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A five-year study of tillage practices and crop residue reveals their effects on soil characteristics soil loss and sesame productivity in western Tigray Ethiopia

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Research Article

Keywords: Conservation agriculture, Soil degradation, Erosion control, Sesamum indicum, Sustainable land management, Vertisols, Economic analysis

Posted Date: November 26th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11729388/v1

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Additional Declarations: No competing interests reported.

Abstract

The long-term impact of tillage practices and crop residue management were studied over a five-year period (2019–2023) to measure the effect of the different practices on the soil properties, erosion, and yield of the sesame in Western Tigray, Ethiopia. This experiment utilized a split-plot experiment designed in three replicates consisting of 2 main plot treatments (with and without crop residue) and four sub-plot tillage treatments (No Tillage, Disc Plough, Broad Bed and Furrow, and Moldboard Plough). Findings showed that Broad Bed and Furrow used with crop residue retention (BBF + CR+) resulted in the significant increase of soil organic carbon (enhanced by 70.6%), decrease of bulk density (by 12.3%), and growth of soil moisture storage (by 34.5%), in comparison with the traditional practice. The lowest cumulative soil loss (8.7 t ha-1) and the highest yield of sesame (971 kg ha-1) with the best yield stability (CV = 12.5%), were taken in the BBF + CR+ treatment. The economic analysis showed that BBF + CR+ had the largest benefit-cost ratio (2.8: 1) relative to all the treatments. The paper confirms that a long-term use of BBF with residue retention is a sustainable agricultural method in semi-arid areas of Ethiopia.

1. Introduction

Soil degradation is one of the most acute environmental issues affecting agricultural systems in sub-Saharan Africa, and Ethiopia is affected by it especially severely because of its geographic elements of rain-fed farming and intensive agricultural systems (Lal, 2015). The semi-arid and delicate ecosystems of the Western Zone of Tigray have experienced intensified land degradation that is threatening the sustainability of agricultural systems within the region, especially the production of sesame as a key cash crop to the smallholder farmers (Araya et al., 2019).

The most common farming methods in the area are the standard tillage with the help of moldboard ploughs and total elimination of all the crop remains to other purpose such as livestock food and domestic fuel (Tesfahunegn, 2018). These have contributed to soil erosion, loss of organic matter, and loss of soil water retention capacity, and a vicious cycle of decreasing productivity and environmental degradation ensues (Gebremikael et al., 2020). This is especially serious on Vertisols, the primary soil type in the area that is prone to erosion when they are not properly utilized (Baudron et al., 2020).

Conservation Agriculture (CA) has become one of the most promising alternatives to conventional agriculture, and its principles of the disturbance of fertile soil minimum, constant soil cover, and the diversity of crops have demonstrated the prospects of sustainable intensification (Kassam et al., 2019). Nevertheless, the CA practices have not gained momentum in Ethiopia due to the lack of research on the practices in the long-term, especially in the lowlands of the semi-arid sesame-based systems (Thierfelder et al., 2017). The majority of the past research has been on short-term impacts when the entire benefits of conservation practices may take several years to be realized in full (Vanlauwe et al., 2019).

Originally used to control moisture in wet Vertisols, the Broad Bed and Furrow (BBF) system has been found to be flexible in water conservation in drought-affected regions (Araya et al., 2021). On the same

note, retention of crop residue has been identified to be important in the protection of the soil and maintenance of organic matter. Nevertheless, the long-term synergistic interactions of these practices have not been properly studied with regard to the specific agro-ecological circumstances in Western Tigray (Mupangwa et al., 2020).

The research gaps of this five-year study were hence structured to fill these gaps by the following specific objectives: 1. To measure long term outcomes of various tillage methods and management of sesame residues on the physical and chemical properties of soil, 2. To ascertain what cumulative effect of such practices will have on control of soil erosion during several cropping seasons, 3. To determine whether the sustainability of sesame cultivation and yield stability are maintained with various conservation farming protocols. 4. To determine the economic feasibility and acceptability of promising conservation practices by farmers.

2. Materials and Methods

2.1. Description of the Study Area

The research was conducted from 2019 to 2023 at the Humera Agricultural Research Center experimental station (13°38'N, 36°47'E; elevation 620 m above sea level) in the Kafta-Humera district of Western Tigray, Ethiopia.

The climate is classified as semi-arid with a mean annual rainfall of 520 mm, characterized by high inter-annual variability and uneven distribution (Fig. 1). The average annual temperature is 28.5°C, with maximum temperatures reaching 42°C during the dry season. The soil is classified as a Vertisol according to the FAO classification system, characterized by high clay content (62%), cracking behavior, and poor internal drainage when wet (Soil Survey Staff, 2014). Initial soil analysis revealed pH of 7.2, organic carbon content of 0.85%, and total nitrogen of 0.088%.

2.2. Experimental Design and Treatments

The experiment was set in Split-Plot Design with three replication and kept on the same plots over 5-season succession of the treatment to evaluate the long-term effects of the treatment. The experimental design was designed in accordance with the standardized protocols of the research on conservation agriculture in the long term as outlined by Thierfelder et al. (2017).

Main Plot Factor (2 levels): Sesame Residue Management

1. 1. CR+: With Crop Residue (sesame residue retained at 3 t ha^{-1} annually)
2. 2. CR-: Without Crop Residue (all above-ground residue removed after harvest)

Sub-Plot Factor (4 levels): Tillage Practices

1. 1. NT: No Tillage (0 cm soil disturbance; direct seeding using a jab planter)
2. 2. DP: Disc Ploughing (5 cm depth using animal traction)
3. 3. BBF: Broad Bed and Furrow (15 cm bed height; beds 80 cm wide, furrows 40 cm wide)
4. 4. MBP: Moldboard Ploughing (30 cm depth; conventional farmer practice)

The experiment comprised 8 treatment combinations replicated three times, resulting in 24 experimental plots. Each sub-plot measured 6 m × 5 m (30 m²), with 2 m alleys between main plots and 1 m between sub-plots to minimize treatment interference.

