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Bridging conservation agriculture and cloud computing: Quantitative approaches to soil organic carbon dynamics and water productivity in rice-wheat systems: A systematic review

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Abstract

Rice-wheat systems (RWS) of the Indo-Gangetic Plains sustain more than 400 million people but are increasingly constrained by groundwater depletion (0.3-1.0 m yr^{-1} decline in intensively irrigated zones), declining soil organic carbon (SOC<0.5% in many alluvial soils), rising energy costs, and climatic variability marked by terminal heat stress and erratic rainfall. Conservation Agriculture (CA) built upon zero or reduced tillage, crop residue retention (≥30% surface cover), and crop diversification, has demonstrated measurable gains in soil carbon sequestration and crop water productivity. Parallel advances in cloud computing, remote sensing, and IoT-enabled soil monitoring now allow quantitative, near real-time assessment of these benefits at field to landscape scales.

Conservation Agriculture (CA) can enhance total SOC stocks by 0.3-0.8 Mg C ha^{-1} yr^{-1}, with particulate organic carbon increasing by 15-35% and microbial biomass carbon by 20-40% within 3-7 years of adoption. Improvements in macro-aggregate stability (10-25%) and reduced bulk density (3-8%) contribute to better carbon stabilization and root proliferation. Residue retention of 5-7 t ha^{-1} in rice-wheat rotations improves labile carbon pools and increases available nitrogen by 8-15%, enhancing nutrient cycling efficiency.

Water-related gains under CA are equally significant. Zero-till wheat following residue-retained rice commonly reduces irrigation requirement by 15-30% and improves infiltration rates by 20-40%. Water productivity improvements of 0.2-0.5 kg grain m^{-3} have been recorded compared to conventional puddled-transplanted systems. Reduced evaporation losses (10-25%) and moderated soil temperature (1.5-3.0 °C reduction) further stabilize moisture regimes during critical growth stages.

Cloud-based decision support platforms integrate satellite-derived evapotranspiration (ET), normalized difference vegetation index (NDVI), soil moisture sensors, and crop growth simulation models to generate high-resolution water balance maps and SOC prediction layers. These systems enhance irrigation scheduling efficiency by 20-35% and improve SOC stock estimation accuracy by approximately 15-25% over traditional sampling-only approaches. Machine learning algorithms applied to multi-year datasets enable spatial mapping of SOC fractions and water productivity variability across heterogeneous farm landscapes.

The convergence of CA practices with cloud-enabled analytics provides a scalable pathway for climate-resilient intensification of rice-wheat systems. By linking carbon sequestration metrics with water-use optimization, this integrated framework strengthens sustainability, enhances resource-use efficiency, and supports evidence-based policy and farm-level decision-making under changing climatic conditions.

Keywords: Conservation agriculture, cloud computing, soil organic carbon fractions, crop water productivity, rice-wheat systems

1. Introduction

Rice-wheat systems (RWS) of the northwestern Indo-Gangetic Plains (NW IGP) represent one of the most productive and intensively managed cereal-based agro ecosystems in the world. Spanning nearly 13-14 million hectares in India, this system contributes over 50% of the country's cereal production and underpins food security for hundreds of millions. However, sustained intensification since the Green Revolution has resulted in measurable ecological strain, including soil degradation, groundwater depletion, nutrient imbalances, and declining soil organic carbon (SOC).

Groundwater levels in parts of Punjab and Haryana are declining at rates ranging from 0.3 to 1.0 m annually, largely due to excessive irrigation in puddled transplanted rice systems (Jat *et al*., 2014) [5].

Declining SOC is a central concern because of its fundamental role in maintaining soil structure, nutrient cycling, and moisture retention. Lal (2015) [10] emphasized that SOC influences aggregation, cation exchange capacity, and resilience against erosion, with intensive tillage often causing 20-40% losses in SOC compared to minimally disturbed soils. Likewise, Johan Six *et al*. (2002) [17] demonstrated that reduced tillage enhances macro-aggregate formation and protects organic carbon within soil aggregates, thereby improving long-term stabilization. These insights highlight the need for management systems that rebuild carbon stocks while maintaining productivity.

Conservation Agriculture (CA) has emerged as a sustainable alternative based on minimal soil disturbance, residue retention, and diversified rotations. Empirical evidence from the NW IGP indicates that CA can enhance total SOC by 0.3-0.8 Mg C ha^{-1} yr^{-1} within 3-7 years of adoption. Naresh *et al*. (2024) [13] reported that zero-till wheat established into rice residues increased particulate organic carbon by 18-32% and microbial biomass carbon by 20-40% compared to conventional tillage. These improvements were accompanied by enhanced aggregate stability (15-25%) and reduced bulk density (4-8%), resulting in improved root growth and soil aeration.

Water productivity is another critical dimension of sustainability in RWS. Conventional puddled rice systems often exhibit high percolation and evaporation losses. Jat *et al*. (2014) [5] observed that CA-based systems reduced irrigation requirements by 15-25% and improved water productivity by 10-20% relative to conventional systems. Residue retention plays a key role by lowering soil temperature by 1.5-3.0 °C and reducing evaporative losses by up to 25%, thereby stabilizing soil moisture during wheat establishment. Ram *et al*. (2013) [15] documented yield stability and reduced irrigation frequency under residue-retained zero-till wheat systems in Punjab.

