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Original Paper

Comparative Evaluation of the Effects of Conservation Agriculture Integrated with Various Land Management Practices on Vertisol Productivity in Highlands of Ethiopia

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***Abstract*— Vertisols are dark-colored clays that develop cracks when it expands and contracts with changes in moisture content. Tillage techniques and frequency have an impact on crop harvesting, drainage, soil erosion, moisture conservation, and weeding in Ethiopia's highlands. Five tillage methods, namely, broad bed and furrows (BBF), permanently raised bed with no-tillage (PRB+NT), permanently raised bed with no-tillage, and 30% stubble retention (PRB+NT+M), flatbed with no-tillage (Flat+NT), and flatbed with no-tillage and 30% stubble retention (Flat+NT+M), were evaluated for their effects on the productivity of vertisol. This study was conducted in Moretna Jiru wereda, Enewari, for seven years (2015 to 2022) in the central highlands of Ethiopia. In this study, soil indicators such as moisture content, bulk density, organic carbon, pH, available phosphorus, extractable potassium, electrical conductivity, and total nitrogen, as well as productivity indicators such as plant height, grain yield, and straw yield, were measured. The results indicated that Flat+NT+M and Flat+NT significantly increased wheat grain yield by 13.4% and 11.2%, respectively compared with BBF, for the experimental years 2015/16 and 2017/18. In the experimental years 2019/20 and 2021/22, the wheat yield was greater under BBF than conservation agriculture practices. Compared with conservation agriculture practices, BBF resulted in the highest grain yield of faba bean. The soil property data imply that PRB+NT+M, Flat+NT, and Flat+NT+M improved the total nitrogen, soil pH, organic carbon, moisture holding capacity, and extractable potassium. Economically, Flat+NT was the most profitable practice, with an 1147.6% marginal rate of return (MRR). Based on the results, Flat+NT and Flat+NT+M are beneficial for wheat production during dry years, while BBF is beneficial for fababean production.**

Keywords*— *BBF, flatbed; no-tillage; permanently raised, stubble

I. INTRODUCTION

Vertisols are dark-colored clay soil that develops cracks when it expands and contracts with changes in moisture levels. Despite their high fertility, these soils pose challenges because of their shrink-swell behavior and inadequate drainage. These soils are widespread in Ethiopia, particularly in the central highlands, covering approximately 7.6 million hectares and ranking fourth in coverage [1]. In Ethiopia's highlands, waterlogging limits traditional agriculture due to heavy rainfall and low evaporation rates [2]. Challenges with Vertisols include excessive seedbed preparation, such as frequent plowing in muddy conditions, and grazing during wet periods. These practices reduce the growth period and crop yield, contribute to soil erosion, and degrade the soil's physical, chemical, and biological quality over time [3]. Increased tillage frequency resulted in the loss of soil organic matter due to the mixing of soil and crop residues, disruption of aggregates, and increased aeration [4]. Tillage activities also leave the soil vulnerable to erosion, compaction, and pan formation, which hinder hydrological conductivity and create perched water on the surface.

Proper Vertisol management is crucial for high productivity and soil health. In vertisol, conservation agriculture mitigates soil erosion, improves water infiltration, and promotes better root development for crops like wheat and Fababean [5]. Experience from Australia and India has shown that adopting conservation agriculture on vertisols significantly improves yields, ranging from 20% to 120% [6]. In India, broad bed and furrow systems have proven effective in reducing water runoff, soil loss, and enhancing crop yields [7]. Similarly, studies conducted in Austria have demonstrated that practices like minimum cultivation and residue retention can contribute to improved crop yields and sustainability [5]. However, further research is needed to fully understand the long-term impact of conservation agriculture on soil health and productivity in Vertisol [8],[9], [10], [11], [12], as well as soil microbiology and organic matter dynamics in Vertisol management [13].

