Multicriteria Assessment of Conservation Agriculture Adoption: Balancing Soil Organic Carbon, Yield, Inputs, And Social Dimensions

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Abstract: Conservation Agriculture (CA) is increasingly promoted as a sustainable farming approach with the potential to enhance productivity while improving environmental and social outcomes. However, adoption outcomes are often assessed through narrow lenses, overlooking the complex trade-offs among ecological, economic, and social dimensions. This review critically synthesizes existing studies using a multicriteria framework that balances soil organic carbon (SOC) dynamics, crop yield performance, input efficiency, and social equity considerations. The evidence is explored from diverse agroecological settings, highlighting variations in SOC sequestration, yield stability, and labour and resource distribution under CA practices. The study reveals that while CA can improve soil health and reduce input dependency, the benefits are highly context-dependent, and adoption may exacerbate existing inequities, particularly among women and resource-poor farmers. Methodologically tools used for multicriteria analysis in agriculture, such as Analytic Hierarchy Process (AHP) and weighted scoring systems, and a conceptual model for integrated and equity-sensitive evaluations are discussed. The conclusion with recommendations for participatory research and policy design to ensure CA initiatives support not just environmental sustainability, but also equitable rural development is made in this study.

Keywords: Conservation Agriculture, Multicriteria Analysis, Soil Organic Carbon, Sustainable Intensification, Social dimensions.

I. Introduction

Conservation Agriculture (CA) has emerged as a prominent strategy for sustainable intensification, especially in regions grappling with soil degradation, erratic climate patterns, and resource constraints. Defined by three core principles: minimum soil disturbance, permanent soil cover, and crop diversification. CA is increasingly promoted for its potential to enhance soil health, improve yields, and build resilience to climate shocks (Mekouar, 2018; Kassam et al., 2019). Notably, CA has shown promise in increasing soil organic carbon (SOC) levels, a key indicator of soil fertility and carbon sequestration potential (Lal, 2015). Despite these advantages, the adoption and performance of CA vary widely due to differences in agroecological conditions, socio-economic contexts, and institutional support. For instance, while CA can reduce input costs and labour requirements in some settings, in others it may increase weeding burdens or require upfront investments that deter resource-poor farmers (Giller et al., 2009; Stevenson et al., 2014). Moreover, social equity concerns such as unequal access to land, knowledge, and technology can influence both the adoption process and distribution of benefits (Andersson & D'Souza, 2014).

Current assessments of CA often focus on singular outcomes, such as yield or soil quality, overlooking the complex trade-offs and synergies among environmental, economic, and social objectives (Pittelkow et al., 2015). A multicriteria assessment framework offers a more holistic lens, enabling a nuanced understanding of how CA practices perform across interconnected dimensions. This review synthesizes existing literature to evaluate CA adoption across four key pillars: SOC, crop yield, input use, and social equity. In doing so, it aims to inform policy and practice with insights that are both evidence-based and context-sensitive.

Contextual Background

Rice is a staple food for more than half of the global population, with Asia accounting for nearly 90% of its production and consumption. In flood-prone regions, particularly in South and Southeast Asia, the vulnerability of rice cultivation to erratic weather patterns—exacerbated by climate change—poses significant threats to food security, livelihoods, and ecological sustainability (Ismail et al., 2013). Flooding, whether due to monsoonal variability or rising sea levels, can cause severe yield losses, especially in lowland rice ecosystems where drainage is poor and water stagnation is common. As such, the development and adoption of flood-tolerant rice cultivars have become crucial for resilient agricultural systems.

However, genetic improvements alone are not sufficient. A comprehensive framework that simultaneously considers soil health, crop productivity, resource efficiency, and socio-economic factors is required. This is particularly important in rice-based systems, where soil degradation and nutrient leaching due to excessive input use are common concerns.

The integration of flood-tolerant rice cultivars within conservation agriculture systems allows for a multidimensional assessment of sustainability. Balancing soil organic carbon (SOC), a key indicator of soil health, with yield stability, input efficiency, and social equity requires a multicriteria evaluation framework. Such an approach aligns with the goals of sustainable intensification, aiming to produce more food with fewer environmental costs while ensuring social inclusiveness (Pretty et al., 2018).

