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Agro-Economic Evaluation of Alternative Crop Management Options for Teff Production in Midland Agro-Ecology, Ethiopia

Fekremariam Asargew Mihretie [1,2,*], Atsushi Tsunekawa [3], Nigussie Haregeweyn [4], Enyew Adgo [5], Mitsuru Tsubo [3], Tsugiyuki Masunaga [6], Derege Tsegaye Meshesha [5], Kindiye Ebabu [3,5] and Muluken Bayable [1,2]

1 United Graduate School of Agricultural Sciences, Tottori University, 4-101 Koyama-Minami, Tottori 680-8553, Japan; d18a3106y@edu.tottori-u.ac.jp
2 Amhara Regional Agricultural Research Institute, Bahir Dar P.O. Box 527, Ethiopia
3 Arid Land Research Center, Tottori University, 1390 Hamasaka, Tottori 680-0001, Japan; tsunekawa@tottori-u.ac.jp (A.T.); tsubo@tottori-u.ac.jp (M.T.); kebabu@tottori-u.ac.jp (K.E.)
4 International Platform for Dryland Research and Education, Tottori University, 1390 Hamasaka, Tottori 680-0001, Japan; nigussie_haregeweyn@tottori-u.ac.jp
5 College of Agriculture and Environmental Sciences, Bahir Dar University, Bahir Dar P.O. Box 1289, Ethiopia; enyewadgo@gmail.com (E.A.); deremesh@yahoo.com (D.T.M.)
6 Faculty of Life and Environmental Science, Shimane University, Shimane 690-8504, Japan; masunaga@life.shimane-u.ac.jp
* Correspondence: Fikruas2005@gmail.com

Abstract: Teff is an important crop for smallholder farmers in Ethiopia. Improved crop management practices are needed to increase teff productivity and decrease production costs. Here, we used a split–split plot design to evaluate the impacts of different tillage, sowing, and soil compaction practices, and their combinations, on agronomic performance, weed population, lodging, and cost in teff production at the Aba Gerima watershed in northwestern Ethiopia in 2018–2020. Reduced tillage (RT) improved soil moisture, resulting in increased agronomic performance and decreased production costs compared with conventional tillage (CT); however, the weed population was substantially larger with RT than with CT. Row planting (RP) reduced seed cost and lodging but increased sowing and weeding costs compared with broadcast planting (BP). Plant population and leaf area index were substantially greater with BP than with RP during early-stage growth, but this reversed during late-stage growth. Despite labor costs being significantly greater with (WC) compaction than without (NC), little to no differences were observed in the weed population or in agronomic performance. Partial cost–benefit analysis revealed that RT–RP–WC followed by RT–RP–NC was the most economical treatment combination, suggesting that RT–RP–NC could be a labor-effective means of increasing teff production by smallholder farms in Ethiopia.

Keywords: compaction; drought; reduced tillage; row planting; soil moisture

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1. Introduction

Teff (*Eragrostis tef*) is an important crop for smallholder farmers in Ethiopia because it contributes to both their food security and income [1]. In Ethiopia, more than three million hectares of land are cultivated with teff annually [2]. However, teff production there is constrained by lodging, drought, reduced soil fertility, and the need for continuous cropping [3]. These problems are worsened by traditional crop cultivation practices such as plant residue removal; frequent tillage and soil compaction; and a lack of knowledge and access to inputs such as improved seed, fertilizers, and irrigation technologies [4]. Usually, teff is cultivated using local cultivars and a high seeding rate (>25 kg ha^{-1}); plowing is usually performed with oxen, and broadcast sowing, harvesting, and threshing are usually performed by hand [5]. Although smallholder farmers have their own reasons for using this approach, these practices are considered to be the inherent cause of low crop productivity and the degradation of natural resources [4]. Thus, cost-effective crop management practices for increasing teff productivity are needed.

Traditionally, farmers will plow their teff fields four to eight times, depending on the area, to create a fine seedbed for better seed establishment and to minimize weed and pest infestations [6]. However, excess tilling wastes money, and disturbing the soil increases erosion and organic matter loss [7]. To address these concerns, and potentially reverse the negative impacts of conventional tillage approaches, the concept of reduced tillage, which encompasses minimizing the amount of tillage, using mixed cropping or crop rotation, incorporating crop residues, and using pre-emergent herbicides to control weeds, was developed [8]. Reduced tillage approaches have been shown to improve crop productivity, improve soil quality, and reduce soil erosion in major cereals such as maize [9], sorghum [10], and wheat [11]. However, because reduced tillage results in large weed populations, which can compete with the crop for nutrients and reduce the crop biomass that will be later used as feed for livestock or as an energy source for cooking, this approach requires application of pesticides that are potentially harmful to the environment [11]. Another drawback of reduced tillage is that it needs to be practiced for a long period of time before the desired changes in soil quality and crop yield are seen [12]; this is problematic because farmers generally prefer to use technologies that offer an immediate economic benefit. Despite these drawbacks, the implementation of reduced tillage activities in Ethiopia has been reported to reduce soil erosion and improve yield in maize [13], sorghum [14], and teff [15].