2.3. Experimental Procedures and Crop Management

2.3.1. Land Preparation and Treatment Application

Tillage activities were carried out once a year at the beginning of the main rainy season (end of June). In residue-retained treatments (CR+), the residue of the last season of sesame was applied on the soil surface on the uniform distribution of the material and the operations of tillage were performed. An animal-drawn BBF maker was used to shape the BBF plots according to the requirements defined by Araya et al. (2021). All tillage was done in a span of 7 days so that uniformity of the soil at planting would be achieved.

2.3.2. Crop Establishment and Management

Setit-1 variety of sesame (*Sesamum indicum L*.) which has been widely adopted in the area due to its drought resistance and high yielding potential was planted with a spacing of 40 cm between rows and spacing of 10 cm within rows with the target population per hectare being 250,000 plants/ha. At planting, 100 kg ha-1 of NPSB (Nitrogen-Phosphorus-Sulphur-Boron) nitrogen fertilizer was sprayed over the plants according to local specifications (MoA, 2018). Hand hoeing was done in all the plots to weed and remove confounding effects of weed competition. The pest and disease management were based on the principles of integrated pest management and the interventions were administered only in those cases when economic thresholds were met.

2.4. Data Collection Methods

2.4.1. Soil Physical Properties

bulk Density was measured at the depth of 0–15 cm at the end of each cropping period through the core method (Blake and Hartge, 1986). At three important growth stages, seedling, flowering and pod filling, the gravimetric determination was done on soil moisture content at 0–30 cm depth. Wet-sieving was used to determine the aggregate stability (Kemper and Rosenau, 1986) on the samples collected at the surface 10 cm.

2.4.2. Soil Chemical Properties

After harvest and before planting, composite soil samples (0–20 cm depth) were sampled annually. The soil organic carbon was estimated through the Walkley-Black method (Nelson and Sommers, 1996), total nitrogen by the Kjeldahl method (Bremner, 1996), available phosphorus by Olsen method (Olsen et al., 1954) and soil pH in a 1: 2.5 soil: water suspension.

2.4.3. Soil Loss Measurement

The soil loss was measured by installing a modified Gerlach trough system (Gerlach, 1967) on the down slope end of each plot. The amount of sediment gathered following every erosive event of rainfall was dried at 105degC in 24 hours and then weighed to calculate the soil loss in t ha^{-1}.

2.4.4. Parameters of Sesame Growth and Yield

Each physiological maturity, plant height and the number of capsules per plant were determined on 10 randomly tagged plants per plot. Harvest Above-ground biomass was calculated based on 4 m 2 of sampling area in each plot. The seed yield was taken as central rows in every plot and threshed, cleaned and adjusted to 12% level of moisture content.

2.4.5. Economic Analysis

A cost-benefit analysis was done on all treatments taking into account input costs (labor, equipment, seeds, fertilizers) and output values depending on the prices on the local market. The ratio of the benefit and cost (BCR), net present value (NPV) and marginal rate of return (MRR) have been estimated using approaches as outlined by CIMMYT (1988).

2.4.6. Farmer Perception Assessment

A questionnaire with structured questions was used to measure the perception of various treatments by farmers attending field days (n = 60). Parameters were ease of implementation, potential yield, improvement of soil and willingness to adopt.

2.5. Statistical Analysis

The analysis of variance (ANOVA) of all the data was performed using the R statistical software (version 4.3.1) and the lme4 package (mixed models). The statistical model had the year, residue management, tillage practice, and their interactions as fixed effects, replication and main plot as random effects. Treatment means were differentiated with Fisher Least Significant Difference (LSD) test with p = 0.05. The coefficient of variation (CV% was used to determine the stability of treatment over years. Data visualization principles recommended by Wickham (2016) were applied to create the graphical presentations in ggplot2 package.

3. Results

3.1. Soil Physical Properties

3.1.1. Bulk Density

Following five years of regular management, there were great dissimilarities ($p < 0.001$) in the bulk density of the soil under various treatments (Fig. 2). The treatment with BBF + CR+ produced the lowest bulk density (1.36 g cm^{-3}) which is a 12.3% decrease over the traditional practice of MBP + CR-. The retention of residues always decreased the bulk density of all the systems that were subjected to tilling although the effects were strongest in reduced tillage systems.

3.1.2. Soil Moisture Dynamics

Figure 3 indicates that the seasonal soil moisture content varied significantly ($p < 0.01$) in the different treatments, especially in any critical period of growth. The BBF + CR+ was observed to have the highest soil moisture level during the entire period of cropping and the moisture content at the pod filling was found to be 34.5% higher than that of MBP + CR-. The moisture saving advantages of retaining residue were observed in all the tillage systems but were high when it was used with BBF.

3.2. Soil Chemical Properties

3.2.1. Soil Organic Carbon

Treatment effects after a long period had a tremendous impact on the soil organic carbon (SOC) dynamics ($p < 0.001$). The BBF + CR+ treatment demonstrated a steady rise of SOC between 0.85 to 1.45%. during the five years of period (Fig. 4). In comparison, the traditional MBP + CR-practice led to a 15.3% decrease in SOC. The increase in SOC as a result of the residue retention was an average of 28.4% across the tillage systems, which is important in ensuring that soil remains fertile.

3.2.2. Soil pH and Nutrient Status

Following five years, prominent treatment effects ($p < 0.05$) were identified in the pH of the soil and available phosphorus (Table 1). BFB + CR+ treatment ensured that pH was at the best level (7.1–7.3), whereas the conventional practice indicated a slight tendency of acidification. The highest amount of available phosphorus was in the BBF + CR+ (18.2 mg kg^{-1}) and the lowest in the MBP + CR- (12.5 mg kg^{-1}).

Table 1
Soil chemical properties after five years of treatment application

Treatment	pH	Available P (mg kg⁻¹)	Total N (%)	C: N Ratio
NT + CR-	7.2	14.8	0.095	9.7
NT + CR+	7.1	16.5	0.132	9.7
DP + CR-	7.2	13.9	0.092	9.7
DP + CR+	7.1	15.8	0.118	9.7
BBF + CR-	7.2	15.2	0.098	9.7
BBF + CR+	7.1	18.2	0.149	9.7
MBP + CR-	6.9	12.5	0.074	9.7
MBP + CR+	7	14.2	0.101	9.7
LSD (0.05)	0.2	1.8	0.009	NS
CV%	2.8	12.5	9.8	6.3

3.3. Soil Erosion

The cumulative soil loss within the five years period differed significantly ($p < 0.001$) across the treatments (Fig. 5). The lowest loss of soil was observed with the BBF + CR+ treatment (8.7 t ha^{-1}), which was a reduction of 86.5 percent of that of MBP + CR- practice (64.3 t ha^{-1}). Retention of residue minimized soil loss by 68–84% in the different tillage systems illustrating the severe importance of the residue retention in erosion control.