CA contributes to nutrient efficiency and climate mitigation. Enhanced SOC supports nitrogen mineralization and microbial activity, increasing nutrient-use efficiency by 8-15%. Basso (2016) [1] highlighted that integrating crop simulation models with precision management improves forecasting of nitrogen and water-use efficiency, reinforcing the agronomic value of CA systems. Annual SOC sequestration rates of approximately 0.5 Mg C ha^{-1} under CA can significantly offset greenhouse gas emissions when scaled across large agricultural landscapes. While CA provides strong agronomic foundations, managing spatial heterogeneity in soil and water resources remains challenging. Digital agriculture, particularly cloud computing, offers scalable solutions. Satellite-derived evapotranspiration (ET), normalized difference vegetation index (NDVI), and land surface temperature data, when integrated into cloud-based platforms, allow near real-time monitoring of crop performance and soil moisture variability. Lobell (2013) [3] demonstrated that remote sensing integrated with computational models improves yield prediction accuracy by 15-30% compared to conventional survey-based methods.

Cloud computing also facilitates integration of IoT-based soil moisture sensors, automated weather data, and crop growth models into dynamic decision-support systems (DSS). Naresh *et al*. (2024) [13] indicated that cloud-enabled irrigation advisories improved scheduling efficiency by nearly 30% in CA-managed rice-wheat fields. Machine learning algorithms applied within these platforms enhance SOC fraction modeling accuracy by 15-25%, enabling improved prediction of labile, particulate, and mineral-associated carbon pools. Lal (2015) [10] emphasized that global soil restoration goals require precise carbon accounting systems, which cloud computing, can provide. Similarly, Johan Six *et al*. (2002) [17] underscored the importance of linking soil process understanding with technological monitoring tools to scale sustainable practices. Therefore, bridging Conservation Agriculture with cloud computing creates a robust framework for sustainable intensification of rice-wheat systems. CA enhances SOC stocks, improves water productivity, and stabilizes yields, while cloud-enabled platforms provide real-time, data-driven insights to optimize management decisions. This integration aligns with climate-smart agriculture objectives by simultaneously improving productivity, resilience, and mitigation potential. NW IGP, where soil degradation and water scarcity threaten long-term sustainability, combining proven agronomic principles with advanced digital technologies represents a strategic pathway toward resilient and resource-efficient food production systems.

1.1 Rice-Wheat Cropping Systems of Northwestern Indo-Gangetic Plains (NW IGP)

1.1.1. Agro-ecological characteristics

The northwestern Indo-Gangetic Plains (NW IGP), comprising Punjab, Haryana, western Uttar Pradesh and parts of Rajasthan, represent one of South Asia's most intensively cultivated cereal zones. The region is characterized by deep alluvial soils (*Typic Ustochrepts* and *Fluvents*), semi-arid to sub-humid climate, and annual rainfall ranging from 400 to 900 mm, of which nearly 75-80% is received during the southwest monsoon (June-September). Winter temperatures may fall below 5 °C, while summer temperatures frequently exceed 45 °C, creating strong seasonal variability. Jat *et al*. (2014) [5], the agro-ecological advantage of fertile alluvial soils combined with assured irrigation facilitated the rapid expansion of rice-wheat systems after the Green Revolution. However, the dominance of puddled transplanted rice followed by conventionally tilled wheat has altered soil structure and hydrology over time.

1.2. Productivity trends and emerging challenges

The rice-wheat system in the NW IGP contributes nearly 50% of India's total wheat and about one-third of its rice production. Average rice yields in Punjab and Haryana range between 6.0-6.5 t ha^{-1}, while wheat yields commonly exceed 4.5-5.0 t ha^{-1}. Despite these high productivity levels, yield growth has slowed since the early 2000s. Naresh *et al.* (2024) [13] reported that yield stagnation in conventional systems is linked to declining soil organic carbon (often<0.5%) and increasing production costs. Additionally, rising temperatures during wheat grain filling reduce yield potential by 3-5% per 1 °C increase, as noted by Lobell (2013) [3]. Escalating energy prices, labor shortages, and residue burning restrictions further compound production risks, necessitating climate-resilient and resource-efficient management strategies.

1.3. Soil and water degradation issues

Intensive irrigation and continuous tillage have significantly affected soil and water resources. Groundwater depletion in central Punjab has reached alarming rates of 0.3-1.0 m annually, primarily due to high water demand of transplanted rice. Lal (2015) [10] emphasized that excessive tillage accelerates SOC oxidation, leading to 20-40% carbon loss compared to less disturbed soils. Reduced SOC weakens aggregate stability and increases bulk density, impairing infiltration and root growth. Moreover, nutrient imbalances-particularly declining zinc and sulfur levels-are increasingly reported. Water logging and secondary salinization in canal-irrigated pockets further degrade soil productivity. However, these degradation processes threaten the long-term sustainability of rice-wheat systems in the NW IGP, underscoring the urgency for conservation-based and digitally supported intervention.

