most effective water-saving technologies, delivering water directly to the crop root zone and substantially improving irrigation efficiency. Sprinkler systems provide more uniform water distribution than traditional flood irrigation, while deficit irrigation strategically applies less water than the full crop requirement during selected growth stages to conserve resources without causing severe yield reductions.

In rice cultivation, alternate wetting and drying (AWD) has gained considerable attention as a climate-smart practice. By allowing fields to dry intermittently instead of maintaining continuous flooding, AWD can reduce irrigation water use by 15–30% and significantly decrease methane emissions. Sensor-based irrigation scheduling and automated irrigation systems further improve efficiency by applying water only when soil moisture levels fall below predetermined thresholds [30, 33]. These water-saving strategies enhance crop resilience during drought conditions, reduce energy consumption for pumping, and contribute to groundwater conservation. The integration of precision irrigation technologies with weather forecasting and remote sensing is expected to further improve irrigation management under changing climatic conditions.

Precision Agriculture and Digital Farming

Precision agriculture has become a major recent development in climate-smart agronomy by enabling site-specific management of agricultural inputs. The approach uses technologies such as GPS, remote sensing, drones, soil sensors, Internet of Things (IoT) devices, and artificial intelligence to monitor crop and soil conditions in real time.

Remote sensing and drone imagery can detect crop water stress, nutrient deficiencies, and pest infestations before visible symptoms become severe. Soil sensors continuously measure moisture and nutrient levels, allowing farmers to optimize irrigation and fertilization schedules. Variable-rate application equipment can then adjust input rates according to field variability, improving resource-use efficiency [34]. Artificial intelligence and machine learning are increasingly being used to analyze large datasets and generate predictive recommendations for irrigation, fertilization, and pest management. Digital decision-support systems help farmers respond rapidly to changing weather conditions and reduce the uncertainty associated with climate variability.

The benefits of precision agriculture include reduced input costs, lower greenhouse gas emissions, improved crop productivity, and more efficient use of water and nutrients. However, challenges such as high initial investment, technical expertise requirements, and limited digital infrastructure can restrict adoption, particularly among smallholder farmers. As technology becomes more affordable and accessible, precision agriculture is expected to play an increasingly important role in mitigating climate change effects on crop production.

Agroforestry and Integrated Farming Systems

Agroforestry and integrated farming systems have gained significant attention as climate-resilient agronomic approaches capable of simultaneously enhancing productivity, environmental sustainability, and farmer income stability. Agroforestry involves the deliberate integration of trees with crops and/or livestock within the same land management unit. This combination creates a more diverse production system that can better withstand climatic variability than conventional monoculture farming [35]. Trees in agroforestry systems provide numerous ecological benefits that help mitigate climate change effects on crop production. Their canopies reduce wind speed and moderate temperature extremes, creating a favorable microclimate for understory crops. Deep-rooted tree species can access water and nutrients from lower soil layers, improving overall resource utilization and reducing competition with annual crops. Leaf litter and pruned biomass contribute organic matter to the soil, enhancing nutrient cycling, soil structure, and microbial activity.

Integrated farming systems extend the concept of diversification by combining crop production with livestock, aquaculture, agroforestry, or other complementary enterprises. Such systems improve resource recycling through the utilization of crop residues, animal manure, and farm by-products. Diversification also reduces economic risk because income is generated from multiple sources rather than a single crop. Recent studies have shown that integrated systems often exhibit greater resilience to drought, flooding, and market fluctuations while improving overall farm profitability and sustainability.

Carbon-Smart Agronomic Practices

Carbon-smart agronomic practices are designed to increase carbon sequestration while reducing greenhouse gas emissions from agricultural systems. These practices have become increasingly important because agriculture is both affected by climate change and contributes significantly to global greenhouse gas emissions through soil disturbance, fertilizer use, and land management practices.

