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Precision resource management strategies for climate-resilient crop production

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Abstract

Agriculture is increasingly exposed to climate-related stresses such as drought, heat waves, erratic rainfall, and declining soil health, all of which threaten crop productivity and farmer livelihoods. Improving the resilience of cropping systems therefore requires more efficient and judicious use of key resources including soil, water, and nutrients. Precision Resource Management (PRM) offers a practical and technology-driven approach to achieve this goal. This paper discusses major precision-based strategies such as site-specific nutrient management, sensor-guided nitrogen application, variable rate technology, micro-irrigation, and soil moisture-based irrigation scheduling. The use of Geographic Information Systems (GIS), remote sensing tools, drones, and artificial intelligence-supported decision systems enables farmers to monitor crop conditions in real time and apply inputs more accurately. These approaches not only enhance water and nutrient use efficiency but also help stabilize yields, reduce input losses, and minimize environmental impacts under changing climatic conditions. Although challenges such as high investment costs and limited technical awareness remain, precision resource management has strong potential to improve both productivity and sustainability. Strengthened extension services, farmer training, and supportive policies can play a crucial role in wider adoption. Integrating precision technologies with climate-smart agronomic practices can significantly contribute to building resilient and resource-efficient crop production systems.

Keywords: Precision agriculture, climate resilience, resource use efficiency, site-specific nutrient management, variable rate technology, micro-irrigation, digital agriculture, sustainable crop production

1. Introduction

Climate change is increasingly affecting crop production through rising temperatures, irregular rainfall, droughts, floods, soil degradation, and increasing pressure on water and other agricultural resources. Conventional resource management practices often rely on uniform application of inputs, which can result in inefficient use of water, fertilizers, energy, and other resources. Precision resource management (PRM) integrates technologies such as remote sensing, geographic information systems (GIS), sensors, Internet of Things (IoT), drones, artificial intelligence (AI), and data-driven decision-support systems to manage agricultural resources according to spatial and temporal variability. These approaches improve resource-use efficiency, reduce production costs and environmental impacts, and enhance crop productivity under changing climatic conditions. Therefore, precision resource management provides an important pathway for developing climate-resilient and sustainable crop production systems. Agriculture is highly vulnerable to the impacts of climate change, including rising temperatures, irregular rainfall patterns, increased frequency of droughts and floods, and soil degradation. These stresses not only reduce crop productivity but also threaten long-term food and nutritional security. In developing countries such as India, where agriculture is largely climate-dependent, improving the resilience of crop production systems has become a critical priority. Conventional resource management practices often involve uniform application of water, fertilizers, and other inputs across fields, leading to inefficient resource use, nutrient losses, environmental pollution, and increased production costs. Such approaches are becoming increasingly unsustainable under conditions of climate variability and resource scarcity. Therefore, innovative strategies are

required to optimize resource use while maintaining crop productivity and environmental sustainability. Precision Resource Management (PRM) has emerged as a transformative approach in modern agriculture. It integrates advanced technologies such as Geographic Information Systems (GIS), Global Positioning Systems (GPS), remote sensing, soil and crop sensors, drones, and artificial intelligence (AI)-based decision-support tools to identify and manage spatial and temporal variability within agricultural fields. By enabling site-specific and need-based application of inputs, PRM can improve resource-use efficiency, reduce input losses, and minimize environmental impacts. Integrating precision technologies with climate-smart agronomic practices can further strengthen the adaptive capacity and resilience of cropping systems. Efficient nutrient management, precise irrigation scheduling, and real-time crop monitoring can help stabilize crop yields under climatic stress and contribute to sustainable agricultural development. Therefore, this review aims to critically examine precision resource management strategies for climate-resilient crop production, with particular emphasis on precision water and nutrient management, soil and crop monitoring, remote sensing, GIS, IoT, artificial intelligence, and data-driven decision-support systems. The review further evaluates their potential to improve resource-use efficiency, enhance crop resilience to climate variability, reduce environmental impacts, and identify research gaps and future directions for sustainable and climate-resilient agriculture. To critically review precision resource management strategies and their role in improving resource-use efficiency, crop productivity, and resilience to climate variability while reducing environmental impacts and supporting sustainable crop production. To review precision water, nutrient, soil, and crop resource management strategies. To evaluate the role of GIS, GPS, remote sensing, IoT, sensors, drones, and AI/ML in precision agriculture. To assess the contribution of precision resource management to climate-resilient crop production. To examine improvements in water-, nutrient-, and energy-use efficiency. To identify current research gaps, technological limitations, and future opportunities for integrating precision agriculture with climate-smart farming.