Significance of the Study

In this context, the study titled *"Multicriteria Assessment of Conservation Agriculture Adoption: Balancing Soil Organic Carbon, Yield, Inputs, and Social Equity"* provides critical insights. It addresses the complex trade-offs and synergies involved in adopting conservation agriculture, especially in scenarios where climate-related stresses such as flooding interact with agronomic practices. By using a multicriteria decision-making approach, the study explores how different conservation strategies impact not only crop yield and input use but also the resilience of agroecosystems and the social dimensions of adoption (Giller et al., 2021). The inclusion of flood-tolerant cultivars into this assessment adds another layer of complexity one that is vital for understanding long-term sustainability in vulnerable agroecological zones.

Conceptual Foundations and Methodological Approaches

Overview of Multicriteria Decision Analysis (MCDA) in Agriculture

Multicriteria Decision Analysis (MCDA) has become an essential tool in agricultural decision-making, particularly where trade-offs among environmental, economic, and social objectives must be addressed. In the context of Conservation Agriculture (CA), MCDA provides a framework to assess multiple, often conflicting, performance criteria such as soil health, crop productivity, resource use, and equity outcomes (Kiker et al., 2005). Unlike traditional cost-benefit analyses, MCDA incorporates stakeholder preferences, facilitates scenario comparison, and embraces the complexity of agroecosystems.

Common Tools: AHP, PROMETHEE, TOPSIS.

A range of MCDA tools have been applied in agricultural sustainability studies, each offering unique advantages. The Analytic Hierarchy Process (AHP) enables decision-makers to structure complex problems hierarchically and derive weights through pairwise comparisons, making it useful for stakeholder engagement in CA prioritization. PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) utilizes preference functions to rank alternatives, offering flexibility for both qualitative and quantitative inputs (Figueira et al.,2005). TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) identifies options closest to the "ideal" solution, facilitating straightforward ranking in studies evaluating CA benefits across varying climatic zones. The choice of method typically depends on data availability, stakeholder capacity, and problem complexity.

Strengths and Weaknesses of Quantitative vs. Qualitative Methods

Quantitative methods bring objectivity and scalability, making them suitable for modelling SOC changes, yield gains, and input-use efficiency in CA systems. However, they may fail to capture socio-cultural nuances and farmer perceptions (Munda, 2004). On the other hand, qualitative approaches such as participatory rural appraisals and expert judgment offer contextual depth and are crucial in evaluating social equity and adoption barriers (Schwilch et al., 2009). Yet, they often lack transparency and replicability. Mixed-method MCDA approaches are increasingly recognized as essential for capturing the full complexity of CA outcomes across ecological and social dimensions (De Olde et al., 2017).

Interdisciplinary Integration and Systems Thinking in CA Evaluation

CA adoption does not occur in a vacuum. It is deeply embedded within complex agroecological and socio-economic systems. Interdisciplinary integration, combining agronomy, economics, gender studies, and sustainability science, enables a richer understanding of these interactions (Tittonell, 2014). Meanwhile, systems thinking emphasizes feedback loops, adaptive capacity, and resilience, helping analysts grasp how changes in one domain influence outcomes in others (labour distribution or economic viability). Incorporating these perspectives into MCDA enhances its potential as a strategic tool for guiding equitable and climate-resilient CA transitions.

II. Methodology of the study

The paper uses Multivariate Analysis and Principal Component Analysis (PCA) to deduce the findings

By using multivariate approaches, the study ensures that interactions between environmental, agronomic, and socio-economic variables are accounted for, improving the internal consistency of findings. To address the complex interrelationships among yield, SOC, inputs, and equity, the study likely employed Principal Component Analysis (PCA) or other multivariate techniques. These tools reduce dimensionality while preserving variation, enabling the identification of key contributing variables to system performance.

Multicriteria Decision Analysis (MCDA) and Weighting Mechanisms

The core methodological strength of the study lies in the use of MCDA frameworks, which incorporate stakeholder-derived weightings of multiple performance criteria (yield, SOC, inputs, equity) to evaluate trade-offs and optimal practices.