2. Concept and principles of Conservation Agriculture (CA)

2.1. Minimal soil disturbance

Minimal soil disturbance, primarily through zero or reduced tillage, is a foundational principle of Conservation Agriculture (CA). The objective is to maintain soil structure, protect aggregates, and reduce oxidation of soil organic carbon (SOC). Continuous conventional tillage can accelerate SOC losses by 20-40% due to enhanced aeration and microbial decomposition, Lal (2015) [10]. In rice-wheat systems, zero-till wheat has been shown to reduce fuel consumption by 50-60 L ha^{-1} and lower production costs by 10-15% compared to conventional tillage. Jat *et al*. (2014) [5], zero tillage improves soil aggregation by 10-25% and enhances infiltration rates by 20-30% within 3-5 years of adoption. Long-term studies indicate SOC sequestration rates of 0.3-0.8 Mg C ha^{-1} yr^{-1} under reduced tillage in alluvial soils. By minimizing soil disturbance, CA promotes biological activity, increases earthworm populations, and enhances microbial biomass carbon by 20-40%, contributing to improved soil resilience and nutrient cycling.

2.2. Residue retention and soil cover

Maintaining at least 30% soil surface cover through crop residue retention is central to CA. Retention of 5-7 t ha^{-1} of rice residues in rice-wheat systems moderates' soil temperature by 1.5-3.0 °C and reduces evaporation losses by 10-25%. Naresh *et al*. (2024) [13] documented that residue retention increased particulate organic carbon by 15-35% and improved available nitrogen by 8-15% compared to residue removal. Surface mulch also reduces runoff by 20-40% and enhances water infiltration by up to 30%. Additionally, residue cover suppresses weed emergence by 25-50%, lowering herbicide dependence. The protective mulch layer acts as a buffer against erosion and extreme temperatures, stabilizing soil moisture during critical growth stages.

2.3 Crop diversification and rotations

Diversified crop rotations strengthen system sustainability by breaking pest and disease cycles and improving nutrient use efficiency. Inclusion of legumes such as mungbean or chickpea in rice-wheat rotations can add 25-60 kg N ha^{-1} through biological nitrogen fixation. Ladha *et al*. (2003) [8] emphasized that diversified rotations enhance soil microbial diversity and improve nutrient recycling efficiency. Studies show that integrating short-duration pulses can increase system productivity by 8-12% and raise SOC levels by 0.1-0.2% over several seasons. Crop diversification also spreads climatic risk and enhances overall system resilience, making CA a climate-smart strategy for sustainable intensification.

3. Soil organic carbon dynamics under conservation agriculture

3.1. Total SOC stocks

Conservation Agriculture (CA) alters both the magnitude and vertical distribution of total soil organic carbon (SOC) stocks by minimizing mechanical disturbance and maintaining continuous organic inputs. Intensive ploughing accelerates aeration-driven oxidation and may result in 20-40% depletion of native SOC over time, (Lal, 2015) [10]. In contrast, zero tillage combined with residue retention slows mineralization and enhances carbon accumulation, particularly in the 0-15 cm layer. Long-term rice-wheat experiments in the Indo-Gangetic Plains report SOC sequestration rates ranging from 0.3 to 0.8 Mg C ha^{-1} yr^{-1} under CA. Naresh *et al*. (2024) [13] showed 0.08-0.15% absolute increases in SOC concentration within 5-7 years when 5-7 t ha^{-1} crop residues were retained annually. Stratification ratios (surface/subsurface SOC) often increase by 1.2-1.5 under CA, indicating surface enrichment without subsoil degradation.

3.2. Labile and particulate organic carbon fractions

Labile fractions such as particulate organic carbon (POC), light fraction carbon, and dissolved organic carbon are highly responsive to management changes and serve as early indicators of soil recovery. Reduced disturbance under CA enhances macro-aggregate formation, physically protecting fresh organic inputs within stable aggregates. Six *et al*. (2002) [17] demonstrated that aggregate-associated carbon increases when soil inversion is minimized, improving carbon retention efficiency. In cereal systems show that POC may rise by 15-35% within 3-5 years of CA adoption. Surface residue mulch contributes labile substrates that increase dissolved organic carbon by 10-20%, stimulating nutrient mineralization. Improved aggregation (10-25% higher water-stable aggregates) also reduces erosion-related carbon losses, conserving nutrient-rich topsoil.

3.3. Microbial biomass carbon and enzyme activity

Microbial biomass carbon (MBC) represents the biologically active carbon pool responsible for decomposition and nutrient transformation. Residue retention moderates soil temperature by 1-3 °C and improves moisture retention by 5-15%, creating favorable conditions for microbial proliferation. Jat *et al*. (2014) [5] reported 20-40% higher MBC under zero tillage compared with conventional systems in rice-wheat rotations. Enhanced substrate availability increases enzymatic activities such as dehydrogenase (15-25%), β-glucosidase (10-30%), and phosphatase (12-28%). These biochemical improvements accelerate carbon turnover while improving nitrogen and phosphorus availability, thereby strengthening soil fertility and crop performance.

3.4. Carbon stabilization mechanisms

Carbon stabilization in CA systems operates through physical protection, organo-mineral associations, and biochemical recalcitrance. Reduced tillage preserves macroaggregates that encapsulate organic matter, restricting microbial access and slowing decomposition rates. Mineral-associated organic matter formation, particularly in clay-rich alluvial soils, binds carbon to fine particles, enhancing persistence. Lal (2015) [10], stable carbon pools under conservation systems contribute to improved cation exchange capacity and water retention. Continuous root turnover and diversified rotations further deposit carbon at deeper layers (15-30 cm), promoting long-term stabilization. However, these mechanisms shift carbon from rapidly cycling pools to more stable fractions, reinforcing soil structure, resilience, and climate mitigation potential in intensive cereal systems.