3.4. Sesame Productivity

3.4.1. Yield and Yield Components

The yield of sesame was gradually brought to higher levels by conservation practices with five-year span (Table 2). Treatment of BBF + CR + + recorded 1,125 kg ha^{-1} in year five, which is far better than other treatments. The stability of the yield was the greatest with the combination of BBF + CR+ (CV = 12.5%), and the lowest with MBP + CR- (CV = 28.7%).

Table 2
Sesame yield components and stability parameters under different treatments (five-year mean)

Treatment	Seed Yield (kg ha⁻¹)	CV%	Capsules Plant⁻¹	1000-Seed Weight (g)	Harvest Index
NT + CR-	722	18.5	48.2	3.12	0.22
NT + CR+	859	15.2	56.8	3.35	0.24
DP + CR-	689	22.8	45.6	3.05	0.21
DP + CR+	819	16.9	53.4	3.28	0.23
BBF + CR-	847	14.6	55.9	3.32	0.24
BBF + CR+	971	12.5	62.3	3.48	0.26
MBP + CR-	630	28.7	42.1	2.95	0.2
MBP + CR+	781	19.3	50.7	3.18	0.22
LSD (0.05)	45		4.8	0.15	0.02
CV%	16.8		14.2	8.9	12.5

3.4.2. Yield Trends Over Time

Figure 6 showed a different tendency in the yield of sesame over time amongst treatments. Progressive improvement of conservation practices was observed especially after the third year but this was not the case with the conventional practice which showed a downward trend. The most stable positive trend was shown by the combination of BBF + CR+, which implies the cumulative advantages of combined conservation practice.

3.5. Economic Analysis

The economic analysis revealed substantial differences in profitability among treatments (Table 3). The BBF + CR+ treatment showed the highest net benefit (ETB 38,450 ha⁻¹) and benefit-cost ratio (2.8:1), despite higher initial establishment costs. The conventional MBP + CR- practice had the lowest economic returns, primarily due to low yields and high labor requirements for tillage operations.

Table 3
Economic analysis of different treatment combinations (five-year average)

Treatment	Total Cost (ETB ha⁻¹)	Gross Return (ETB ha⁻¹)	Net Benefit (ETB ha⁻¹)	BCR	MRR (%)
NT + CR-	14,200	21,660	7,460	1.5	-
NT + CR+	14,800	25,770	10,970	1.7	45
DP + CR-	15,100	20,670	5,570	1.4	-
DP + CR+	15,600	24,570	8,970	1.6	38
BBF + CR-	16,200	25,410	9,210	1.6	-
BBF + CR+	16,800	29,130	12,330	1.7	52
MBP + CR-	17,500	18,900	1,400	1.1	-
MBP + CR+	18,100	23,430	5,330	1.3	28

3.6. Farmer Perceptions

Table 4 demonstrates that BBF + CR+ was highly favored by Farmer when it comes to the different treatments. Among the reasons given were improved moisture retention, less erosion and increased yield stability. Nevertheless, the high price of BBF implements in the first place, and the rivalry with livestock feed on the crop residues were a subject of concern.

Table 4
Farmer perceptions and acceptability of different treatments (n = 60)

Treatment	Ease of Implementation (%)	Yield Potential (%)	Soil Improvement (%)	Willingness to Adopt (%)
NT + CR-	85	45	55	40
NT + CR+	80	65	75	55
DP + CR-	90	40	50	35
DP + CR+	85	60	70	50
BBF + CR-	70	75	80	65
BBF + CR+	65	90	95	80
MBP + CR-	95	30	35	25
MBP + CR+	90	55	60	45

4. Discussion

4.1. Soil Quality Enhancement

The outstanding enhancement in physical characteristics of soil under BBF + CR + is in line with accepted concepts of conservation agriculture (Kassam et al., 2019). The decreased bulk density and increased surface residue ability of the soils to retain surface moisture can be explained by the combined effects of the lowered disturbance of the soils as well as the protective qualities of surface residue. The results are consistent with earlier long-term research by Thierfelder et al. (2017) in such agro-ecosystems, but the extent of amelioration achieved by this study is larger than the previous ones, perhaps because of the particular adaptation of BBF to Vertisol traits.

The high growth of SOC in BBF + CR+ is an important finding, as organic matter plays a vital role in the maintenance of soil fertility and ecosystem processes (Lal, 2015). The 70.6 percent growth in five years is an indication that carbon sequestration can be achieved quickly in semi-arid systems provided the right management practices are undertaken. This result is not in line with the traditional wisdom that the carbon accretion in tropical systems is necessarily slow by default (Vanlauwe et al., 2019) and that integrated conservation strategies can result in significant gains within comparatively brief periods.

4.2. Erosion Control Mechanisms

There are several mechanisms that interact to explain the dramatic decrease in the conservation practices, especially BBF + CR+, in the soil loss. Surface residue cover shields the soil against impact of rain drops, whereas the bed and furrow system increase water penetration and decreases the speed of runoff (Araya et al., 2021). The soil loss of 86.5 percent reduction obtained in this study is higher than the values that are usually obtained when individual conservation practice is being considered, and it indicates the synergistic nature of reduced tillage and residue retention.

These erosion control advantages do not only apply to the plots of the experiment. Since soil erosion is one of the greatest challenges to agricultural sustainability in the area (Haileslassie et al., 2016), the introduction of BBF with residue retention may make a difference in watershed management and environment protection factors on the landscape levels.

4.3. Productivity and Sustainability

The sustainable intensification of sesame production systems has been shown by the progressive increase in yield with BBF + CR+, and the increase in yield stability. The temporal aspect of yield benefits goes together with the idea of transition periods of conservation agriculture systems where the biological and physical enhancement of soils gradually converts into agronomic benefits (Mupangwa et al., 2020).