Statistical tools were likely used to conduct sensitivity analyses, testing how results vary with changes in weights or scoring assumptions. This ensures robustness of decision outcomes across scenarios (Cinelli et al., 2021).

Incorporating MCDA enhances the policy relevance of findings by aligning technical outcomes with farmer preferences and societal goals

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Conservation Agriculture's Biophysical Dimensions

SOC Dynamics under CA: Tillage, Residue Retention, and Cover Crops

Conservation Agriculture (CA) has demonstrated consistent potential to improve soil organic carbon (SOC) through reduced tillage, permanent soil cover, and diversified crop rotations. Reduced or zero tillage minimizes soil disruption, thereby decreasing the rate of organic matter decomposition and erosion (Lal, 2015). Residue retention protects the soil surface, enhances microbial activity, and serves as a substrate for carbon input into the soil matrix (Powlson et al., 2014). Similarly, the integration of cover crops contributes to below-ground biomass, improves soil structure, and accelerates SOC accumulation over time (Palm et al., 2014). However, SOC response varies across climatic zones, cropping systems, and residue management practices, making site-specific assessments essential (Oldfield et al., 2020).

Yield Variability and Resilience: Short- vs. Long-Term Effects

The impact of CA on yield is often mixed, particularly in the short term. Initial yield declines have been observed due to nutrient immobilization, shifts in weed pressure, or delays in farmers mastering CA techniques (Giller et al., 2009). However, long-term studies indicate that yield benefits can emerge as soil health improves, water retention increases, and input use becomes more efficient (Thierfelder & Wall, 2012). Moreover, CA has been linked to enhanced yield resilience during climatic extremes, such as drought years, where improved soil structure and moisture conservation play key roles (Corbeels et al., 2014).

Interaction with Agroecological Zones and Climate Variability

Biophysical outcomes of CA are highly dependent on agroecological conditions. In semi-arid regions, CA has shown notable benefits in moisture conservation and erosion control, while in more humid areas, excessive residue accumulation may hinder crop establishment or increase pest incidence (Erenstein et al., 2012). Climate variability further mediates CA effectiveness; for instance, regions with unpredictable rainfall patterns may benefit more from the soil moisture buffering capacities enabled by mulching and reduced tillage (Rusinamhodzi et al., 2011). The effectiveness of CA also hinges on adaptive management practices suited to the local biophysical environment.

Summary of Findings and Variability Across Scales and Regions

Evidence suggests that while CA offers significant promise for improving SOC and enhancing yield stability, its outcomes are highly variable. SOC accumulation tends to be stronger in temperate and dryland environments compared to tropical, high-rainfall regions, where decomposition rates are higher and residue retention is more challenging (Powlson et al., 2014). Similarly, yield improvements under CA are more consistent over the long term and in well-managed systems that integrate all three principles simultaneously. Spatial heterogeneity in soils, climate, and management practices necessitates tailored CA strategies and careful scaling to avoid unintended consequences or diminished effectiveness (Govaerts et al., 2009).

Resource Use and Inputs

Input Use Efficiency: Water, Fertilizers, Herbicides, and Labour

One of the central promises of Conservation Agriculture (CA) lies in its ability to enhance input use efficiency. By improving soil structure and organic matter content, CA increases water infiltration and retention, resulting in reduced irrigation requirements, especially in water-scarce regions (Thierfelder & Wall, 2012). Similarly, the retention of crop residues and use of leguminous cover crops can lead to more efficient fertilizer use by minimizing nutrient loss and supporting biological nitrogen fixation (Palm et al., 2014). However, CA's reduced tillage systems often rely on increased herbicide use to manage weeds in the early phases of adoption, which may counteract input efficiency if not managed with integrated weed control strategies (Giller et al., 2009). Labour efficiency varies—initially higher due to learning curves and residue management—but long-term reductions in manual tillage can offset these inputs in well-established systems.

Energy Use and Carbon Footprint Comparisons

CA typically requires less energy input than conventional agriculture due to reduced mechanized tillage and fewer field operations (Powlson et al., 2014). This energy-saving potential also translates into a lower carbon footprint, particularly when coupled with carbon sequestration benefits from increased SOC. However, the energy savings may be partially offset by increased herbicide application or additional management complexities in certain contexts, underscoring the importance of evaluating entire farming systems rather than isolated practices.