Another characteristic of traditional teff farming in Ethiopia is the use of broadcast sowing (hand-scattering at a high seeding rate) as a means of controlling weeds, producing high-quality straw for livestock, and reducing labor costs [16]. However, broadcast sowing results in uneven seed distribution and low tillering capacity, and allows weeds to compete with the crop for applied nutrients. Row sowing is an alternative to broadcast sowing, and although the effects of row sowing are highly dependent on soil type, the tillering capacity of the cultivar used, timing and amounts of nutrients applied, and seeding density and spacing between rows, this approach has been shown in teff to improve growth and yield, and to use less seed than broadcast sowing [16,17]. In addition, unlike in broadcast sowing, in row sowing nutrients can be placed near the root zone [18]. It has been suggested that the improvements in teff productivity brought about by row sowing are the result of efficient resource utilization, increased tillering, reduced lodging, and the facilitation of farm activities [19]. In teff, row sowing has also been shown to be more economical than broadcast sowing and seedling transplantation [16]. Despite these many advantages, the current adoption of row sowing in teff cultivation is very low due to the high labor costs associated with row-making, sowing, and weeding, and because this approach results in poor-quality (tough) straw for livestock.

A unique practice in teff production is the process of compacting the soil by human or animal (cattle, donkey, or horses) trampling immediately before sowing [15]. The purpose is to increase the contact area between the seed and the soil, reduce the risk of the seed being displaced by rain water, and seal the soil surface to reduce the loss of moisture through evaporation [20]. However, compaction is a costly practice because it requires a large number of people or animals to thoroughly compact large planting areas. Compacting the soil is also known to aggravate soil loss via runoff by reducing rainwater infiltration [21]. Recently, [4] have reported that trampling has little or no impact on economic yield in teff.

In addition, crop cultivation by the smallholder farmers in Ethiopia is largely contributing to land degradation through less efficient crop management systems such as intensive tillage operations, soil compaction, and the application of less input than removed from the soil [22]. Farmers also keep animals as a source draft power for tillage and soil compaction in Ethiopia that caused overgrazing leading to land degradation and reduced crop productivity [23]. Keeping animals for the sake of a specific farm activity (e.g., tillage, soil compaction and threshing) without any additional economic benefits will expose farmers to unnecessary costs for feed, shelter and healthcare [24]. Conservation agriculture that minimizes soil disturbance and restores soil degradation such as reduced tillage and avoiding soil compaction together with crop residue retention, crop rotation and intercropping practices improves crop productivity and farmer's income with no or less impact on the environment [25].

Although reduced tillage, row sowing, and avoiding soil compaction have been demonstrated to have agronomic, economic, and environmental advantages over traditional teff production practices, little is known about their impacts when applied in combination. However, previous findings do suggest that combining these practices may be a cost-effective means of improving teff productivity. Here, we examined whether the application of these three farming practices, individually and in combination, could improve the agronomic (plant population, plant height, panicle length, loading, and yield) and economic performance of teff cultivation in the northwestern highlands of Ethiopia.

2. Materials and Methods

2.1. Study Area

The study was performed in the Aba Gerima watershed (11°38′40.65′′ N, 37°29′30.02′′ E), which was selected as an area representative of the midland agro-ecological zone in the northwestern Ethiopia [4]. Based on long-term observations (Figure 1), the study area receives an average annual rainfall ranging from 900 to 2000 mm and an average monthly maximum temperature of 26 °C and minimum temperature of 15 °C. The main rainy season (growing season) falls from June to September. The soils in the study area are predominantly luvisols and leptosols; soil parameters measured for soil samples collected at the study site are shown in Table 1.