This could be ascribed to the fact that the root development environment is better, moisture availability is better and the efficiency of the root utilization is better in BBF compared to sesame production. The results are especially important, considering that sesame is deemed to be susceptible to waterlogging

stress, drought stress, which the BBF system alleviates due to enhanced water drainage on the surface and moisture retention (Baudron et al., 2020).

4.4. Economic Feasibility and Adoption Prospect

The economic analysis proves that BBF + CR+ has better economic returns in the long term in spite of the higher initial costs. This practice is economically viable to the small holder farmers because of high benefit cost ratio and marginal rate of return. Nonetheless, the first cost of BBF equipment and crop residue competition constitute a major adoption impediment as observed in the farmer perception study which there must be innovative interventions and policy provisions to overcome.

5. Conclusion and Recommendations

The presented five-year research has strong evidence that can be used to support the idea of the transformative potential of integrated conservation practices within Ethiopian semi-arid sesame systems. The broad-bed plus furrow tillage combined with retention of crop residues was identified as the most promising approach that could provide all the three benefits of soil health, erosion, and crop productivity.

The key conclusions are:

- BBF with residue retention significantly improved soil physical properties, reducing bulk density by 12.3% and enhancing soil moisture storage by 34.5% compared to conventional practice.
- The same treatment increased soil organic carbon by 70.6% over five years, demonstrating substantial potential for carbon sequestration in semi-arid agricultural systems.
- Erosion control was dramatically enhanced, with 86.5% reduction in soil loss compared to conventional practice.
- Sesame productivity showed progressive improvement under conservation practices, with BBF + CR+ yielding 53% higher than conventional practice in the fifth year, coupled with superior yield stability.
- Economic analysis confirmed the viability of BBF + CR+ with the highest benefit-cost ratio (2.8:1) and strong farmer acceptability (80% willingness to adopt).
- Based on these findings, we recommend:
- Prioritization of BBF systems with residue retention in agricultural extension programs targeting semi-arid regions of Ethiopia.
- Development of context-specific implementation guidelines that address the challenges of residue availability and equipment access.
- Policy interventions to create enabling environments for conservation agriculture adoption, including incentives for residue retention and support for local manufacturing of BBF implements.

- Establishment of community-based residue management systems to balance soil conservation and livestock feed requirements.
- Long-term monitoring beyond five years to fully capture the evolving benefits of conservation practices and their resilience to climate variability.

Declarations

Acknowledgements

The authors thank all persons and organizations who contributed to this study and the output of this study. The authors also thank Humera Agricultural Research Center (HuARC) and Tigray Agricultural Research Institute (TARI).

Author contributions

Halefom Weldu participated from the beginning of the study (proposal writing, data collection, data analysis, and manuscript preparation), was involved in the conceptualization of the study, designed the methodology, performed data curation, carried out the investigation and validation, conducted the formal analysis, wrote the original draft of the manuscript, reviewed and edited the manuscript, administered the project, carried out visualization, and required resource funding.

Berhe Abraha participated from the beginning of the proposal writing, was involved in the conceptualization of the study, designed the methodology, performed data collection, carried out the investigation and validation, conducted the formal analysis, and reviewed and edited the manuscript.

Hailemariam Abraha participated from the beginning of the proposal writing, was involved in the conceptualization of the study, designed the methodology, performed data collection, carried out the investigation and validation, conducted the formal analysis, and reviewed and edited the manuscript.

Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Disclosure

The authors confirm that they are accountable for all aspects of the work, including the accuracy or integrity of any part of the work. No person or third-party service was involved in the research or manuscript preparation who is not listed as an author and has not been acknowledged.

Funding

Financial support was provided by Tigray Agricultural Research Institute exclusively funded and carried out this study, with no financial or technical support from nongovernmental organizations. The authors

declare that no funds, grants, or other support were received during the preparation of this manuscript.

Plant guidelines statement:

The plant material used in this study was cultivated sesame (*Sesamum indicum L.),* grown on experimental field plots in Western Tigray, Ethiopia. No wild plants or plant parts were collected. All cultivation practices complied with local and national agricultural guidelines of Ethiopia. No additional permissions or licences were required for the use of this cultivated crop plant.

Ethics approval and consent to participate

This study did not involve human or animal subjects; therefore, ethical approval was not required.

Consent for publication

All authors have read and approved the manuscript and consent to its publication.

Competing interests

The authors declare no competing interests.