2. Climate change and agricultural vulnerability

Climate change has emerged as a major threat to agricultural productivity and food security, particularly in regions where crop production is highly dependent on climatic conditions. Rising temperatures, changing precipitation patterns, prolonged droughts, extreme rainfall events, floods, heat waves, and increasing frequency of other climatic extremes can alter crop growth, phenology, water requirements, nutrient availability, and yield stability. These changes also accelerate soil degradation and increase pressure on already limited water and land resources, thereby increasing the vulnerability of agricultural production systems. The vulnerability of crops to climate change varies with crop type, growth stage, soil characteristics, availability of irrigation, and prevailing climatic conditions. Water scarcity and irregular rainfall can reduce crop establishment and productivity, while excessive rainfall and flooding may cause waterlogging, nutrient losses, soil erosion, and root-zone deterioration. Increasing temperatures can enhance evapotranspiration and crop water demand, accelerate crop development, and reduce yield potential. Similarly, changes in temperature and moisture conditions can influence nutrient availability and uptake, increasing the risk of inefficient fertilizer use and environmental losses. Conventional resource management practices, which commonly apply water, fertilizers,

and other inputs uniformly across fields, may not adequately address the spatial and temporal variability created by changing climatic conditions. Consequently, resources may be over-applied in some areas and under-applied in others, resulting in reduced resource-use efficiency, increased production costs, and environmental degradation. Climate change therefore requires a shift from uniform resource application toward adaptive, site-specific, and data-driven management approaches. Precision Resource Management (PRM) provides an opportunity to address these challenges by integrating field-level information on soil, crop, weather, and resource conditions with advanced sensing and decision-support technologies. The application of remote sensing, GIS, GPS, IoT-based sensors, drones, and artificial intelligence can facilitate real-time assessment of crop and resource variability and support precise management of water, nutrients, soil, and other agricultural inputs. Such approaches can improve the capacity of cropping systems to respond to climatic variability while maintaining productivity and reducing resource losses. Climate change has become one of the most critical challenges affecting global agriculture. Rising temperatures, shifting rainfall patterns, frequent droughts, floods, and increased incidence of extreme weather events are significantly influencing crop growth and productivity. These climatic uncertainties disturb crop phenology, reduce water availability, accelerate evapotranspiration, and increase pest and disease pressure. In India and other tropical regions, rainfed farming systems are particularly vulnerable due to their dependence on monsoon rainfall. Erratic rainfall distribution often results in delayed sowing, moisture stress during critical growth stages, and yield instability. Similarly, prolonged heat stress affects photosynthesis, pollination, and grain filling, ultimately reducing crop output and quality. Soil degradation, salinity, and nutrient imbalance further aggravate the situation under changing climatic conditions. Traditional blanket recommendations for fertilizer and irrigation management fail to address field-level variability and climate-induced stress dynamics. Uniform input application often leads to nutrient losses through leaching, volatilization, and runoff, especially during heavy rainfall events. This not only reduces input efficiency but also contributes to environmental pollution and greenhouse gas emissions. Therefore, enhancing resilience in agricultural systems requires adaptive and location-specific management strategies. Climate-resilient agriculture focuses on improving productivity, strengthening adaptive capacity, and reducing vulnerability to climate risks. Precision-based interventions offer an effective mechanism to achieve these goals by enabling real-time monitoring, site-specific input application, and efficient resource utilization. Understanding the nature of climate-induced vulnerabilities is essential before designing precision resource management strategies. Addressing variability at spatial and temporal scales forms the foundation for building sustainable and resilient cropping systems. Therefore, understanding the relationship between climate change and agricultural vulnerability is fundamental to developing effective precision resource management strategies. Integrating climate information with spatial and temporal resource variability can support adaptive decision-making, enhance resource-use efficiency, stabilize crop production under climatic stress, and strengthen the resilience and sustainability of agricultural systems.

3. Framework of precision resource management

Precision Resource Management (PRM) is an integrated, data-driven approach for managing agricultural resources according

to their spatial and temporal variability. The framework combines field-level information, sensing technologies, geospatial tools, data analytics, and decision-support systems to optimize the application of water, nutrients, energy, soil amendments, and other production inputs. The primary objective is to achieve higher resource-use efficiency while maintaining crop productivity, reducing environmental impacts, and strengthening the resilience of cropping systems under changing climatic conditions. The PRM framework begins with data acquisition, which involves collecting information on soil properties, crop growth, weather conditions, water availability, nutrient status, and field variability. Technologies such as remote sensing, GPS, GIS, drones, proximal soil and crop sensors, and IoT-based monitoring systems enable the collection of spatially and temporally distributed information. These data provide the basis for identifying variability in crop and resource conditions within agricultural fields. The second component is data processing and analysis, where collected information is integrated and interpreted using geospatial analysis, statistical techniques, crop models, and artificial intelligence (AI)- and machine learning (ML)-based approaches. Spatial variability maps and temporal datasets can be developed to identify differences in soil moisture, nutrient availability, crop health, water requirements, and other important management parameters. The third component is decision support and management planning. Based on the processed information, site-specific recommendations can be generated for irrigation scheduling, nutrient application, crop protection, soil management, and other field operations. These recommendations allow inputs to be applied according to actual crop and soil requirements rather than through uniform application across the entire field. The fourth component involves precision application and field implementation. Variable-rate irrigation systems, fertigation equipment, precision fertilizer applicators, automated machinery, drones, and other smart agricultural equipment can be used to implement management decisions at the required location and rate. This enables more efficient allocation of limited agricultural resources and minimizes unnecessary input use. The final component is monitoring, evaluation, and feedback. Crop responses, resource consumption, yield, and environmental indicators are continuously monitored to assess the effectiveness of management interventions. The resulting information can be fed back into the decision-support system, allowing management strategies to be adjusted according to changing crop, soil, weather, and resource conditions. Precision Resource Management (PRM) is based on the principle that agricultural fields are spatially and temporally variable systems. Variations in soil fertility, moisture availability, topography, and crop growth patterns influence yield outcomes significantly (Pierce & Nowak, 1999) ^[59]. Managing this variability through uniform input application often results in suboptimal productivity and resource wastage (Gebbers & Adamchuk, 2010) ^[32]. Precision agriculture integrates advanced technologies such as Geographic Information Systems (GIS), Global Positioning Systems (GPS), remote sensing, soil sensors, and variable rate technology (VRT) to monitor and manage field variability (Zhang *et al.*, 2002) ^[76]. These tools allow farmers to apply inputs such as fertilizers, water, and pesticides based on site-specific requirements rather than blanket recommendations (Robert, 2002) ^[63]. The framework of PRM generally involves four major components: Overall, the PRM framework can be represented as a continuous cycle of data acquisition, data integration and analysis, decision-making, precision application, monitoring and feedback.