Vertisol management technologies are expected to increase Ethiopian productivity and food security. One such technology is the broad bed and furrow surface drainage method. This method was developed at ICRISAT in India [14]. Traditional methods, like those used by Shuribie in North Shewa, have also shown promise. Studies have demonstrated that using the broad bed and furrow method improves crop yields on Vertisols compared to flat seedbeds [15], [16]. In the study area, there was a lack of understanding among local farmers and experts regarding the impact of tillage practices on soil physical-chemical properties, crop yield, and climate change mitigation. Despite the yield advantages, it is important to test and develop alternative methods based on existing technologies and global experiences. Therefore, this study aimed to evaluate the effectiveness of integrating conservation agriculture with different land management practices for improving the productivity of Vertisols and to introduce cost-effective and environmentally friendly land management methods for Vertisols.

II. Materials And Methods

A. Description of the study area

The study was conducted in Moretna Jiru Woreda, North Shewa, and Ethiopia. It is situated at 39°9.5'E longitude and 9°53'N latitude, 198 km northeast of the capital city of Addis Ababa as shown in (Figure 1). The altitude of the experimental site is 2664 meters. It has an unimodal rainfall distribution with a mean annual rainfall of 1142.1 mm, while the minimum and maximum temperatures are 9.43°C and 21.14°C, respectively. June, July, and August receive large portions of the annual rainfall. The study area is predominantly covered with heavy clay soil (pellic Vertisols) and is severely affected by waterlogging. The dominant land use is seasonal crops such as wheat (Triticum aestivum L.), tef (Eragrostis tef), lentil (Lens culinaris Medik), and faba bean (Vicia faba). Marginal lands along roadsides, gully bottoms, and floodplains are the primary grazing grounds.

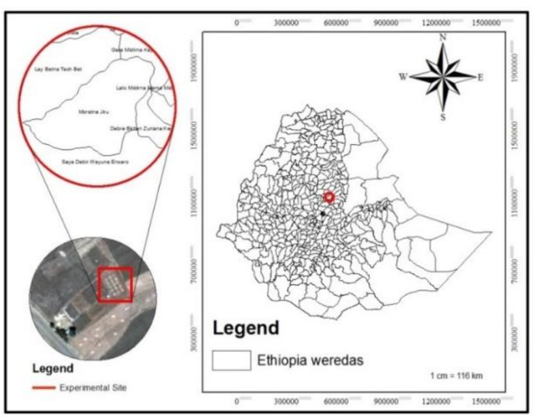

Fig. 1. Location map of the study area

B. Experimental Procedures and Treatment Description

The total area of the experimental site was 18 m by 30 m. The plot size was 4 m × 4.8 m, and the experimental arrangement was a randomized complete block design with three replications. Tillage plowing was performed with a handmade digging hoe. The first plowing started in mid-April, depending on the moisture availability for the BBF treatment. Seeds were sown by hand drilling with 20 cm spacing between rows for wheat. Faba bean seeds were sown with a spacing of 10 cm between plants and 40 cm between rows. The varieties of the test crops used were Menzie and Lalo for bread wheat and faba bean, respectively. The seed rate for the test crop was 131.25 kg/ha for wheat, and there was 10 cm spacing between plants for faba bean. The fertilizer rate used for this experiment was 275 kg/ha urea, 272.36 kg/ha NPS for wheat, and 121 kg/ha NPS fertilizer for faba bean.

The evaluated tillage practices were as follows:

1) Broad bed and Furrows (BBF)

This treatment was prepared using a wide bedmaker (BBM), an oxen-drawn wooden plow adapted for creating elevated beds and furrows. The design intends to improve surface drainage by using the furrows between the beds, enabling crops to flourish on the beds. Effective bed widths are 80 cm, and bed furrows are 40 cm. Broad beds and furrows served as the control treatment for this experiment because this technique was already implemented in the study region.