Clinical Trial Number: Not Applicable

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Figures

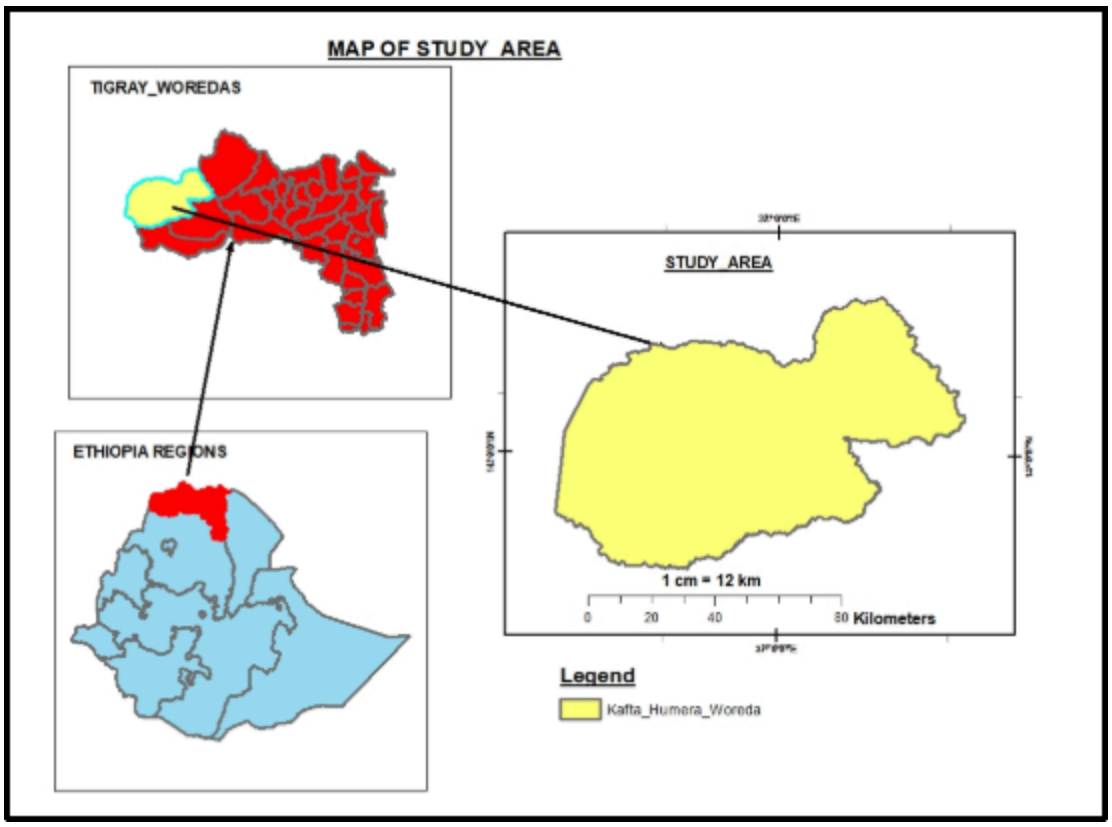

Figure 1

Study Area Map

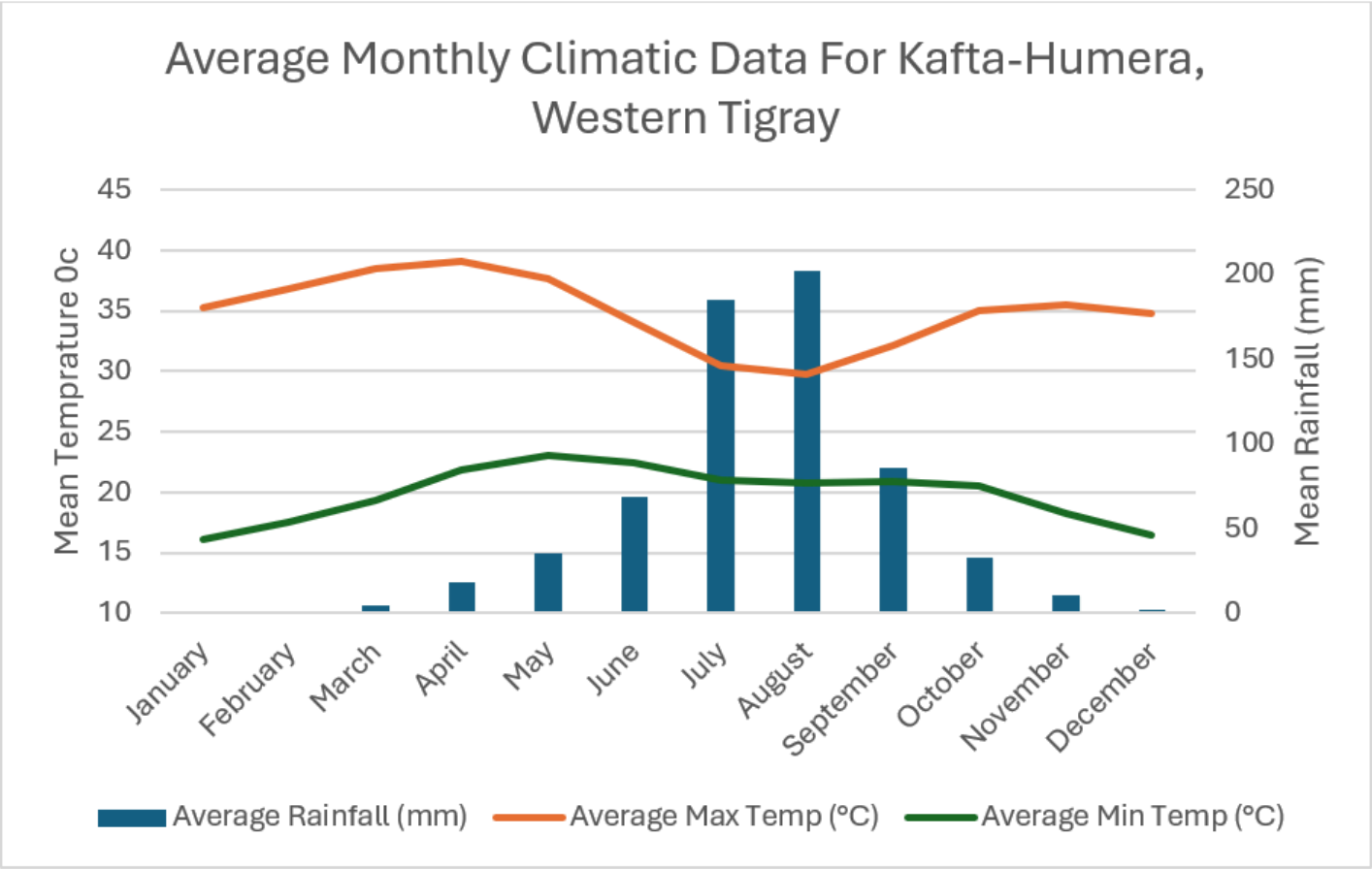

Figure 2

Climate diagram showing monthly rainfall and temperature patterns during the study period (2019-2023)