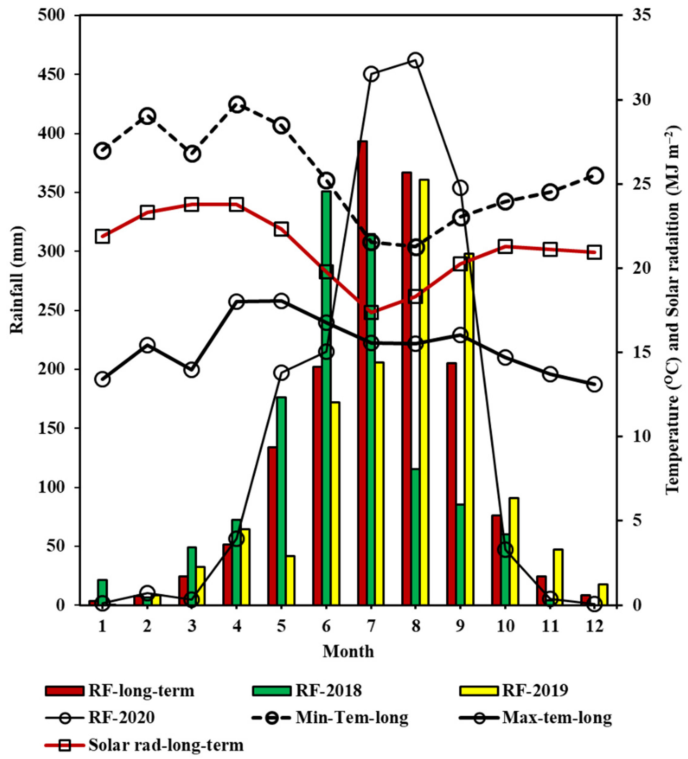

Figure 1. Long-term (2000–2020) average monthly rainfall (RF-long-term), maximum temperature (Max-tem-long), minimum temperature (Min-tem-long), and solar radiation (Solar rad-long-term) in the study area. The total monthly rainfall for the present study period (RF-2018, RF-2019 and RF-2020) is also shown.

Table 1. Soil parameters for a composite topsoil (0–20 cm) sample collected from the experimental plots before the start of the experiment in 2018.

Parameter	Value
Total nitrogen (%)	1.2
Total organic carbon (%)	0.1
Bulk density (kg m^{-3})	1200
pH	5.6
Available P (ppm)	16.6
Exchangeable K ($cmol_c$ kg^{-1})	1.1

2.2. Experimental Setup

Experimental plots were established to evaluate two tillage practices (conventional tillage, CT; reduced tillage, RT), two seeding practices (broadcast planting, BP; row planting, RP), and two soil compaction practices (with compaction, WC; with no compaction, NC) as follows:

Tillage: In accordance with current practice in the study area, CT plots were plowed four times: once in April, two times in June, and once in July. RT plots were plowed once at planting in July. In all plots, plowing was performed manually using a hand-hoe.

Planting: In accordance with current practice in the study area, BP was performed by manually scattering seed at a rate of 25 kg ha^{-1}. In RP plots, teff was planted in rows at a spacing of 25 cm and a seeding rate of 10 kg ha^{-1}.

Soil compaction: In accordance with current practice in the study area, soil compaction was performed immediately before planting by using human labor. No trampling was conducted in the plots without soil compaction.

Treatments were arranged following a split–split plot design with four replications. Tillage was assigned to the main plots, planting to the sub plots, and soil compaction to the sub- sub plots. The gross plot size was 5 m × 3 m; the net plot size was 4 m × 2 m; spacing between blocks was 0.6 m. Planting was performed on 25 July 2018, 29 July 2019, and 7 August 2020. The teff variety "Quncho" was used. To help determine the amount of fertilizer to be applied, composite topsoil samples of the studied plots were analyzed for selected parameters (Table 1, see also Section 2.3). Nitrogen (N) and phosphorous (P) were applied at rates of 64 kg N ha^{-1} and 46 kg P ha^{-1}, respectively. All P and half of the N was applied at planting; the remaining N was applied at 30 days after planting. Weeding was performed two times, at 30 and 45 days after sowing. Harvesting was performed on 5 November 2018, 27 November 2019, and 2 December 2020.

2.3. Data Collection and Analysis

To evaluate the soil properties of the experimental plots, a composite topsoil (0–20 cm) sample from the experimental plots was collected before the start of the experiment (in 2018) and analyzed for total nitrogen, total organic carbon, bulk density, pH, available P, exchangeable K, and electrical conductivity (Table 1). Total nitrogen was determined by using the Kjeldahl method [26]. Total organic carbon was determined as described by Nelson and Sommers [27]. Available P was determined by using the Olsen extraction method [28]. pH and electrical conductivity were determined based on the potentiometer principle [29]; using a soil: water (1:25) solution, pH was determined using a pH meter and electrical conductivity was measured with a conductivity meter.

During the experiment in 2019 and 2020, soil moisture was monitored every 30 min by using a moisture sensor (Decagon EC-5, METER Group, Inc., Pullman, WA, USA) and data logger (EM 50) installed in each plot at a depth of 40 cm.