2) Permanently raised bed with no-tillage (PRB+NT)

These beds were prepared with a 1.2 m bed width and a 40 cm furrow. After the start of the experiment, the plots were left fallow until small pots were perforated for sowing. The seeds were drilled and covered in a single tillage operation using a local peg for both test crops. This practice aimed to minimize presowing soil disturbance, reduce the oxidation of soil organic matter, and maintain surface cover to decrease soil erosion. The treatments remained constant while two crops, wheat and faba bean, were rotated according to their traditional sequence. In this treatment, the bed and furrow were left undisturbed to facilitate the drainage of excess water from the field. All the cultural practices other than the treatments were implemented according to the recommendations for the respective crops.

3) Permanently raised bed with no-tillage and 30% stubble retention (PRB+NT+M)

This treatment was similar to a permanently raised bed with no-tillage (PRB+NT), except that 30% of the stubble was retained in the field. The stubble retention in this experiment was achieved by cutting the test crop at 30% of its height during harvesting. This practice aimed to reduce raindrop impacts and improve soil organic matter.

4) Flatbed with no-tillage (Flat + NT)

This treatment kept the field flat and untilled throughout the entire season. The test crops were grown by perforating small slots. The seeds were drilled and covered in a single tillage operation using a local peg for both test crops. This practice aimed to minimize presowing soil disturbance, reduce the oxidation of soil organic matter (SOM), and maintain surface cover to decrease soil erosion. All cultural practices, except for the treatments, were implemented under the recommendations for the respective crops. The flat land left untreated in this study was suggested to contribute to aggregate stability and biological tillage by creating favorable conditions for microorganisms.

5) Flatbed with no-tillage and 30% stubble retention (Flat+NT+M)

This treatment was similar to the flatbed with no tillage method, except that 30% of the stubble remained in the field at the time of harvesting. The stubble retention in this experiment was achieved by cutting the test crop at 30% of its height during harvesting. This practice aimed to reduce soil erosion and improve soil organic matter and soil nitrogen.

C. *Conceptual framework*

The conceptual framework (Figure 2), indicates the relationship between plant parameters (plant height, straw yield, and grain yield) and soil physio-chemical properties in response to various tillage practices (BBF, PRB+NT, PRB+NT+M, Flat+NT, and Flat+NT+M). This experiment was carried out for seven years, the plant parameter data were collected and measured for each experimental year. The soil samples were taken to analyze the response of soil physio-chemical properties to the tillage practices used. Crop rotation, fertilizer application, and weeding were implemented across all tillage practices, to minimize the influence of extraneous variables, the experiment was replicated three times.

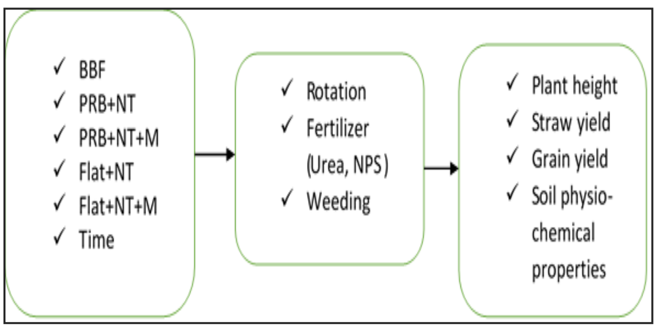

Fig. 2. Conceptual framework of the study

D. *Data collection and analysis*

The extent of ripening was rated on a scale of 1 – 5 as 1=mature green; 2=breaker (green, tarnish yellow, red colour not more than 10% surface area); 3=turning (orange to red colouration greater than 10% but not more than 30% aggregate surface area); 4=pink (orange to red colouration greater than 30% but not more than 60% surface area); 5= light red (red colouration greater than 60% but not more than 90% surface area); 6=red ripe (red colouration greater than 90% surface area) according to Anon et al [22]. Ripening rating was done for mature-green and breaker-stage fruits only.