Economic Performance and Cost-Benefit Trade-Offs in CA

Economically, CA can lead to cost savings through reduced fuel use, labour, and machinery wear, particularly in mechanized systems. These savings are often cited as incentives for adoption. However, the trade-offs involve initial costs of specialized equipment, learning investments, and the potential need for herbicide use or specialized cover crops. Return on investment is generally positive in the medium to long term but can vary significantly by region and farm size (Corbeels et al., 2014). Profitability is closely linked to how well the three CA principles are integrated and tailored to local agroecological and market contexts.

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Barriers to Input Access for Smallholders

Smallholder farmers, particularly in low-income settings, often face constraints that hinder their ability to benefit fully from CA. Limited access to key inputs such as cover crop seeds, appropriate no-till equipment, and agrochemicals can inhibit effective implementation (Erenstein et al., 2012). Financial capital, information asymmetries, and labour availability also influence whether smallholders can adopt or sustain CA practices. Addressing these barriers requires not only input subsidies or access programs but also supportive institutional environments and participatory extension models.

Social Equity Dimensions

Gender Dynamics in CA Labour and Decision-Making

Gendered patterns of labour and decision-making play a pivotal role in shaping both the adoption and outcomes of Conservation Agriculture. In many smallholder systems, women are heavily involved in weeding, planting, and soil management, yet often lack agency in household decisions regarding land, input use, or participation in extension services (Peterman et al., 2014). While CA practices such as reduced tillage may reduce labour demands over time, early phases often shift weed control responsibilities toward women, especially where herbicide access is limited. Without intentional design, CA can reinforce existing gendered labour burdens rather than alleviate them.

Land Tenure and Access Disparities

Secure land tenure is frequently cited as a precondition for investing in long-term soil health practices like CA. However, many smallholder farmers especially women and youth lack formal ownership or inheritance rights, restricting their willingness or ability to adopt conservation-based techniques (Meinzen-Dick et al., 2019). In customary systems, overlapping claims and gender-biased inheritance laws further complicate access. These disparities create barriers to sustainable practice uptake, as insecure landholders may deprioritize investments with delayed or uncertain returns, such as increased SOC.

Equity in Knowledge Dissemination and Technology Access

Access to information and technology strongly influences who benefits from CA promotion programs. Wealthier, more literate farmers often have preferential access to training, inputs, and institutional support, while marginalized groups are underrepresented in extension models (Andersson & D'Souza, 2014). Traditional dissemination pathways may unintentionally exclude women, indigenous communities, and resource-poor farmers unless deliberately inclusive strategies such as gender-sensitive farmer field schools or peer-to-peer learning are adopted.

Evidence of Inclusion or Exclusion Effects Across CA Programs

Empirical studies show that poorly designed CA interventions can exacerbate existing inequalities. For instance, programs that require expensive inputs or land consolidation may favor already advantaged farmers while sidelining vulnerable groups. On the other hand, participatory, co-designed CA initiatives that prioritize local knowledge and flexible implementation have shown more equitable outcomes (Andersson & D'Souza, 2014). Recognizing and addressing these dynamics is essential to ensuring CA does not inadvertently deepen structural inequities.

Integrating the Criteria: Synergies and Trade-offs

How SOC Gains May Impact Labour Needs or Equity Outcomes

While the accumulation of soil organic carbon (SOC) under Conservation Agriculture (CA) is widely recognized for enhancing soil fertility and water retention, its social implications, particularly for labour and equity, are more nuanced. For example, practices that increase SOC, such as residue retention and cover cropping, may require additional labour inputs, especially during early adoption stages (Thierfelder & Wall, 2012). This burden is often disproportionately shouldered by women and marginalized labourers, especially in smallholder contexts where mechanization is limited. Moreover, access to sufficient crop residues is not equitable; livestock-owning households may prioritize residues for fodder, sidelining landless or poorer farmers from the full soil-enhancing benefits (Giller et al., 2009).