Integration of these components with climate information and predictive technologies can transform precision agriculture from input optimization toward adaptive resource management, thereby improving resource-use efficiency, reducing environmental impacts, and enhancing climate resilience in crop production systems.

3.1 Data Collection and Field Mapping

Field-level data on soil properties, crop condition, weather, moisture, and nutrient status are collected using GPS, GIS, remote sensing, drones, and sensors. These data are used to identify spatial and temporal variability within agricultural fields. Soil sampling, yield mapping, satellite imagery, and drone-based sensing are used to generate spatial data on crop and soil variability (Mulla, 2013) ^[53]. Digital soil mapping improves understanding of nutrient distribution and soil health status (McBratney *et al.*, 2003) ^[51].

3.2 Data Analysis and Decision Support

Collected data are analysed using GIS, statistical methods, AI/ML, and decision-support systems to identify crop and resource requirements. The analysis supports site-specific decisions for irrigation, nutrient management, and other inputs. Collected data are processed using decision support systems and artificial intelligence-based models to generate actionable insights (Basso & Antle, 2020) ^[4]. These systems predict crop response under varying climatic and soil conditions.

3.3 Site-Specific Input Application

Water, fertilizers, and other agricultural inputs are applied according to the specific requirements of different field zones using variable-rate technologies and automated equipment. This improves resource-use efficiency and reduces input losses. Variable rate applicators enable differential fertilizer and irrigation application across field zones (Kitchen *et al.*, 2005) ^[45]. Sensor-based nitrogen management improves nutrient use efficiency and reduces environmental losses (Raun *et al.*, 2002) ^[61].

3.4 Monitoring and Feedback

Crop growth, soil moisture, nutrient status, and resource use are continuously monitored using sensors, remote sensing, and field observations. The feedback is used to adjust management practices and improve crop resilience under changing climatic conditions. Continuous monitoring through remote sensing and IoT-based devices ensures adaptive management throughout the crop growth cycle (Wolfert *et al.*, 2017) ^[74]. Under climate variability, such precision-based frameworks enhance adaptive capacity by optimizing resource allocation, stabilizing yields, and minimizing risk (Lipper *et al.*, 2014) ^[49]. By aligning agronomic practices with real-time field conditions, PRM strengthens resilience while promoting sustainability.

4. Precision nutrient management strategies

Precision nutrient management (PNM) aims to supply essential nutrients according to the spatial and temporal requirements of crops. It integrates soil testing, crop sensing, remote sensing, GIS, GPS, and variable-rate application technologies to improve nutrient-use efficiency while reducing fertilizer losses and environmental impacts. By matching nutrient application with crop demand, PNM can maintain productivity under climate variability and improve the resilience and sustainability of crop production systems. Efficient nutrient management is central to achieving climate-resilient crop production. Conventional

blanket fertilizer recommendations often ignore spatial variability in soil fertility and crop demand, resulting in low nutrient use efficiency and increased environmental losses (Tilman *et al.*, 2002) ^[70]. Under climate change scenarios, erratic rainfall and temperature fluctuations further aggravate nutrient leaching, volatilization, and denitrification losses (Lobell *et al.*, 2008) ^[50]. Precision Nutrient Management (PNM) focuses on applying the right source of nutrient at the right rate, right time, and right place—commonly referred to as the 4R nutrient stewardship principle (Bruulsema *et al.*, 2009) ^[10]. By integrating spatial soil data, crop sensors, and decision-support tools, PNM enhances synchronization between crop nutrient demand and supply (Robertson & Vitousek, 2009) ^[64].