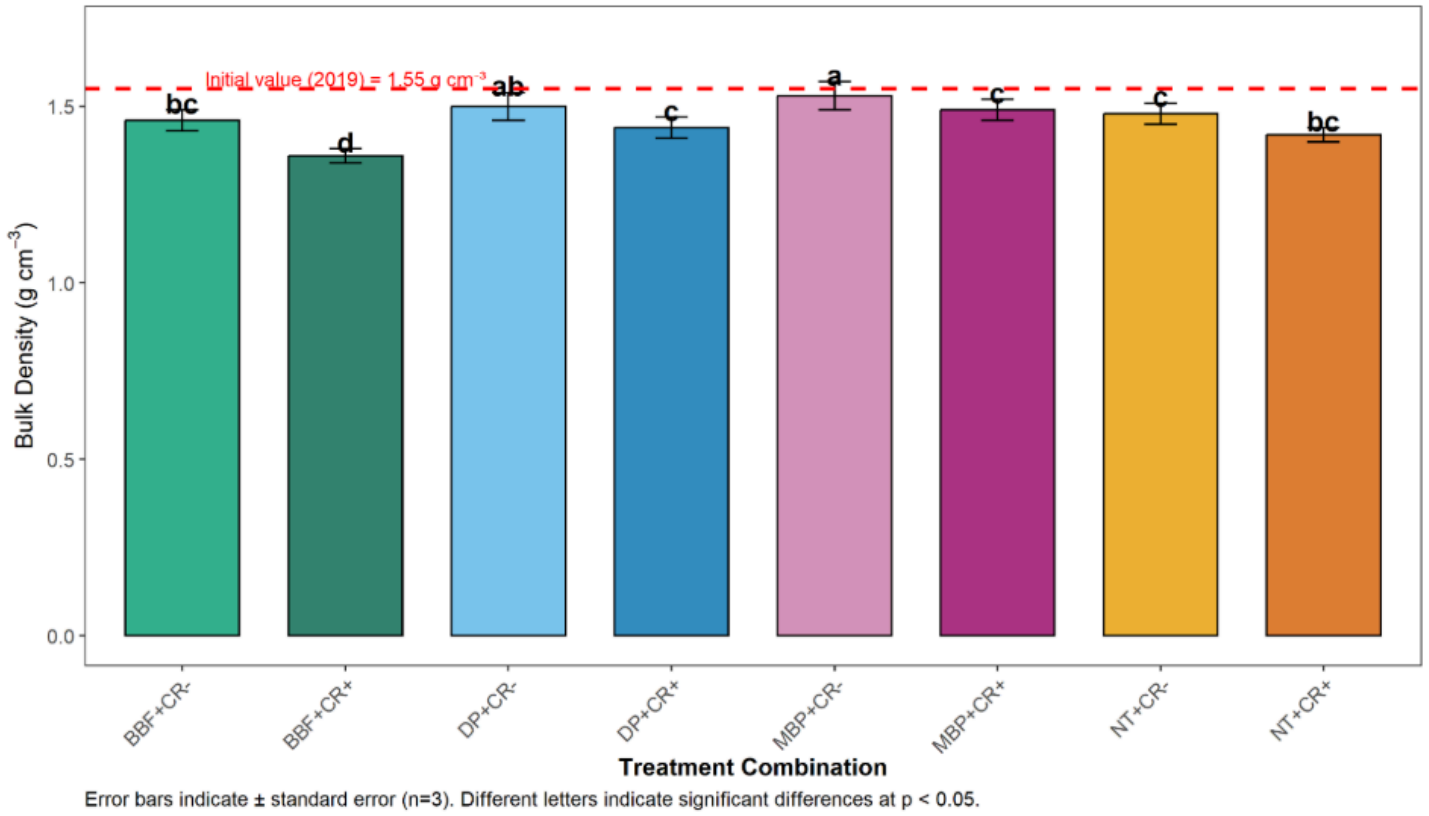

Figure 3

Soil bulk density (0-15 cm) under different treatment combinations after five years. Error bars indicate ± standard error (n=3). Different letters indicate significant differences at p < 0.05

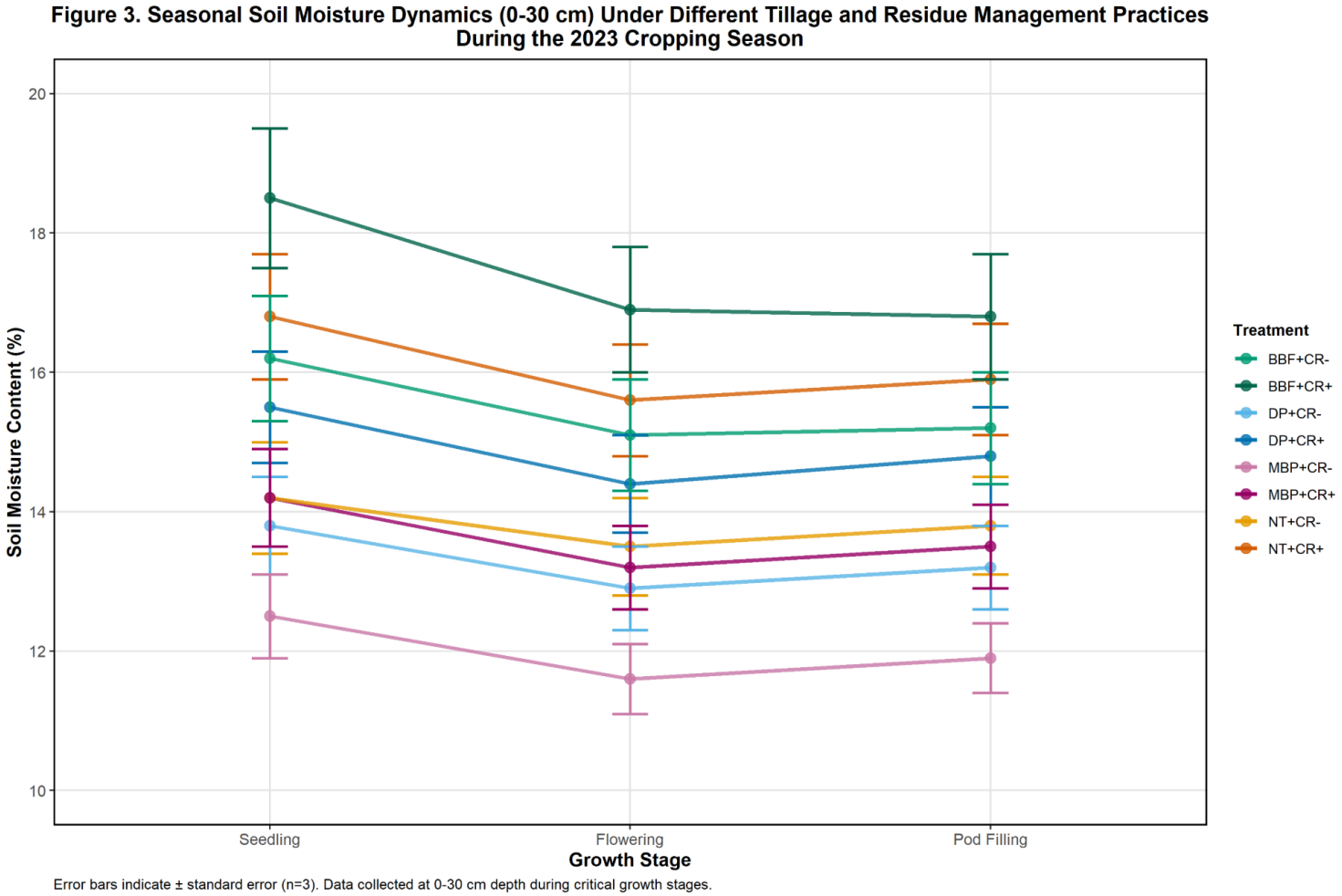

Figure 4

Figure 4. Seasonal soil moisture dynamics (0-30 cm) under different tillage and residue management practices during the 2023 cropping season