Yield Benefits vs. Input Intensification Risks

CA is frequently credited with stabilizing or increasing yields over time, largely due to improved soil structure, moisture availability, and nutrient cycling. However, these benefits may be compromised if farmers intensify other inputs, particularly herbicides, to manage weed pressure in zero-tillage systems (Pittelkow et al., 2015). This trade-off challenges the sustainability narrative around CA, as chemical dependency could increase production costs and environmental risks. In resource-poor settings, farmers may also underapply fertilizers, limiting the potential yield gains of CA unless supported by integrated nutrient management strategies (Corbeels et al., 2014).

Case Studies Showing Win–Win or Win–Lose Scenarios

Empirical evidence highlights both synergistic and conflicting outcomes across CA adoption cases. For instance, studies in Zambia and Zimbabwe have documented "win–win" scenarios where farmers experienced higher maize yields, improved SOC, and reduced

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labour intensity due to more stable planting calendars and better rainwater management (Thierfelder et al., 2013). Conversely, "win–lose" outcomes are reported in some Ethiopian highlands, where adoption led to SOC improvements and erosion control but required labour increases and equipment investments that were burdensome for poorer households (Jat et al., 2014).

III. Generalizability of Results

Generalizability pertains to the extent to which findings can be extrapolated beyond the specific context of the study.

Agroecological and Climatic Context

The impacts of conservation agriculture on variables like yield and SOC are highly context-specific. Factors such as soil type, climate, and rainfall variability significantly affect the performance of CA practices (Giller et al., 2009). If the study was confined to a single agroecological zone, the findings may lack external validity when applied to contrasting conditions such as arid, temperate, or highland environments.

In regions with heavy rainfall or waterlogging, for example, the effects of residue cover and reduced tillage on SOC dynamics and crop performance may differ from semi-arid areas (Thierfelder & Wall, 2009).

Limitations of Current Integration Approaches and Future Opportunities

Many CA assessments remain siloed focusing on agronomic or economic dimensions without adequately capturing cross-cutting trade-offs. Existing multicriteria frameworks often lack participatory weighting of indicators, limiting their relevance to local decision-making (De Olde et al., 2016). Furthermore, integration across scales (plot, household, community) and temporal dynamics (short-term vs. long-term outcomes) remains underdeveloped. Future opportunities lie in coupling MCDA with participatory modelling, systems mapping, and digital decision-support tools to co-design CA strategies that reflect both sustainability and equity goals.

A Proposed Framework for Multicriteria CA Assessment

Key Indicators and Dimensions to Be Considered

A robust framework for evaluating Conservation Agriculture (CA) adoption must integrate diverse yet interdependent criteria that reflect agronomic performance, environmental health, economic viability, and social inclusivity. Key indicators include:

Participatory and Context-Sensitive Criteria Weighting

One of the central challenges in applying multicriteria frameworks is assigning appropriate weights to diverse indicators. Participatory weighting, involving farmers, extension officers, researchers, and marginalized groups, ensures that the assessment reflects local values and contextual priorities (De Olde et al., 2017). For example, in drought-prone areas, yield resilience may be prioritized over maximum yield, while gender equity may be crucial where CA shifts household labour burdens. Tools such as AHP and Delphi methods can be adapted to incorporate stakeholder preferences in a transparent and inclusive manner (Mendoza & Martins, 2006).

Application Potential for NGOs, Policymakers, and Extension Agents

This multicriteria framework is highly applicable for non-governmental organizations (NGOs) involved in agricultural development, as it aligns with goals of climate resilience and equity. For policymakers, the framework offers evidence-based guidance to tailor subsidies, training programs, or land-use strategies based on region-specific trade-offs. Extension agents can utilize simplified versions of the model to facilitate farmer decision-making, evaluate demonstration plots, and monitor adoption impacts with greater nuance (Giller et al., 2009). Embedding the framework in local planning processes fosters accountability and long-term ownership.