III. RESULTS AND DISCUSSION

A. *Effect of conservation agriculture on the yield and yield components of wheat*

Flat+NT and Flat+NT+M gave greater wheat yield than BBF for the first two experimental years, 2015/16 and 2017/18 as shown in TABLE 1. During these experimental years, there was no rainfall in October and November, as shown in (Figure 3**)**. Compared with traditional farming practices, conservation agriculture helps conserve more soil moisture. Taking all specific practices into account, conservation agriculture significantly increased wheat crop yield by 4.37% to 13.4% compared to BBF. Statistical differences were observed in specific effect sizes among the conservation agriculture practices ($P < 0.05$). Flat +NT +M and Flat +NT treatments yielded significantly greater wheat grain yields. The yield advantages were 13.47% and 11.2% over those under BBF, respectively. This finding aligns with the study conducted by [20], which indicated that BBF led to a significant 35% decrease in wheat grain yield in certain regions of the Ethiopian highlands. Similar to our findings, conservation agricultural techniques in China, such as the preservation of straw, significantly increased crop productivity [5]. Similarly, the study conducted in India [21], showed wheat yield improvement by 7.2-27.1% due to the application of conservation agriculture practices. Similarly, the study by [22], found 19% of wheat yield improvement due to zero tillage practices. Another study by [23], [24] reported significantly greater wheat yields under straw retention than under conventional tillage, especially in dry years. In dry years, conservation agricultural techniques like minimal tillage and residue retention work better [5], these practices conserve available moisture and protect evaporation from the crop field.

However, the wheat yield for the next two experimental years, 2019/20 and 2021/22, was lower in Flat+NT and Flat+NT+M than in PRB+NT+M, PRB+NT, and BBF, as shown in TABLE 1. The rainfall in those cropping seasons was high compared to that in the previous experimental year, as shown in (Figure 3). There was no moisture deficiency up to the harvesting time. In this experimental year, BBF was more advantageous than conservation agriculture. According to Field observations, there was waterlogging in the Flat+NT+M and Flat+NT compared to the BBF, PRB+NT, and PRB+NT+M treatments. Taking all specific practices into account, conservation agriculture practices reduced wheat crop yield by 1.9% to 19.3% compared to BBF. These findings disagree with the study by [20], which reported that BBF significantly reduced the grain yield of wheat by 35% in certain regions of the Ethiopian highlands. Similarly, our Findings disagree with the findings of [22], 19% of wheat yield increased due to reduced tillage than conventional tillage.

B. *Effect of conservation agriculture on the yield and yield components of Faba beans*

BBF gave a higher faba bean grain yield compared with all other tested conservation agriculture methods, as shown in TABLE 2. Although the difference was not statistically significant ($p < 0.05$), the yield of faba bean was greater under BBF. The growth parameter (plant height) was high in BBF. During the three experimental years, the study area had an average of 372.2 mm of rainfall in July, 385.8 mm in August, 75.9 mm in September, and 29.1 mm of rainfall in October. This might influence the performance of faba beans in mulch treatments. Based on field observations in the experimental years, stubble retention has been found to excessively increase soil moisture, which may lead to lower yields. In line with our study, BBF has a 98% yield advantage over the flatbed tillage system [25]. In addition, stubble retention could depress crop growth by immobilizing nutrients in soil microbes and increasing residue-borne diseases. Straw retention improves soil moisture conditions by enhancing soil structure and reducing soil water evaporation, thus benefiting crop growth under dry conditions. However, Straw retention may reduce crop productivity in high-rainfall areas by causing waterlogging [26].