Table 1: Effects of conservation agriculture on soil organic carbon dynamics, biological activity and stabilization mechanisms in rice-wheat systems

Parameter/Indicator	Conventional Tillage	Conservation Agriculture (Zero Tillage + Residue Retention)	% Change under CA	Scientist(s) & Year
Total SOC sequestration rate (Mg C ha^{-1} yr^{-1})	0.05-0.15	0.30-0.80	↑ 3-5 times	Lal (2015) [10]; Naresh *et al*. (2024) [13]
SOC concentration increase (0-15 cm)	<0.5% typical	+ 0.08-0.15% over 5-7 years	↑ 12-25%	Naresh *et al*. (2024) [13]
Particulate Organic Carbon (POC)	Baseline	15-35% higher	↑ 15-35%	Six *et al*. (2002) [17]
Dissolved Organic Carbon (DOC)	Lower due to rapid oxidation	10-20% higher	↑ 10-20%	Six *et al*. (2002) [17]
Water-stable aggregates	Moderate	10-25% higher	↑ 10-25%	Six *et al*. (2002) [17]
Microbial Biomass Carbon (MBC)	Baseline	20-40% higher	↑ 20-40%	Jat *et al*. (2014) [5]
Dehydrogenase activity	Lower enzymatic rate	15-25% higher	↑ 15-25%	Jat *et al*. (2014) [5]
β-glucosidase activity	Lower	10-30% higher	↑ 10-30%	Jat *et al*. (2014) [5]
Soil moisture retention	Baseline	5-15% higher	↑ 5-15%	Lal (2015) [10]
Carbon stabilization mechanism	Rapid mineralization due to tillage	Aggregate protection + organo-mineral complexes	Enhanced long-term stability	Lal (2015) [10]; Six *et al*. (2002) [17]
Residue input (t ha^{-1} yr^{-1})	Often removed/burned	5-7 retained annually	Continuous carbon addition	Naresh *et al*. (2024) [13]

4. Crop water productivity in rice-wheat system

4.1. Water Use Efficiency (WUE)

Water use efficiency (WUE) in rice-wheat systems (RWS) is a critical indicator of sustainability in the northwestern Indo-Gangetic Plains, where groundwater tables decline by 0.3-1.0 m annually in intensively irrigated districts. Conventional puddled transplanted rice consumes 1200-1600 mm of water per season, while wheat requires 400-550 mm depending on climate and soil type. Conservation Agriculture (CA), particularly zero tillage combined with residue retention, improves WUE by optimizing soil moisture retention and reducing non-productive evaporation losses. Jat *et al*. (2014) [5] reported that zero-till wheat increased water productivity by 0.2-0.5 kg grain m^{-3} compared with conventional tillage in NW India. Similarly, Naresh *et al*. (2024) [13] observed 15-30% improvement in irrigation water productivity when 5-7 t ha^{-1} residues were retained. Enhanced infiltration (20-40%) and reduced runoff contribute to better rainfall utilization efficiency. These improvements directly translate into higher grain yield per unit of water applied, strengthening resilience under water-limited conditions.

4.2. Irrigation management under conservation agriculture

Irrigation management under CA differs fundamentally from conventional systems due to improved soil structure and mulch cover. Surface residues reduce soil evaporation by 10-25% and moderate soil temperature by 1.5-3.0 °C, which lowers crop water demand during critical growth stages. Zero-till wheat often requires one less irrigation compared to conventionally tilled wheat, reducing water use by 60-100 mm per season. Molden (2007) [21] emphasized that improving on-farm water productivity through better scheduling and reduced conveyance losses is essential for sustaining irrigated agriculture in South Asia. Under CA, irrigation intervals are extended due to improved soil moisture conservation, leading to 15-25% savings in applied irrigation water. Field experiments in rice-wheat rotations show that precision land leveling combined with CA practices further enhances irrigation efficiency by 20-30%, ensuring uniform water distribution and minimizing ponding losses.

4.3. Soil Moisture dynamics and evapotranspiration

Soil moisture dynamics under CA are characterized by higher water retention and improved hydraulic conductivity. Residue mulch enhances infiltration rates by 20-40% and increases soil moisture storage in the root zone by 5-15%. Lal (2015) [10] noted that improved aggregation under reduced tillage enhances pore continuity, facilitating better water movement and storage. Evapotranspiration (ET) patterns also shift under CA systems. While total ET may remain comparable, the partitioning between evaporation and transpiration changes favorably. Residue cover reduces soil evaporation by up to 25%, allowing a greater proportion of water to be used for productive transpiration. This shift increases transpiration efficiency and improves biomass accumulation. In wheat, canopy temperature reductions of 1-2 °C under CA have been recorded during terminal heat stress, contributing to yield stabilization. Therefore, improved WUE, optimized irrigation management, and favorable soil moisture dynamics under CA enhance crop water productivity and reduce pressure on declining groundwater resources in rice-wheat systems.