4.1 Site-Specific Nutrient Management (SSNM)

SSNM aims to tailor fertilizer application based on soil nutrient status and crop requirement at specific field locations (Dobermann *et al.*, 2002) ^[18]. Research has shown that SSNM improves nitrogen recovery efficiency and grain yield while reducing excess fertilizer use (Peng *et al.*, 2010) ^[57]. Under drought-prone conditions, optimized nutrient placement enhances root growth and stress tolerance. SSNM determines nutrient application based on soil fertility, crop demand, yield targets, and field variability. It improves nutrient-use efficiency by supplying nutrients at the right rate, time, and location while reducing nutrient losses.

4.2 Sensor-Based Nitrogen Management

Optical sensors such as GreenSeeker and chlorophyll meters enable real-time nitrogen assessment in crops (Raun *et al.*, 2002) ^[61]. These tools help determine mid-season nitrogen requirements and prevent over-application. Studies indicate that sensor-guided nitrogen management can increase nitrogen use efficiency by 15-30% while maintaining yield stability (Arnall *et al.*, 2009) ^[2]. Crop and soil sensors provide real-time information on crop nitrogen status, chlorophyll content, and soil nutrient availability. This information enables timely and need-based nitrogen application, reducing both deficiency and excessive fertilizer use.

4.3 Variable Rate Technology (VRT)

Variable Rate Technology allows differential fertilizer application across management zones within a field (Kitchen *et al.*, 2005) ^[45]. GPS-enabled applicators adjust nutrient rates according to pre-defined soil fertility maps. VRT not only reduces input wastage but also mitigates greenhouse gas emissions associated with excessive nitrogen use (Snyder *et al.*, 2009) ^[69]. VRT uses GPS, GIS, sensors, and automated equipment to vary fertilizer application rates across different field zones. It allows nutrients to be applied according to spatial variability, improving fertilizer efficiency and reducing environmental losses.

4.4 Integration with Climate-Smart Practices

Integrating precision nutrient management with conservation agriculture, crop residue management, and organic amendments enhances soil carbon sequestration and improves resilience to climate stress (Lal, 2015) ^[47]. Balanced fertilization under precision frameworks supports sustained productivity while reducing environmental footprint. Precision nutrient management can be integrated with climate-smart practices such as conservation agriculture, balanced fertilization, organic amendments, and efficient irrigation. This integration improves nutrient-use efficiency, reduces greenhouse-gas emissions and

nutrient losses, and enhances crop resilience under climate variability. Overall, precision nutrient strategies significantly contribute to yield stability, improved nutrient recovery, and reduced climate-induced risks. By minimizing nutrient losses and optimizing input efficiency, these approaches strengthen the adaptive capacity of cropping systems.

5. Precision water management

Water scarcity is one of the most serious constraints to agricultural productivity under climate change. Increasing temperature, irregular rainfall distribution, and declining groundwater levels are intensifying moisture stress in cropping systems (IPCC, 2021) ^[38]. In rainfed and semi-arid regions, inefficient irrigation practices often result in water wastage, reduced water use efficiency, and yield instability (Rockström *et al.*, 2010) ^[65]. Precision water management optimizes irrigation according to soil moisture, crop water requirements, weather conditions, and spatial variability within fields. It integrates sensors, remote sensing, micro-irrigation, and climate data to improve water-use efficiency, reduce water losses, and maintain crop productivity under climate variability. Precision Water Management (PWM) focuses on optimizing irrigation scheduling and water application based on real-time crop water requirements and soil moisture status (Evans & Sadler, 2008) ^[23]. By integrating sensor-based technologies and climate forecasting tools, PWM enhances adaptive capacity under variable weather conditions.

5.1 Soil Moisture Sensor-Based Irrigation

Soil moisture sensors such as tensiometers, capacitance probes, and Time Domain Reflectometry (TDR) devices provide real-time information on soil water availability (Jones, 2004) ^[40]. These tools enable irrigation scheduling based on actual crop demand rather than fixed calendar-based methods. Research indicates that sensor-based irrigation can improve water use efficiency by 20-40% compared to conventional practices (Feres & Soriano, 2007) ^[28]. Soil moisture sensors continuously monitor soil water availability in the crop root zone and provide information for irrigation decisions. Irrigation can be applied only when soil moisture falls below a defined threshold, reducing over-irrigation and water losses.

5.2 Micro-Irrigation and Drip Systems

Drip and micro-sprinkler irrigation systems deliver water directly to the root zone, minimizing evaporation and runoff losses (Postel *et al.*, 2001) ^[60]. Under water-limited environments, drip irrigation has been shown to enhance yield stability while reducing total water consumption (FAO, 2017) ^[24]. Precision-controlled drip systems further allow fertigation, ensuring synchronized nutrient and water supply. Drip and other micro-irrigation systems deliver water directly to the crop root zone at controlled rates. When combined with fertigation and automated control, these systems improve water-use efficiency and reduce evaporation, runoff, and deep percolation losses.