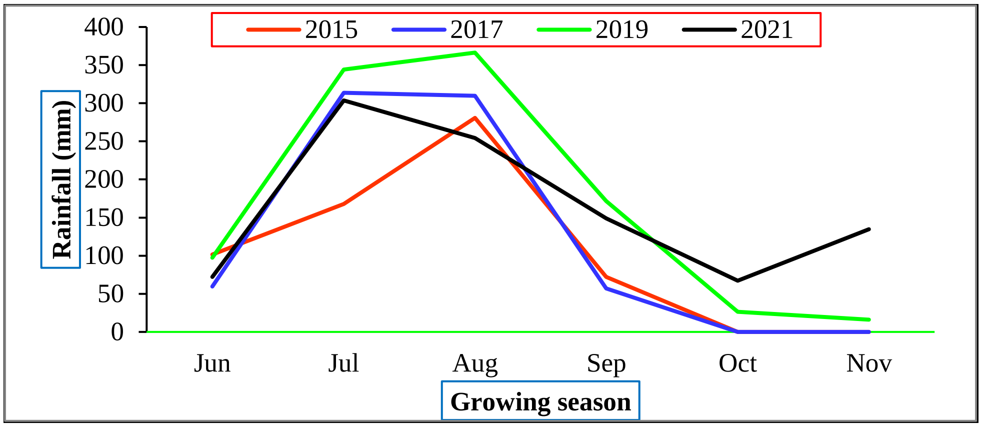

Fig. 3. The Distribution of Rainfall during the Growing Seasons of the Experiment

TABLE 1: EFFECTS OF CONSERVATION AGRICULTURE PRACTICES ON WHEAT YIELD

Treatments	**2015/16**		**2017/18**		**2019/20**		**2021/22**	
	GY	**ST**	**GY**	**ST**	**GY**	**ST**	**GY**	**ST**
BBF	5245.4ab	8000.9ab	4500b	7541.7	3743.1a	5861.1a	4566	5854.2a
PRB+NT	5007.8b	7518.7bc	5240a	8171.9	3519.5ab	4617.2c	4593.8	5480.5a
PRB+NT+M	5130.2b	7247.6c	5040.7ab	8341.2	3304.7bc	5317b	4566.4	4132.8b
Flat+NT	5420.1a	8344.5a	5416.7a	8891.7	3203.1bc	4250c	4479.2	6208.3a
Flat+NT+M	5520.8a	7985.6ab	5537.5a	9271.7	3020.8c	4732.1c	3849	3833.3b
Mean	5264.9	7819.5	5147.1	8443.6	3358.2	4955.5	4410.9	5101.8
CV	2.9	4.3	6.9	8.4	6	5.3	7.8	9.7
LSD (0.05)	286.9	627.8	664.9	ns	379.6	503.2	ns	927

GY: grain Yield and SY: straw yield

C. Effect of CA on selected soil physiochemical properties

1) Effect of conservation agriculture on selected soil chemical properties

As shown in TABLE 3, the soil available phosphorus was greater in the BBF treatment than in the PRB+NT, PRB+NT+M, Flat+NT, and Flat+NT+M treatments. The soil's available phosphorus content increased after crop harvest, possibly as a result of the residual effects of the fertilizer applied to the test crop. The increase in soil phosphorus (P) reported in this study after crop fertilization is consistent with earlier findings [27].

TABLE 2: EFFECTS OF CONSERVATION AGRICULTURE PRACTICES ON FABA BEAN YIELD

Treatment	**2016/17**			**2018/19**			**2020/21**		
	GY	**ST**	**PH**	**GY**	**ST**	**PH**	**GY**	**ST**	PH
BBF	3943.3	4063.7	101.8a	3158	2887.5	87a	2178.8a	1149.3	69.7a
PRB+NT	3541.7	3807.3	99.2a	2650.7	2427.7	77.8b	1505.2b	903.6	68.1a
PRB+NT+M	3828.1	4259.7	99.9a	2185.6	2915.8	76.5b	1466.1b	882.8	65.8a
Flat+NT	3507	3652.8	91.2b	2393.2	2447.9	72.9bc	1597.2b	1024.3	65.7a
Flat+NT+M	3763.9	4221.2	92.1b	1953.2	3192.7	69.7c	1927.1ab	871.5	57.2b
Mean	3716.8	4000.9	96.8	2468.1	2774.3	76.7	1734.9	966.3	65.3
CV (%)	4.6	7.5	3.04	18.6	14.1	4.59	15.8	16.7	5.1
LSD (0.05)	ns	ns	5.55	ns	ns	6.64	516.9	ns	6.3