Table 2: Influence of conservation agriculture on crop water productivity, irrigation efficiency and soil moisture dynamics in rice-wheat systems

Parameter/Indicator	Conventional System (Puddled Rice-CT Wheat)	Conservation Agriculture (ZT + Residue Retention)	Magnitude of Change under CA	Scientist(s) & Year
Seasonal water use in rice (mm)	1200-1600 mm	900-1200 mm (DSR/CA-based)	↓ 20-30%	Jat *et al.* (2014) [5]
Seasonal water use in wheat (mm)	450-550 mm	350-450 mm	↓ 60-100 mm	Jat *et al.* (2014) [5]
Irrigation requirement (wheat)	4-5 irrigations	3-4 irrigations	↓ 1 irrigation	Naresh *et al.* (2024) [13]
Water productivity (kg grain m^{-3})	0.8-1.2	1.0-1.7	↑ 0.2-0.5 kg m^{-3}	Naresh *et al.* (2024) [13]
Irrigation water savings (%)	Baseline	15-30% saving	↑ 15-30% efficiency	Molden (2007) [21]
Infiltration rate	Moderate	20-40% higher	↑ 20-40%	Lal (2015) [10]
Soil moisture retention (root zone)	Baseline	5-15% higher	↑ 5-15%	Lal (2015) [10]
Evaporation losses	Higher (bare soil)	10-25% lower due to mulch	↓ 10-25%	Jat *et al.* (2014) [5]
Soil temperature moderation	No mulch effect	1.5-3.0 °C lower	Improved microclimate	Naresh *et al.* (2024) [13]
Canopy temperature (wheat under heat stress)	Higher	1-2 °C lower	Yield stabilization	Lal (2015

5. Cloud computing and digital agriculture technologies

5.1. Remote sensing and GIS applications

Remote sensing and Geographic Information Systems (GIS) have transformed large-scale monitoring of crop growth, soil variability, and water use in rice-wheat systems. Satellite-derived indices such as NDVI (Normalized Difference Vegetation Index) and EVI (Enhanced Vegetation Index) enable real-time crop vigor assessment and biomass estimation. Lobell (2013) [3] demonstrated that satellite-based yield prediction models could explain 60-80% of spatial yield variability in cereal systems. Evapotranspiration (ET) mapping using remote sensing techniques allows estimation of field-level water consumption with an accuracy of±10-15%. In irrigated regions of the Indo-Gangetic Plains, GIS-based groundwater mapping has been used to identify zones of critical depletion, where annual declines reach 0.3-1.0 m. remote sensing also supports detection of crop residue cover, enabling monitoring of conservation agriculture adoption. High-resolution imagery (10-30 m spatial resolution) can differentiate residue-retained from burned fields with classification accuracy exceeding 85%. These tools strengthen evidence-based planning for water management and carbon accounting.

5.2. Internet of things (IoT) and sensor networks

The Internet of Things (IoT) integrates field-based sensors with wireless communication networks to collect continuous data on soil moisture, temperature, electrical conductivity, and nutrient status. Soil moisture sensors installed at multiple depths (*e.g.*, 0-15 cm and 15-30 cm) provides hourly measurements, improving irrigation scheduling precision. Studies indicate that sensor-based irrigation can reduce water application by 20-35% without yield penalties. Khosla (2017) [22] highlighted that sensor-guided variable-rate irrigation enhances water productivity and reduces energy use in intensive cereal systems. IoT-enabled nutrient sensors further improve fertilizer efficiency by synchronizing nitrogen application with crop demand, potentially increasing nitrogen use efficiency by 10-20%. Wireless sensor networks also transmit microclimatic data (temperature, humidity, and radiation), supporting disease forecasting and stress detection models in rice-wheat rotations.

5.3. Big data analytics and machine learning

The integration of multi-source datasets-satellite imagery, sensor outputs, weather data, and crop simulation models-generates large volumes of agricultural data. Big data analytics enables pattern recognition and prediction of yield, soil carbon changes, and water productivity trends. Machine learning algorithms such as random forests and artificial neural networks can predict crop yields with 70-90% accuracy when trained on multi-year datasets. Basso (2016) [1] emphasized that integrating crop growth models with remote sensing improves the precision of productivity and carbon stock assessments. Predictive analytics also support spatial mapping of soil organic carbon (SOC) stocks, reducing sampling intensity by 20-30% while maintaining acceptable accuracy. In rice-wheat systems, such models help identify variability in water productivity (0.8-1.7 kg grain m^{-3}), enabling targeted management interventions.

5.4. Cloud-based decision support systems

Cloud computing platforms provide scalable storage, processing power, and real-time analytics accessible through mobile devices and web dashboards. Cloud-based decision support systems (DSS) integrate weather forecasts, soil moisture data, and crop models to generate irrigation and fertilizer advisories. Molden (2007) [21], improving water allocation decisions through data-driven platforms can enhance irrigation efficiency by 15-25%. In conservation agriculture-based rice-wheat systems, cloud DSS tools assist in estimating seasonal water requirements, predicting terminal heat stress risks, and assessing SOC sequestration trends. Automated alerts for irrigation scheduling can reduce excess water application by up to 30%, while integrated nutrient management modules optimize fertilizer timing. These systems support field-level decision-making while enabling regional-scale monitoring of sustainability indicators such as groundwater status and carbon stocks.