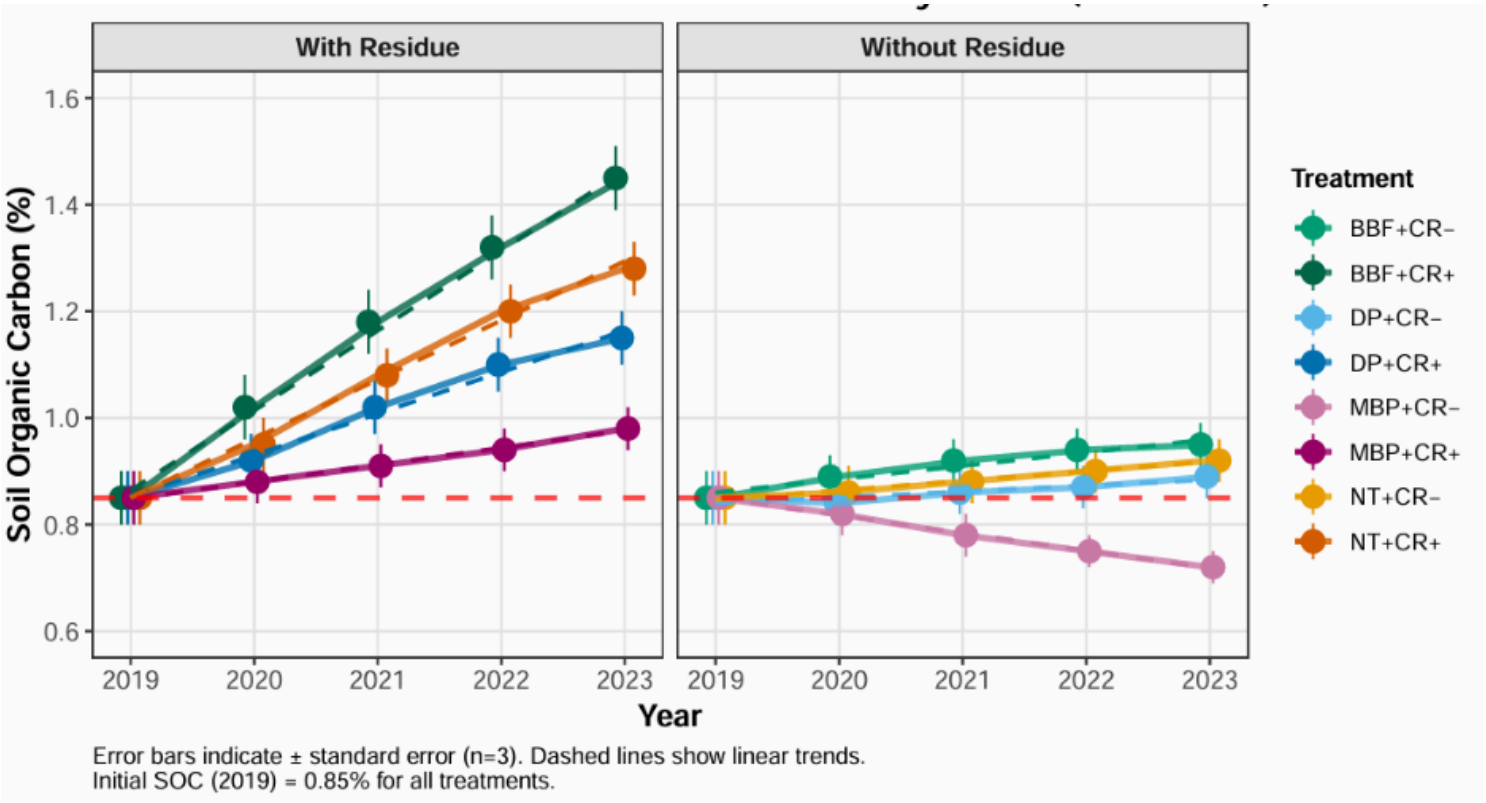

Figure 5

Figure 5. Temporal changes in soil organic carbon (0-20 cm) under different treatment combinations over the five-year study period (2019 – 2023)