GY: grain yield and SY: straw yield in Kg/ha and PH: plant height(cm)

The pH for all treatments ranged from 6.6 to 6.7. For most crops, the pH range of 6.0 to 6.8 is optimal as it aligns with the most important plant nutrients' optimal solubility. PRB+NT+M, Flat+NT, and Flat+NT+M resulted in a net increase of 0.64–1.27% in soil organic carbon content and organic matter compared with BBF. In line with our study [28], compared with conventional tillage, no-tillage with residue retention and reduced tillage with residue retention increased the soil organic carbon stock by 29% and 27%, respectively. Other studies in India have shown that conservation agriculture enhances soil properties such as organic carbon and microbial biomass carbon. Similarly [29], and [30] reported that compared with conventional tillage, zero tillage resulted in a net increase of 16–27% in soil carbon content. In addition, PRB+NT and PRB+NT+M improved the total nitrogen content by 0.64% and 3.18%, respectively compared with BBF. In this study, the electrical conductivity results were similar for all tillage treatments, indicating normal levels and the absence of salinity issues. Compared with BBF, the Flat+NT+M and Flat+NT treatments improved the exchangeable potassium Content by 5.6% and 26.1%, respectively. Similarly, other studies have revealed that the level of extractable potassium (K) increases at the soil surface with reduced tillage intensity and increased residue retention [31], [32]. The effect of conservation tillage on enhancing soil organic carbon (SOC) sequestration has been reported by several researchers [33]–[36]. There was a significant difference ($P < 0.001$) in the mean pH, total mineral N, and percentages of organic and microbial biomass C contents obtained after harvest [37].

2) Effect of conservation agriculture on soil moisture content

According to the soil sample analysis, the three-year moisture data indicate that, compared to BBF, the other tested conservation agriculture tillage practices improve soil moisture to some extent. As shown in (Figure 4), Flat+NT, Flat+NT+M, PRB+NT, and PRB+NT+M improved soil moisture by 3.4%, 6.9%, 3.4%, and 5.8%, respectively, compared to BBF. There was no shortage of rainfall during the cropping seasons for the moisture data collected. As a result, it was difficult to visually observe the impact of conservation agriculture tillage practices on crop yield due to the consistent moisture levels. This might be important during years of moisture deficit. In line with our results, other studies have shown that soil moisture content improves with increased use of crop residues as a soil cover [38].