5.3 Remote Sensing and Crop Water Monitoring

Satellite imagery and drone-based thermal sensors help assess crop water stress through vegetation indices and canopy temperature measurements (Jackson *et al.*, 1981) ^[39]. These technologies assist in identifying water-deficit zones within fields, enabling site-specific irrigation management. Integration of GIS and weather-based evapotranspiration models further improves irrigation precision (Allen *et al.*, 1998) ^[1]. Satellite imagery, drones, and thermal sensors can monitor crop health,

canopy temperature, vegetation indices, and spatial variations in crop water status. These data help identify water-stressed areas and support site-specific irrigation management.

5.4 Climate-Responsive Irrigation Scheduling

Climate-smart irrigation incorporates short-term weather forecasts and long-term climate projections to adjust irrigation timing and quantity (Lipper *et al.*, 2014) ^[49]. Decision-support systems linked with IoT devices automate irrigation under dynamic climatic conditions, reducing risk of drought-induced yield losses. Climate-responsive irrigation scheduling integrates weather forecasts, evapotranspiration, soil moisture, crop growth stage, and rainfall information to determine irrigation timing and amount. This approach enables irrigation to be adjusted according to changing climatic conditions, improving water productivity and crop resilience. Precision water management not only conserves scarce water resources but also enhances crop resilience by maintaining optimal soil moisture during critical growth stages. Improved water productivity, reduced energy use, and minimized environmental impact collectively contribute to sustainable and climate-resilient crop production systems.

6. Precision soil management

Soil health plays a fundamental role in determining crop productivity and resilience under changing climatic conditions. Climate change accelerates soil degradation processes such as erosion, organic matter decline, salinization, and nutrient imbalance (Lal, 2015) ^[47]. Maintaining soil structure, fertility, and biological activity is therefore essential for sustaining agricultural production. Precision soil management uses spatial soil information, digital technologies, and site-specific practices to manage soil resources according to field variability. It aims to maintain soil health, improve nutrient and water availability, reduce degradation, and strengthen soil resilience under changing climatic conditions. Precision Soil Management (PSM) involves the assessment and management of spatial variability in soil properties using digital tools and geospatial technologies (McBratney *et al.*, 2003) ^[51]. Unlike conventional uniform soil management practices, PSM enables location-specific interventions that improve soil function and long-term sustainability.

6.1 Digital Soil Mapping and GIS Applications

Digital soil mapping integrates field sampling data with Geographic Information Systems (GIS), remote sensing, and statistical modeling to generate high-resolution soil property maps (McBratney *et al.*, 2003) ^[51]. These maps provide detailed information on soil texture, nutrient status, pH, organic carbon, and salinity levels. Spatial soil variability mapping allows targeted amendment application and optimized land management (Mulla, 2013) ^[53]. Digital soil mapping integrates GIS, remote sensing, GPS, proximal sensors, and soil sampling data to characterize spatial variability in soil properties. These maps support site-specific decisions for nutrient application, irrigation, soil amendments, and land management.

6.2 Soil Organic Carbon and Climate Resilience

Soil organic carbon (SOC) is a key indicator of soil health and climate adaptation capacity. Higher SOC improves water retention, nutrient buffering capacity, and microbial activity (Lal, 2004) ^[46]. Precision-based carbon management practices such as site-specific residue incorporation and variable-rate organic amendment application enhance soil carbon

sequestration while mitigating greenhouse gas emissions (Paustian *et al.*, 2016) ^[56]. Precision management of soil organic carbon (SOC) improves soil structure, water-holding capacity, nutrient cycling, and biological activity. Practices that increase SOC can enhance soil resilience to drought and erosion while contributing to carbon sequestration.

6.3 Managing Soil Salinity and Degradation

Under climate variability, increased evapotranspiration and improper irrigation practices contribute to salinity build-up in many regions (Rengasamy, 2010) ^[62]. Precision monitoring tools help detect salinity-prone zones and enable localized reclamation strategies. Site-specific gypsum application and improved drainage management reduce yield losses in salt-affected soils. Remote sensing, soil electrical conductivity sensors, and GIS can identify salinity, erosion, compaction, and other forms of soil degradation at field scale. Site-specific reclamation, irrigation, drainage, and amendment strategies can then be implemented to restore soil productivity.

6.4 Integration with Conservation Practices

Combining precision soil assessment with conservation agriculture practices such as minimum tillage, crop rotation, and cover cropping improves soil aggregation and reduces erosion (Hobbs *et al.*, 2008) ^[37]. These integrated approaches strengthen the soil's adaptive capacity to climate stress while improving long-term productivity. Precision soil management can be integrated with conservation tillage, residue management, cover cropping, crop rotation, mulching, and integrated nutrient management. Combining these practices with spatial soil information improves resource-use efficiency, reduces soil degradation, and enhances climate resilience. Precision soil management enhances resource efficiency by aligning nutrient and water management decisions with soil-specific characteristics. By improving soil structure, carbon status, and nutrient dynamics, PSM significantly contributes to the resilience and sustainability of cropping systems.