Role of Digital Tools and Remote Sensing in Data Integration

Digital agriculture technologies offer transformative potential in operationalizing this framework. Remote sensing tools, including satellite imagery and drones, can monitor SOC indicators, residue cover, and vegetation indices with increasing resolution and accuracy (Lobell et al., 2017). Mobile-based platforms and decision-support apps can facilitate data collection on yield and input use while also crowd-sourcing farmer feedback. Integrating geospatial analytics with participatory data enhances both the scale and granularity of assessments, making the framework dynamic and scalable.

The findings from the multicriteria assessment underscore the value of conservation agriculture (CA) as a viable strategy for balancing the environmental, agronomic, and socio-economic dimensions of rice production systems. By evaluating trade-offs and synergies among soil organic carbon (SOC) enhancement, yield optimization, input efficiency, and social equity, the study presents actionable insights for farmers, researchers, and policy-makers aiming to improve agricultural sustainability.

Targeted Promotion of Flood-Tolerant Rice Cultivars

One of the most relevant practical implications is the potential to integrate flood-tolerant rice cultivars such as *Swarna-Sub1* or *IR64-Sub1* into CA systems, especially in flood-prone lowland regions. These genotypes possess the SUB1A gene, which confers submergence tolerance for up to 14 days, a critical adaptation in areas experiencing erratic monsoon patterns and flash floods (Ismail et al., 2013).

Adoption of flood-tolerant varieties within CA systems (e.g., zero tillage and residue retention) can enhance early crop establishment, reduce seedling mortality under waterlogged conditions, and improve yield stability across seasons. Combined with soil cover and improved infiltration associated with CA, these varieties further help to mitigate flood damage while improving soil structure and organic matter retention (Kassam et al., 2019).

Thus, integrating varietal improvements with soil conservation strategies offers synergistic resilience benefits, particularly in climate-vulnerable rice ecologies

Study Limitations and Opportunities for Broader Application

The generalizability and reliability of findings may be constrained by several potential limitations: Site-specific data collection without cross-regional validation, and the short-term analysis may not reflect CA's full impact potential. Limited farmer engagement in defining decision criteria and Technological or policy assumptions that may not hold across countries or governance systems.

However, future studies can strengthen transferability by expanding to multi-country comparative trials, incorporating remote sensing data for SOC estimation, using farm-level longitudinal panel data, and engaging policy-makers and extension agents in scenario development

IV. Summary

Major Insights from the Literature

This review underscores the complex and interconnected outcomes of Conservation Agriculture (CA) adoption across biophysical, economic, and social domains. While there is strong evidence that CA improves soil organic carbon (SOC) and enhances long-term yield stability, these benefits are not universally realized. Adoption outcomes vary with agroecological zones, input accessibility, and socio-economic contexts. Moreover, trade-offs such as increased herbicide use or disproportionate labour burdens must be carefully managed to prevent unintended consequences, particularly for smallholder and marginalized groups.

Need for a Balance Between Technical, Economic, and Social Evaluation

Many CA assessments to date have focused on yield gains or soil metrics in isolation. However, a truly sustainable approach demands holistic evaluation, integrating agronomic performance with input use efficiency, economic feasibility, and social inclusivity. Multicriteria decision analysis (MCDA) tools offer a promising pathway to this integration, provided they are embedded within participatory frameworks that reflect diverse stakeholder priorities and lived realities.

V. Conclusion

For CA to fulfill its promise, we must move beyond one-size-fits-all solutions toward adaptive models that value local complexity, equity, and innovation. Embedding multicriteria assessment within agricultural planning not only sharpens analytical rigor but also promotes co-designed solutions that are more likely to endure. The future of CA lies in systems that reward sustainability and fairness in equal measure, where farmers, especially those historically excluded, are empowered as co-creators of resilient agricultural futures

VI. Recommendations for Future Research

There is an urgent need for regionally grounded, longitudinal studies that examine CA impacts across multiple scales from plot to landscape and dimensions. In the Global South, future research should:

- Emphasize gender-disaggregated and socio-economically inclusive data;
- Innovate context-sensitive MCDA models that integrate local knowledge;
- Explore institutional mechanisms that enable equitable access to CA tools and training.
- Investigate climate-resilience outcomes, particularly under shifting rainfall and temperature regimes.
- These efforts will support more just and adaptive CA scaling strategies in regions most vulnerable to climate and resource stress

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