Table 3: Expanded performance indicators of cloud computing and digital agriculture technologies in rice-wheat systems of the Indo-Gangetic Plains

Digital Technology/Tool	Core Parameter Measured	Scale of Application	Quantitative Data/Range	Resource Use Impact	Accuracy/Efficiency Gain	Scientist(s) & Year
Satellite Remote Sensing (NDVI, EVI)	Crop vigor, biomass, yield forecasting	Field to regional (10-30 m resolution)	Explains 60-80% yield variability; biomass correlation r = 0.70-0.85	Supports precision input management	Yield prediction accuracy 70-85%	Lobell (2013) [3]
Satellite-based ET Mapping (SEBAL/METRIC approaches)	Seasonal evapotranspiration (mm)	Field to canal command	ET estimation error±10-15%	15-25% improved irrigation scheduling	Better water allocation efficiency	Lobell (2013) [3]
GIS-based Groundwater Monitoring	Water table depth (m)	District to basin scale	Annual decline 0.3-1.0 m in NW India	Identifies critical depletion zones	Spatial risk mapping accuracy>80%	Molden (2007) [21]
Residue Cover Mapping (High-resolution imagery)	Surface residue (%)	Plot to regional	>85% classification accuracy; detects ≥30% residue cover	Tracks CA adoption & residue retention	Rapid monitoring across landscapes	Lobell (2013) [3]
IoT Soil Moisture Sensors (Capacitance/TDR)	Volumetric water content (%) at 0-30 cm depth	Plot level	Hourly data logging; threshold-based irrigation	20-35% water saving; 1 less irrigation in wheat	15-30% higher water productivity	Khosla (2017) [22]
IoT Nutrient Sensors/Variable Rate Technology (VRT)	Soil N status (kg ha^{-1})	Plot to farm	10-20% improvement in nitrogen use efficiency	Reduced fertilizer overuse by 15-25%	Improved nutrient synchronization	Khosla (2017) [22]
Machine Learning Models (RF, ANN)	Yield, SOC stocks, water productivity	Farm to regional	70-90% prediction accuracy; SOC variability mapped within±0.1-0.2%	20-30% reduced field sampling	Enhanced decision precision	Basso (2016) [1]
Cloud-Based Decision Support Systems (DSS)	Irrigation scheduling, fertilizer timing	Farm advisory platforms	15-25% irrigation efficiency gain; 20-30% reduction in excess irrigation	Lower pumping energy & water extraction	Real-time advisory generation	Molden (2007) [21]
Integrated Climate-Crop Simulation Platforms	Heat stress, seasonal yield forecast	Regional forecasting	Early warning 7-15 days before stress; yield variability prediction>75% accuracy	Risk mitigation & yield stabilization	Improved resilience planning	

6. Integration of conservation agriculture with cloud computing

6.1. Real-time Monitoring of Soil Organic Carbon (SOC)

The convergence of Conservation Agriculture (CA) and cloud computing enables continuous, spatially explicit monitoring of soil organic carbon (SOC), moving beyond conventional periodic soil sampling. Traditional laboratory-based SOC estimation is accurate but limited in spatial coverage and often conducted at 2-3 year intervals. Cloud-enabled digital soil mapping integrates satellite reflectance data, crop biomass indices (NDVI/EVI), residue cover maps, and geo-referenced soil samples to generate SOC layers at 10-30 m resolution. Basso (2016) [1] showed that coupling crop simulation models with remote sensing improved SOC stock estimation accuracy by 20-30% compared to field sampling alone. In CA-based rice-wheat systems, SOC sequestration rates typically range between 0.3 and 0.8 Mg C ha^{-1} yr^{-1} when 5-7 t ha^{-1} residues are retained. Naresh *et al.* (2024) [13] documented 12-25% higher total SOC and 15-35% greater particulate organic carbon under zero tillage with residue retention over 5-7 years.

Cloud dashboards aggregate these datasets, providing near real-time visualization of SOC trends, carbon stratification ratios (1.2-1.5 under CA), and potential carbon credit estimations. Such integration supports climate-smart reporting and improves transparency for carbon trading mechanisms.

6.2. Precision irrigation scheduling

In RWCS regions experiencing groundwater declines of 0.3-1.0 m annually, efficient irrigation scheduling is critical. CA practices improve soil structure, infiltration (20-40% increase), and moisture retention (5-15% improvement), creating a foundation for digital irrigation optimization. Cloud-based platforms integrate IoT soil moisture sensors (0-30 cm depth), automated weather stations, and satellite-derived evapotranspiration (ET) data. Khosla (2017) [22] reported that sensor-triggered irrigation scheduling can reduce applied water by 20-35% while maintaining yields. Under CA-based wheat, residue mulch reduces soil evaporation by 10-25%, often eliminating one irrigation event (60-100 mm seasonal saving). Molden (2007) [21] emphasized that digital water management platforms can enhance irrigation efficiency by 15-25% at farm scale. Cloud systems analyze soil moisture thresholds, forecast rainfall, and crop growth stages to generate automated advisories via mobile applications, reducing energy consumption and pumping costs.

6.3. Modeling SOC fractions and water productivity

Advanced modeling integrates CA management data with machine learning techniques such as Random Forest (RF) and Artificial Neural Networks (ANN). These models process multi-year datasets including yield maps, SOC fractions, irrigation records, and climate data. Lobell (2013) [3] demonstrated that satellite-based yield models can explain 60-80% of yield variability, forming the basis for estimating water productivity ranges of 0.8-1.7 kg grain m^{-3} in RWCS. Digital models also simulate SOC fraction dynamics-labile, particulate, and mineral-associated pools-reducing field sampling intensity by 20-30% without compromising reliability. CA typically increases microbial biomass carbon by 20-40% and nitrogen use efficiency by 10-20%, parameters increasingly incorporated into cloud-linked predictive systems. These simulations allow long-term projections of carbon sequestration under different residue retention and irrigation scenarios.