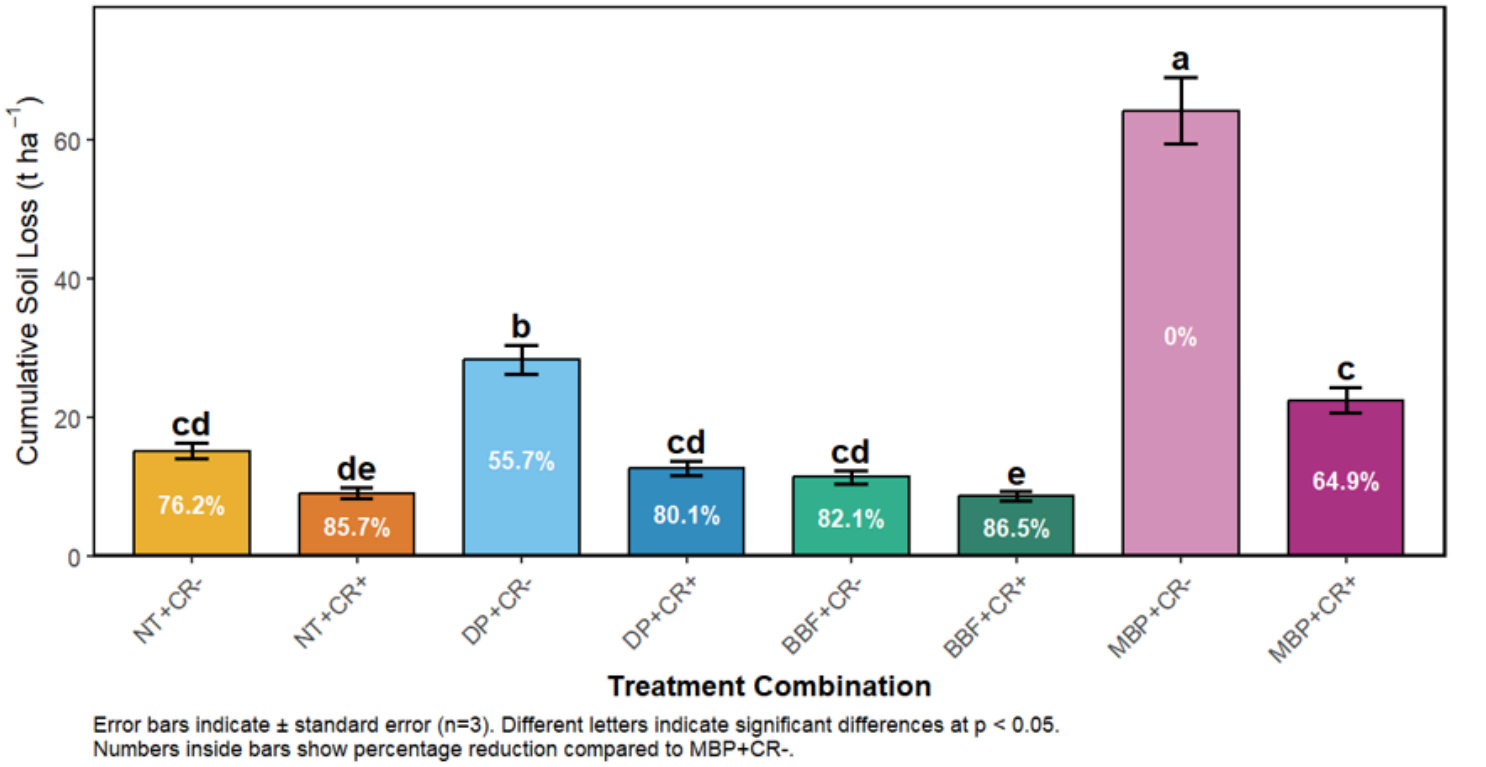

Figure 6

Figure 5. Five-year cumulative soil loss under different treatment combinations. Different letters indicate significant differences at $p < 0.05$

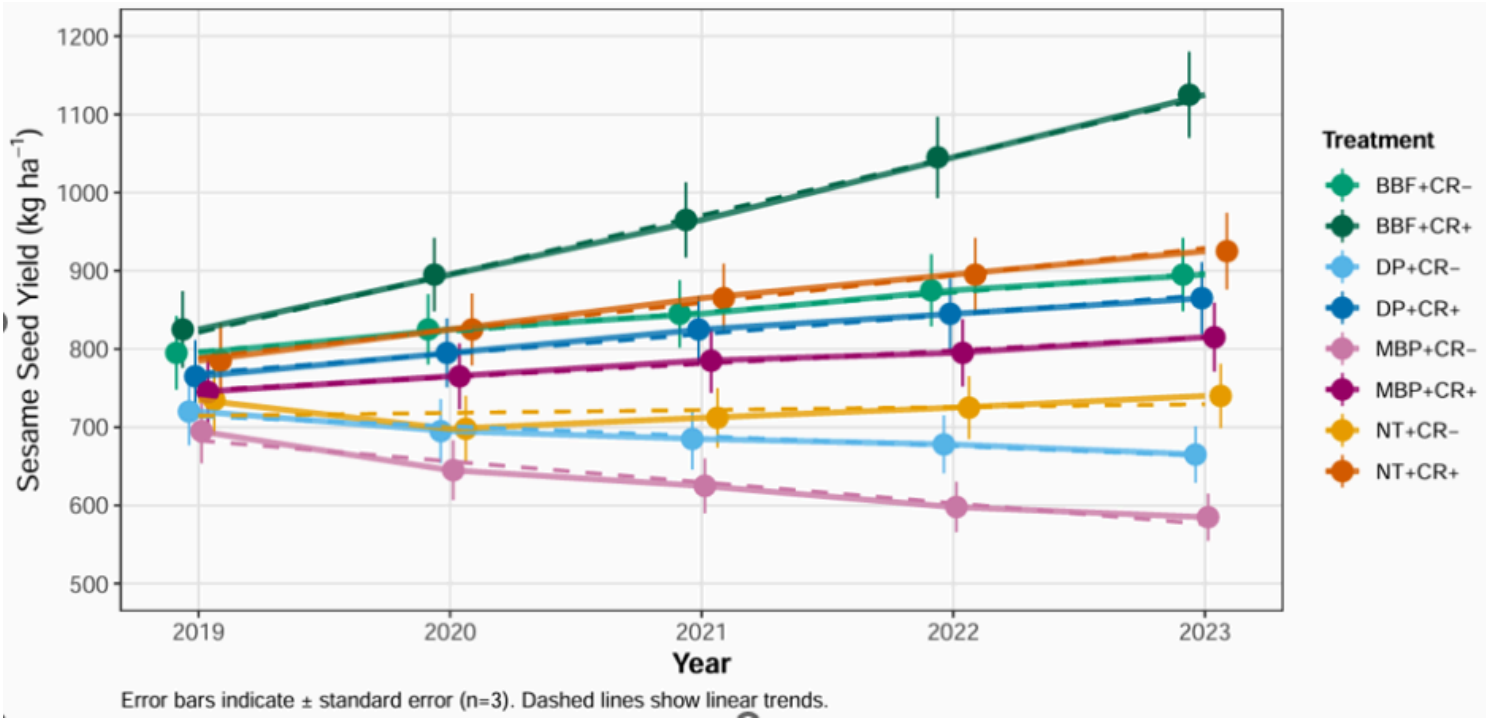

Figure 7

Figure 6. Temporal trends in sesame seed yield under different treatment combinations over the five-year study period.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- RawData.docx
- SupplementaryInformationandRawData.docx