7. Digital agriculture and ai-based innovations

Digital agriculture is transforming traditional farming systems by integrating data-driven technologies into crop production. The convergence of artificial intelligence (AI), Internet of Things (IoT), remote sensing, robotics, and big data analytics enables precise monitoring and management of agricultural resources (Wolfert *et al.*, 2017) ^[74]. Under climate variability, such technologies enhance adaptive decision-making and reduce uncertainty in crop production systems. Digital agriculture integrates sensing, communication, geospatial, and computational technologies to support efficient and timely agricultural decision-making. These technologies enable real-time monitoring of crops and resources, prediction of climate-related stresses, and optimization of water, nutrient, soil, and other farm inputs.

7.1 Remote Sensing and Drone-Based Monitoring

Satellite remote sensing and drones provide spatial information on crop health, vegetation status, soil moisture, nutrient stress, and water stress. These observations enable early detection of field variability and support site-specific resource management. Unmanned Aerial Vehicles (UAVs), commonly known as drones, are increasingly used for high-resolution crop monitoring (Zhang & Kovacs, 2012) ^[75]. Multispectral and hyperspectral imaging helps assess vegetation indices such as NDVI, which indicate crop health and stress conditions. Early

detection of nutrient deficiency, pest incidence, and water stress allows timely corrective measures, thereby stabilizing yields under climatic stress.

7.2 Artificial Intelligence and Machine Learning

AI and machine learning (ML) techniques can analyze large and complex datasets from soil, crop, weather, and remote sensing sources to predict crop performance, water requirements, nutrient needs, and climate-related risks. Their application supports data-driven and adaptive resource management. AI-driven models analyze large datasets including weather data, soil properties, and crop growth parameters to predict yield and stress responses (Basso & Antle, 2020) [4]. Machine learning algorithms assist in irrigation scheduling, fertilizer recommendation, and pest forecasting. These predictive tools improve resource allocation efficiency and minimize climate-related production risks.

7.3 Internet of Things (IoT) in Smart Farming

IoT-based systems connect soil moisture, temperature, humidity, crop, and weather sensors with communication networks and automated equipment. Continuous data collection enables real-time monitoring and automated control of irrigation, fertigation, and other farm operations. IoT-based sensor networks continuously monitor soil moisture, temperature, humidity, and nutrient status (Liakos *et al.*, 2018) [48]. Real-time data transmission enables automated irrigation and fertigation systems, ensuring precise input application. Such smart systems reduce labor dependency and improve operational efficiency.

7.4 Decision Support Systems (DSS)

Decision Support Systems integrate climatic forecasts, soil data, and crop growth models to guide management decisions (Jones *et al.*, 2003) [41]. Climate-responsive DSS platforms help farmers adjust planting dates, irrigation intervals, and fertilizer schedules based on anticipated weather variability. Decision Support Systems integrate field observations, sensor data, weather information, crop models, and AI-based predictions to generate management recommendations. DSS can assist farmers in selecting appropriate irrigation, nutrient, crop, and resource-management strategies under variable climatic conditions. Digital innovations not only enhance productivity but also reduce environmental impacts by minimizing input wastage. By enabling real-time monitoring and adaptive management, AI-enabled precision systems significantly strengthen climate resilience in cropping systems. However, issues such as high technology costs, data accessibility, and digital literacy remain critical challenges for widespread adoption.

8. Impact of precision resource management on climate resilience: Precision Resource Management (PRM) plays a crucial role in enhancing the resilience of cropping systems under climate variability. By optimizing the use of soil, water, and nutrient resources, PRM reduces production risks associated with drought, heat stress, and erratic rainfall (Lipper *et al.*, 2014) [49]. Efficient input management improves crop adaptability while minimizing environmental degradation. Precision Resource Management (PRM) strengthens climate resilience by enabling agricultural inputs to be managed according to crop requirements, soil variability, and changing climatic conditions. Its integration with digital technologies supports efficient resource allocation, reduces production risks, and improves the capacity of cropping systems to withstand and recover from climate-related stresses.

8.1 Yield Stability under Climate Stress

Climate change often leads to yield fluctuations due to moisture stress, temperature extremes, and nutrient imbalances (Lobell *et al.*, 2008) [50]. Precision-based irrigation and nutrient management synchronize input supply with crop demand, thereby maintaining physiological balance during critical growth stages. Studies indicate that site-specific management practices improve yield stability and reduce year-to-year variability (Basso *et al.*, 2013) [5]. PRM supports timely irrigation, balanced nutrient application, and early detection of crop stress, helping crops maintain productivity under drought, heat, and irregular rainfall conditions. Site-specific management can reduce spatial yield variability and improve yield stability.

8.2 Improvement in Resource Use Efficiency

Precision interventions significantly enhance water use efficiency (WUE) and nutrient use efficiency (NUE) compared to conventional practices (Feres & Soriano, 2007; Raun *et al.*, 2002) [28, 61]. Optimized fertilizer application reduces nitrogen losses through leaching and volatilization, thereby lowering greenhouse gas emissions (Snyder *et al.*, 2009) [69]. Efficient water management reduces energy consumption and groundwater depletion. Precision application of water, fertilizers, energy, and other inputs reduces unnecessary resource use and losses. Improved water-, nutrient-, and energy-use efficiency contributes to higher productivity per unit of resource and supports sustainable crop production.