Reduced tillage and no-till systems help retain soil organic carbon by minimizing soil disturbance and slowing the decomposition of organic matter. Cover cropping maintains continuous soil cover and adds additional biomass to the soil, further enhancing carbon accumulation. Agroforestry systems store substantial amounts of carbon in tree biomass and roots, while improved residue management ensures that crop residues are returned to the soil rather than burned [46, 37]. Recent research has also focused on the application of biochar, a stable carbon-rich material produced through the pyrolysis of organic biomass. Biochar can increase soil carbon storage, improve water retention, and enhance nutrient availability. The combined use of carbon-smart practices not only contributes to climate change mitigation but also improves soil fertility, moisture conservation, and long-term crop productivity. As carbon markets and climate-related incentive programs expand, carbon-smart farming may provide additional economic opportunities for farmers.

Benefits of Agronomic Mitigation Approaches

The integration of climate-smart agronomic practices offers multiple benefits that extend beyond climate change adaptation and mitigation. One of the most important advantages is improved crop yield stability under variable climatic conditions. Practices such as conservation agriculture, diversified cropping, efficient irrigation, and integrated nutrient management help maintain productivity during periods of drought, heat stress, and irregular rainfall.

Enhanced water-use efficiency is another major benefit. Water-saving irrigation technologies and improved soil management practices reduce water losses and increase the amount of water available for crop growth. Better soil structure and higher organic matter content improve infiltration and water retention, allowing crops to withstand moisture stress more effectively.

These agronomic approaches also contribute to improved nutrient-use efficiency and reduced input costs. Precision agriculture, site-specific nutrient management, and fertigation optimize the use of fertilizers and irrigation water, reducing waste and environmental contamination. In addition, increased carbon sequestration, lower greenhouse gas emissions, enhanced biodiversity, and improved soil health contribute to long-term ecosystem sustainability. Collectively, these benefits strengthen farm resilience, increase profitability, and support sustainable agricultural intensification under changing climatic conditions.

Challenges and Constraints

Despite the substantial benefits of climate-smart agronomic practices, several challenges continue to limit their widespread adoption. A major constraint is the high initial investment required for technologies such as precision agriculture equipment, drip irrigation systems, remote sensing tools, and automated monitoring devices. Smallholder farmers often lack the financial resources needed to implement these advanced technologies.

Technical knowledge and management skills are also critical barriers. Effective use of conservation agriculture, sensor-based irrigation, precision nutrient management, and digital farming tools requires training and continuous technical support. In many regions, extension services remain inadequate, limiting farmers' access to practical guidance and up-to-date information.

Institutional and policy-related factors further influence adoption. Limited access to credit, fragmented landholdings, weak market infrastructure, and insufficient incentives for sustainable farming can discourage investment in climate-smart practices. Moreover, the performance of specific agronomic interventions may vary depending on local soil conditions, climate, crop type, and socio-economic circumstances, making location-specific recommendations essential.

Addressing these constraints will require coordinated efforts involving researchers, policymakers, extension agencies, financial institutions, and farming communities. Increased investment in farmer training, affordable technologies, supportive policies, and region-specific adaptation strategies will be necessary to accelerate the adoption of agronomic approaches capable of mitigating climate change effects on crop production.

Conclusion

Agronomic approaches are essential for mitigating the adverse effects of climate change on crop production. Recent developments in conservation agriculture, crop diversification, climate-resilient breeding, integrated nutrient management, precision agriculture, water-saving irrigation, and agroforestry have significantly improved the capacity of agricultural systems to adapt to climatic stresses while reducing environmental impacts. These practices enhance soil health, improve water and nutrient-use efficiency, increase carbon sequestration, and strengthen crop resilience to drought, heat, flooding, and other climate-related challenges. The review demonstrates that no single intervention can fully address the complex impacts of climate change on agriculture. Instead, the integration of multiple agronomic strategies within climate-smart farming systems offers the most effective pathway for sustaining productivity and food security. Despite progress in research and technological innovation, widespread adoption remains constrained by economic, technical, institutional, and policy-related barriers, particularly among smallholder farmers. Future efforts should focus on developing affordable and location-specific technologies, strengthening extension services, promoting supportive policies, and integrating digital decision-support tools into farm management. Continued investment in interdisciplinary research and farmer capacity building will be critical for accelerating the transition toward resilient and sustainable agricultural systems capable of meeting future food demands under changing climatic conditions.

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