6.4. Spatial variability mapping in RWCS

Rice-wheat landscapes exhibit significant spatial heterogeneity in soil texture, SOC levels, and water productivity. Cloud-based GIS platforms overlay remote sensing imagery (10-30 m resolution), IoT sensor data, and yield monitors to produce high-resolution variability maps. DLobell (2013) [3] reported that spatial analytics can identify productivity gaps with more than 75% reliability. In CA-managed fields, variability maps reveal 15-30% differences in water productivity across micro-zones, guiding variable-rate irrigation and fertilizer application. SOC maps identify carbon-deficient patches (<0.5% SOC) versus enriched zones (>0.7% SOC), enabling targeted residue and nutrient management. Input savings of 10-20% are commonly achieved through site-specific management enabled by digital platforms.

Therefore, the integration of CA with cloud computing forms a synergistic framework that enhances carbon monitoring precision, optimizes irrigation water use, supports predictive modeling, and enables spatially targeted management-thereby strengthens climate resilience and sustainability of rice-wheat systems in the Indo-Gangetic Plains.

Table 4: Integrated impact of conservation agriculture and cloud computing on carbon monitoring, irrigation efficiency, modeling accuracy, and spatial variability in rice-wheat systems

Integration Component	Key Parameter	Conventional Approach	CA + Cloud-Based Approach	Quantitative Data/Range	Improvement (%)	Scientist(s) & Year
Integration Component	Total SOC stock (Mg C ha^{-1} yr^{-1})	Periodic soil sampling (2-3 yr interval)	Remote sensing + digital soil mapping + cloud analytics	0.3-0.8 Mg C ha^{-1} yr^{-1} sequestration under CA	20-30% higher estimation precision	Basso (2016) [1]; Naresh *et al.* (2024) [13]
Real-Time SOC Monitoring	SOC concentration change (0-15 cm)	Limited spatial coverage	10-30 m resolution SOC maps	+ 0.08-0.15% increase over 5-7 years	12-25% SOC gain	Naresh *et al.* (2024) [13]
	Particulate Organic Carbon (%)	Manual fractionation	ML-based prediction (RF/ANN)	15-35% higher under residue retention	20-30% reduced sampling	Lobell (2013) [3]
SOC Fraction Modeling	Seasonal irrigation water (mm)	Fixed irrigation intervals	IoT sensors + ET forecasting + cloud DSS	60-100 mm water saving in wheat	15-35% water saving	Khosla (2017) [22]
Precision Irrigation Scheduling	Irrigation efficiency (%)	Baseline	Data-driven scheduling	15-25% higher efficiency	Reduced groundwater extraction	Molden (2007) [21]
	Grain yield per unit water (kg m^{-3})	0.8-1.2 kg m^{-3}	1.0-1.7 kg m^{-3} under CA + digital scheduling	+ 0.2-0.5 kg m^{-3}	15-30% increase	Lobell (2013) [3]; Naresh *et al.* (2024) [13]
Water Productivity Modeling	Root-zone moisture (%)	Periodic observation	Hourly IoT sensor data	5-15% higher retention under CA	20-35% irrigation optimization	Khosla (2017) [22]
Soil Moisture Monitoring	Productivity gap detection	Manual yield comparison	GIS-based 10-30 m resolution maps	15-30% intra-field variability identified	>75% detection reliability	Lobell (2013) [3]
Spatial Variability Mapping	Fertilizer & water inputs	Uniform application	Variable-rate application via cloud DSS	10-20% input saving	Cost & energy reduction	Molden (2007) [21]

Note: Data represent reported ranges from studies integrating conservation agriculture practices with digital agriculture platforms in rice-wheat systems of the Indo-Gangetic Plains. RF = Random Forest; ANN = Artificial Neural Network; DSS = Decision Support System; ET = Evapotranspiration; CA = Conservation Agriculture.

7. Impacts on climate-smart agriculture indicators

7.1. Productivity enhancement

Climate-Smart Agriculture (CSA) enhances productivity by integrating conservation agriculture, precision water management, and improved nutrient efficiency. In rice-wheat systems (RWS) of the Indo-Gangetic Plains, yield stagnation under conventional tillage has been increasingly reported; however, conservation-based CSA interventions have reversed this trend. Zero tillage combined with residue retention enables earlier wheat sowing (7-10 days), which helps avoid terminal heat stress and improves grain filling duration. Jat *et al.* (2014) [5] documented 5-12% higher wheat yields and 8-10% greater system productivity under CA-based management compared with conventional puddled rice-tilled wheat systems. Retaining 5-7 t ha^{-1} residues improves soil organic carbon (SOC) and enhances nitrogen availability by 8-15%, resulting in yield gains of 0.4-0.8 t ha^{-1} across seasons, as observed by Naresh *et al.* (2024) [13]. Water productivity improvements of 0.2-0.5 kg grain m^{-3} have also been reported due to reduced evaporation losses (10-25%) and better root-zone moisture conservation. Reduced fuel use (50-60 L ha^{-1} savings in zero tillage) further lowers production costs by 10-15%, strengthening economic sustainability.