8.3 Reduction in Environmental Footprint

Over-application of fertilizers and irrigation water contributes to soil degradation, water pollution, and greenhouse gas emissions (Tilman *et al.*, 2002) [70]. Precision technologies minimize these losses by ensuring need-based input application. Improved soil carbon management further enhances carbon sequestration potential (Paustian *et al.*, 2016) [56]. PRM can reduce nutrient leaching, agricultural runoff, water wastage, soil degradation, and greenhouse-gas emissions through optimized input application. Reduced dependence on excessive inputs can minimize environmental impacts while maintaining crop productivity.

8.4 Economic and Adaptive Benefits

Climate-resilient agriculture must also be economically viable. Precision management reduces unnecessary input costs and improves profitability through higher productivity and efficient resource allocation (Gebbers & Adamchuk, 2010) [32]. By reducing climate-related risks, PRM strengthens farmers' adaptive capacity and long-term sustainability. Precision technologies can reduce input costs, production losses, and labor requirements while improving crop productivity and profitability. More accurate resource allocation also enhances farmers' adaptive capacity by enabling management decisions to respond rapidly to changing weather and climate conditions. Overall, precision resource management contributes to the three core pillars of climate-resilient agriculture: productivity, adaptation, and mitigation. By combining technological innovation with agronomic principles, PRM offers a sustainable pathway for stabilizing food production under changing climatic conditions.

9. Challenges and limitations of precision resource management: Despite its potential to improve resource-use efficiency and climate resilience, Precision Resource Management (PRM) faces several technical, economic,

infrastructural, and institutional challenges. These limitations can affect the adoption, scalability, and effectiveness of precision technologies, particularly among smallholder farmers. Despite its significant potential, the adoption of Precision Resource Management (PRM) faces several technical, economic, and institutional constraints. While precision technologies enhance efficiency and resilience, their large-scale implementation remains uneven, particularly in developing countries (Gebbers & Adamchuk, 2010) [32].

9.1 High Initial Investment and Cost Constraints

Precision technologies such as sensors, drones, GPS equipment, automated machinery, and data-management systems require substantial initial investment. High equipment, maintenance, and data-service costs can limit adoption, particularly among small and resource-constrained farmers. Advanced tools such as drones, variable rate applicators, soil sensors, and AI-based platforms require substantial initial investment (Wolfert *et al.*, 2017) [74]. Small and marginal farmers, who constitute a major proportion of agricultural producers in countries like India, often find it difficult to afford such technologies. Limited access to credit and financial incentives further restricts adoption.

9.2 Technical Knowledge and Skill Gaps

Effective utilization of precision tools requires technical expertise in data interpretation, GIS applications, and digital systems management (Liakos *et al.*, 2018) [48]. Lack of training, digital literacy, and extension support can reduce the effectiveness of these technologies at the farm level. Inadequate awareness about the long-term benefits of precision agriculture also acts as a barrier. Effective implementation of PRM requires knowledge of digital technologies, GIS, remote sensing, sensors, data analysis, and farm management. Limited technical skills among farmers and extension personnel can reduce the effective use and long-term adoption of precision technologies.

9.3 Data Availability and Infrastructure Limitations

Reliable and high-resolution spatial data are essential for precision management. However, inconsistent data availability, limited rural internet connectivity, and poor digital infrastructure hinder real-time monitoring and automated decision-making (Basso & Antle, 2020) [4]. In many regions, data integration platforms remain fragmented and underdeveloped. Reliable PRM depends on the availability of high-quality soil, crop, weather, and spatial data, as well as internet connectivity, electricity, and digital infrastructure. Inadequate data coverage, poor connectivity, and limited access to reliable digital services can restrict precision-based decision-making.

9.4 Field Fragmentation and Small Land Holdings

Precision technologies are often designed for large-scale mechanized farms. Fragmented land holdings and heterogeneous cropping systems limit the efficiency of certain tools such as variable rate machinery (Pierce & Nowak, 1999) [59]. Custom hiring centers and cooperative models may be required to overcome this challenge. Small and fragmented agricultural holdings can make the economic and operational implementation of precision technologies difficult. The cost of equipment and data services may be relatively high compared with the size of individual farms, limiting the feasibility of field-scale precision management.

9.5 Climate and Uncertainty Factors: Although precision tools improve adaptive capacity, extreme climatic events such as

floods or cyclones may still cause significant crop losses beyond technological control (IPCC, 2021) [38]. Therefore, PRM should be integrated with broader climate risk management strategies. Unpredictable rainfall, temperature extremes, droughts, floods, and other climatic events can reduce the reliability of resource-management decisions based on historical or short-term data. Uncertainty in climate forecasts and crop responses highlights the need for adaptive systems that integrate real-time observations, predictive models, and flexible management strategies. In summary, while precision resource management offers substantial agronomic and environmental benefits, its successful implementation depends on supportive policies, financial incentives, capacity building, and improved rural infrastructure. Addressing these constraints is essential for achieving widespread and equitable adoption.