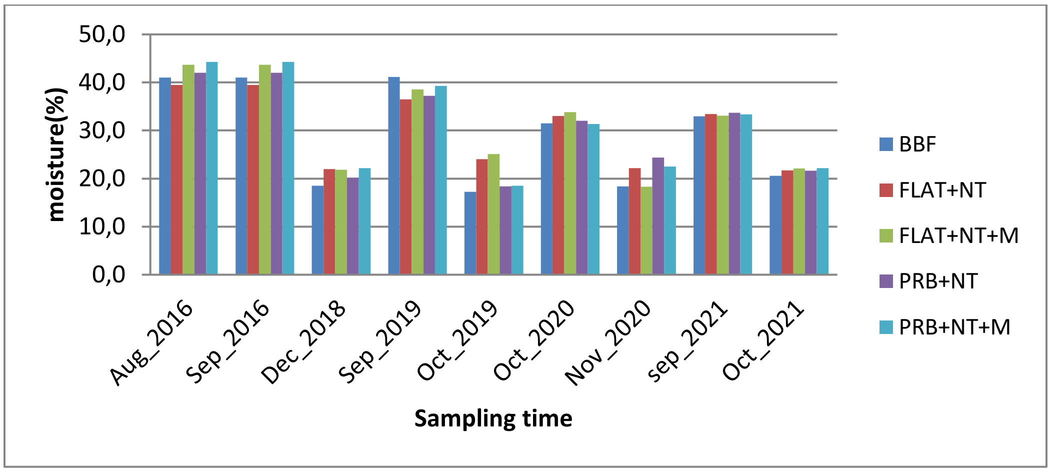

Fig. 4. Effect of Conservation Agriculture on Soil Moisture Content

3) Effect of Conservation Agriculture on Soil Bulk Density

As shown in (Figure 5**)**, the results of the bulk density analysis (g/cm^3) indicate that BBF could reduce surface compaction and bulk density to a small extent compared to conservation agriculture tillage treatments. This reduction may be attributed to the continued soil disturbance in BBF due to bed preparation; the soil excavated for furrow preparation was thrown onto the bed, which may have contributed to a decrease in surface soil bulk density. In line with our study, research by [39] indicated that the bulk density of surface soil (0-15 cm) in conservation agriculture is 2% to 3% greater than that in conventional tillage. Our findings disagree with studies conducted in China, which showed that no-tillage and subsoil tillage reduces soil bulk density by 0.8-1.5% compared to conventional tillage [5]. A review by [40] noted that conservation tillage practices might have increased, decreased, or neutral effects on soil bulk density.

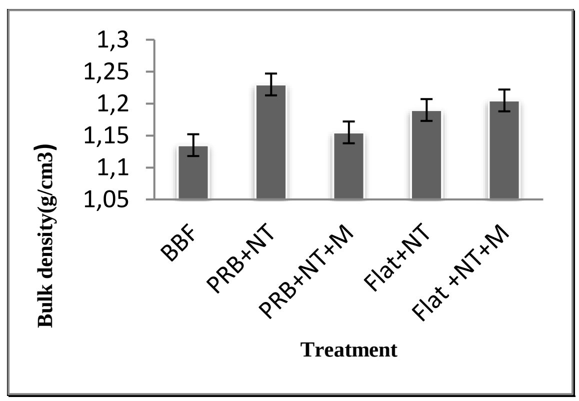

Fig. 5. Effect of Conservation Agriculture on Soil Bulk Density

D. The Economic Viability of Conservation Agriculture

As shown in TABLE 4, the results of the partial budget analysis for the FLAT+NT showed the highest maximum return to resource (MRR) of 1147.6% and the highest net benefit of 64460.2 ETB compared to those of the other treatments. This revealed that the FLAT+NT treatment was economically feasible, and the MRR could outperform the other treatments. In line with our study, the study by [5], showed that

Conservation agriculture-based practices offer farmers a great opportunity to reduce energy inputs in crop production.

IV. Conclusions

The effects of conservation agriculture practices on crop yield were analyzed using seven years of field experimental data. The impact of land management practices on growth parameters (such as plant height), grain yield, and straw yield varies depending on the crop type and year. The observed rainfall data obtained from the Ethiopian National Meteorological Agency Office for experimental years showed varying amounts of rainfall across different years. In the experimental years 2015/16 and 2017/18 the largest wheat grain yield was obtained under Flat+NT+M and Flat+NT than BBF due to the low levels of rainfall experienced throughout the cropping season. Nevertheless, in the experimental years 2019/20 and 2021/22, wheat yield was greater in BBF than in Flat+NT+M and Flat+NT due to the excess amount of rainfall during the cropping season compared to that in the previous experiment. The findings of this study indicated that conservation agriculture improved wheat yield in Vertisols during dry years. However, for regular years, BBF offers high yield advantages compared to conservation agriculture practices. BBF provided the greatest yield of faba beans and the greatest plant height. Flat+NT+M and Flat+NT had a lower impact on the environment and could better preserve soil organic matter, soil organic carbon, and extractable potassium. In particular, Flat+NT is a feasible and energy-saving strategy. The findings of this study led us to the conclusion that while conservation agricultural approaches were not preferable for the production of faba beans, they would be more beneficial for the production of wheat during years with little rainfall based on climate projection. Through a long-term trial, we found that Flat+NT+M and Flat+NT were effective in many dimensions and should be widely employed in dry years.

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