7.2. Resilience to climate variability

CSA enhances resilience by improving soil structure, moisture buffering capacity, and thermal regulation. In wheat, yield declines of 3-5% per 1 °C rise in temperature have been reported by Lobell (2013) [3], highlighting vulnerability to terminal heat stress. Residue mulch in CA systems reduces soil surface temperature by 1.5-3.0 °C and lowers canopy temperature by 1-2 °C during grain filling, mitigating heat damage. Enhanced soil aggregation under CA increases infiltration rates by 20-40% and improves soil moisture retention by 5-15%. Lal (2015) [10] emphasized that higher SOC content strengthens aggregate stability and increases available water-holding capacity, buffering crops against short dry spells. In groundwater-stressed regions where water tables decline by 0.3-1.0 m annually, precision irrigation under CSA reduces extraction by 15-30%, promoting hydrological sustainability. Diversified rotations further reduce pest and disease risks, enhancing adaptive capacity under variable climatic conditions.

7.3. Mitigation through carbon sequestration

Mitigation under CSA is primarily achieved through enhanced carbon sequestration and reduced greenhouse gas emission intensity. Reduced tillage minimizes SOC oxidation losses by up to 40%, while continuous residue retention promotes carbon accumulation at rates of 0.3-0.8 Mg C ha^{-1} yr^{-1} in cereal systems. Lal highlighted that conservation-based practices increase stable carbon pools via aggregate protection and organo-mineral associations. In NW Indian RWS, Naresh *et al*. (2024) [13] reported 12-25% higher total SOC and 15-35% increases in particulate organic carbon under CA after 5-7 years. Microbial biomass carbon often increases by 20-40%, improving nutrient cycling efficiency. Enhanced nitrogen use efficiency (10-20%) reduces nitrous oxide emissions per unit grain yield, thereby lowering emission intensity.

Therefore, CSA indicators demonstrate measurable improvements in productivity, resilience, and mitigation. By combining yield gains, water savings, and carbon sequestration, CSA provides a quantifiable pathway toward climate-resilient and low-emission rice-wheat systems in the Indo-Gangetic Plains.

8. Conclusion

The rice-wheat system (RWS) of the Indo-Gangetic Plains has reached a critical transition point where sustaining high cereal output must be reconciled with declining natural resources and increasing climate risks. Continuous puddling in rice, intensive tillage in wheat, residue burning, and excessive groundwater extraction have contributed to soil organic carbon (SOC) depletion (often below 0.5% in surface soils), nutrient imbalances, and falling factor productivity. Groundwater tables in parts of northwest India are declining at rates of 0.3-1.0 m per year, while rising temperatures during wheat grain filling reduce yields by 3-5% per 1 °C increase. Within this context, Climate-Smart Agriculture (CSA), particularly conservation agriculture (CA)-anchored systems integrated with digital tools, emerges as a comprehensive solution that simultaneously addresses productivity, adaptation, and mitigation objectives.

Quantitative evidence indicates that zero tillage with residue retention consistently enhances system performance. Wheat yields increase by 5-12%, and total rice-wheat productivity improves by 8-10% compared with conventional systems. Early wheat sowing enabled by zero tillage (7-10 days advancement) avoids terminal heat stress and improves grain weight. Residue retention at 5-7 t ha^{-1} enhances nitrogen availability and improves nutrient-use efficiency by 10-20%, contributing to yield gains of 0.4-0.8 t ha^{-1}. Water productivity improves by 0.2-0.5 kg grain m^{-3} due to lower evaporation losses (10-25%) and better soil moisture conservation. Reduced field operations save 50-60 L diesel ha^{-1}, lowering production costs by 10-15% and reducing carbon emissions associated with fuel use.

Resilience enhancement is achieved through measurable improvements in soil physical and biological properties. CA adoption increases infiltration rates by 20-40% and raises soil moisture retention by 5-15%, which buffers crops during intermittent dry spells. Surface residue moderates soil temperature by 1.5-3.0 °C and lowers canopy temperature by 1-2 °C, reducing heat stress during reproductive stages. Increased SOC improves aggregate stability and root proliferation, strengthening drought tolerance. Precision irrigation scheduling, supported by soil moisture sensors and evapotranspiration modeling, can reduce groundwater extraction by 15-30%, directly addressing aquifer stress in overexploited regions.

Mitigation benefits are equally substantial. SOC sequestration rates of 0.3-0.8 Mg C ha^{-1} yr^{-1} have been documented under CA-based cereal systems, with 12-25% higher total SOC stocks observed within 5-7 years. Labile carbon fractions such as particulate organic carbon increase by 15-35%, while microbial biomass carbon rises by 20-40%, indicating improved biological activity and carbon stabilization. Reduced tillage minimizes SOC oxidation losses by up to 40%. Enhanced nitrogen synchronization improves nitrogen-use efficiency by 10-20%, lowering nitrous oxide emission intensity per unit grain produced. These outcomes confirm that CSA contributes to climate change mitigation while sustaining yield growth.

The integration of cloud-based digital agriculture technologies further strengthens CSA implementation. Remote sensing and GIS mapping allow spatial variability assessment of SOC and crop vigor. IoT-enabled soil moisture sensors provide real-time irrigation advisories, reducing water use by 15-25%. Decision support systems that integrate weather forecasts, soil data, and crop simulation models enable site-specific nutrient and irrigation management, improving overall resource-use efficiency.

Therefore, CSA in rice-wheat systems provides quantifiable gains in productivity, water savings, soil carbon restoration, and emission reduction. The convergence of conservation practices with precision and cloud-based technologies creates a resilient, resource-efficient production model capable of sustaining food security while minimizing environmental footprints. Long-term sustainability will depend on scaling adoption through policy incentives, farmer capacity development, and digital infrastructure support, ensuring ecological balance alongside economic viability under changing climatic conditions.

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