10. Future prospects and policy implications

The future of climate-resilient agriculture lies in the intelligent integration of precision technologies with sustainable agronomic practices. Rapid advancements in artificial intelligence, machine learning, satellite-based monitoring, and low-cost sensor technologies are expected to make precision resource management more accessible and affordable in the coming years (Basso & Antle, 2020) [4]. Miniaturization of devices and cloud-based data platforms may further enhance scalability across diverse farming systems. The future of Precision Resource Management (PRM) lies in the integration of AI, IoT, remote sensing, autonomous machinery, and climate forecasting for real-time and adaptive farm management. Greater development of low-cost technologies, open agricultural data platforms, and farmer-oriented decision-support systems can improve accessibility and scalability, particularly for smallholder farming systems. Supportive policies should promote subsidies, financial assistance, digital infrastructure, farmer training, capacity building, and technology-sharing models to encourage adoption. Strengthening research-extension linkages and developing region-specific precision agriculture guidelines can further support climate-resilient and sustainable crop production.

10.1 Scaling Precision Technologies for Smallholders

For countries with small and fragmented landholdings, customized and cost-effective precision solutions are essential. Development of low-cost sensor kits, mobile-based advisory platforms, and community-level drone services can improve accessibility (Liakos *et al.*, 2018) [48]. Establishing custom hiring centers and farmer producer organizations (FPOs) may facilitate shared use of advanced machinery. Development of low-cost, user-friendly, and mobile-based precision technologies can improve accessibility for smallholder farmers. Custom-hire centres, farmer cooperatives, and shared-service models can reduce individual investment requirements.

10.2 Strengthening Extension and Capacity Building

Effective adoption requires strong extension systems and farmer training programs. Capacity building initiatives focused on digital literacy, data interpretation, and climate-smart agronomic practices can bridge the knowledge gap (Lipper *et al.*, 2014) [49]. Collaboration among research institutions, universities, and private technology providers will accelerate innovation diffusion. Effective adoption requires farmer training, digital literacy, technical support, and practical demonstrations. Strengthening agricultural extension services can improve farmers' ability to interpret and apply precision-management information.

10.3 Policy Support and Incentives

Government policies play a crucial role in promoting precision agriculture. Subsidies for micro-irrigation, soil health mapping programs, digital agriculture missions, and climate-smart agriculture initiatives can encourage adoption. Integrating precision agriculture into national climate adaptation strategies will strengthen food security and environmental sustainability (IPCC, 2021) [38]. Government policies should encourage PRM adoption through subsidies, credit facilities, infrastructure development, digital connectivity, and incentives for resource-efficient technologies. Policies should also support data sharing, interoperability, and climate-smart agricultural programmes.

10.4 Research and Innovation Priorities

Future research should focus on developing climate-resilient crop varieties compatible with precision systems, improving interoperability of digital platforms, and enhancing real-time predictive analytics. Integration of big data, weather forecasting models, and crop simulation tools will enable proactive rather than reactive farm management. Future research should focus on AI/ML-based decision systems, low-cost sensors, autonomous technologies, climate prediction, integrated crop-soil-weather models, and multi-objective optimization. Greater emphasis is also needed on field-scale validation, techno-economic assessment, and long-term sustainability of precision technologies. Overall, precision resource management represents a transformative pathway toward sustainable intensification of agriculture. With supportive policies, inclusive innovation models, and strengthened research-extension linkages, precision technologies can significantly enhance resilience, productivity, and environmental stewardship in cropping systems.

11. Conclusion

Climate change presents unprecedented challenges to global agriculture, requiring innovative and adaptive strategies to ensure sustainable and resilient crop production. Conventional resource management approaches are increasingly inadequate under conditions of climatic variability, resource scarcity, and environmental degradation. In this context, Precision Resource Management (PRM) provides a transformative approach for improving resource-use efficiency, climate resilience, and sustainability in cropping systems. By integrating site-specific nutrient management, sensor-based irrigation scheduling, digital soil mapping, remote sensing, variable-rate technologies, and AI-driven decision-support systems, PRM enables precise and efficient management of critical agricultural resources such as water, nutrients, soil, and energy. These approaches can improve resource-use efficiency, enhance yield stability under climatic stress, reduce input losses and greenhouse gas emissions, and improve soil health. The integration of precision technologies with climate-smart agronomic practices further strengthens the adaptive capacity and resilience of cropping systems while minimizing environmental impacts. Despite challenges related to high initial costs, technical skill requirements, data availability, infrastructure, and fragmented land holdings, supportive policies, capacity building, affordable technologies, and inclusive innovation models can accelerate the adoption of PRM, particularly among smallholder farmers. Future advances in artificial intelligence, Internet of Things (IoT), remote sensing, autonomous technologies, and climate forecasting are expected to further enhance adaptive and site-specific resource management. In conclusion, integrating precision resource management strategies into mainstream agricultural systems offers a viable pathway toward climate-resilient crop production,

efficient resource utilization, reduced environmental impacts, and long-term food and nutritional security. Strengthening the integration of digital technologies, climate information, and sustainable agronomic practices will be essential for developing productive, resource-efficient, and resilient agricultural systems under future climate conditions.

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