During the experiment in 2018, 2019, and 2020, plant height was measured every 15 days by randomly sampling 5 teff plants in each plot. Panicle length was measured immediately before harvesting by randomly sampling 5 teff plants from each plot. The plant population was counted within a 0.25-m^2 quadrat placed at two randomly selected points in each plot; counting was conducted twice during the growing period—at the early growth stage (20 days after sowing) and at harvest. The weed population was also counted within a 0.25-m^2 quadrat placed at two randomly selected points in each plot immediately before the first and second weeding. Lodging was visually estimated as a percentage of teff stands in each plot inclined below 45° during physiological maturity. Leaf area index was quantified with an LAI-2200C Plant Canopy Analyzer following standard procedures. Grain and straw yields were quantified using samples collected within a 1-m^2 quadrat at two spots from each plot during physiological maturity. The samples were sun-dried for at least 4 days and manually threshed; husks were manually separated from the grain by using sieves. Grain and straw yields were quantified by using a LABMAN analytical balance.

Labor costs of tillage, sowing, trampling, and the cost of seed were recorded to estimate the variable costs associated with the experimental practices. Non-variable costs such as the costs of fertilizers, harvesting, and threshing were assumed to be constant across treatments. A cost–benefit analysis was performed by using input costs (labor and seed), selling prices of teff grain, and straw yields documented by nearby cooperatives. All costs and benefits (in USD) were calculated as average values across the three monitoring seasons (2018, 2019, and 2020) and are expressed on a per hectare basis. Total variable cost was determined as the sum of the costs of seed and labor for the different tillage, planting, and soil compaction methods. Gross benefit was calculated as the sum of income obtained from grain and straw yield sales. Net benefit was calculated by subtracting the total variable cost from the gross benefit.

R statistical software version 3.3.2 [30] was used to analyze the data. The Shapiro–Wilk test [31] was used to check the normality of the data. The least significant difference test [32] was used to detect differences between treatments. The statistical significance of each difference in the agronomic and economic parameters among treatments was tested at the 1% and 5% probability levels.

3. Results

3.1. Teff Growth

Plant height: Figure 2 shows the effects of tillage (T), sowing (S), and soil compaction (C) on plant height. In all three study years (2018, 2019, and 2020), plant height increased rapidly from August to October and then increased slowly from October to November. Between treatments, the monthly plant height increase was greater with RT than with CT, with RP than with BP, and with compaction than without compaction. In 2018 and 2020, but not in 2019, plant height at maturity (in November) was significantly higher with RT than with CT ($p < 0.05$). In all three years, plant height at maturity was significantly higher with RP than with BP ($p < 0.05$). In all three years, plant height at maturity was comparable WC or NC. No interaction effects for plant height were observed for tillage, sowing, and soil compaction in all three years.

Panicle length: Table 2 shows the effects of tillage, sowing, and soil compaction on panicle length. In all three years, panicle length was significantly higher with RT than with CT ($p < 0.05$). In 2019 and 2020, but not in 2018, panicle length was significantly higher with RP than with BP ($p < 0.05$). In all three years, panicle length was comparable with or without compaction. No interaction effects for panicle length were observed (T × S, T × C, S × C, and T × S × C). The combined effect of treatments was significant in all three years ($p < 0.05$). The longest panicle length was obtained with RT–BP–NC in 2018, RT–RP–NC in 2019, and RT–RP–WC in 2020; the shortest panicle length was obtained with CT–BP–NC in all three years.

Leaf area index: Table 3 shows the effects of tillage, sowing, and soil compaction on leaf area index (LAI) in 2019 and 2020. A significantly lower LAI was obtained with RT than with CT at the tillering stage (September) in 2019 ($p < 0.05$) and LAI was greater with RT than with CT at the post-flowering stage (November) in 2020 ($p < 0.05$). Similarly, a significantly lower LAI was obtained with RP than with BP at the tillering stage (September) in 2019 ($p < 0.05$) and at the post-flowering stage in 2020 ($p < 0.05$). LAI was comparable WC and NC. No interaction effects for LAI were observed (T × S, T × S, S × C, and T × S × C). The combined effects of tillage, sowing, and compaction on LAI were significant only at the tillering stage in 2019 ($p < 0.05$). The highest LAI at tillering was obtained with CT–BP–WC in 2019 and with CT–RP–WC in 2020; the lowest LAI at tillering was obtained with the combination RT–RP–NC in 2019 and with the combination CT–BP–WC in 2020. At the post-flowering stage in 2020, LAI did not differ significantly; however, relatively, the highest LAI was obtained from CT–BP–NC and the lowest was from CT–RP–WC.

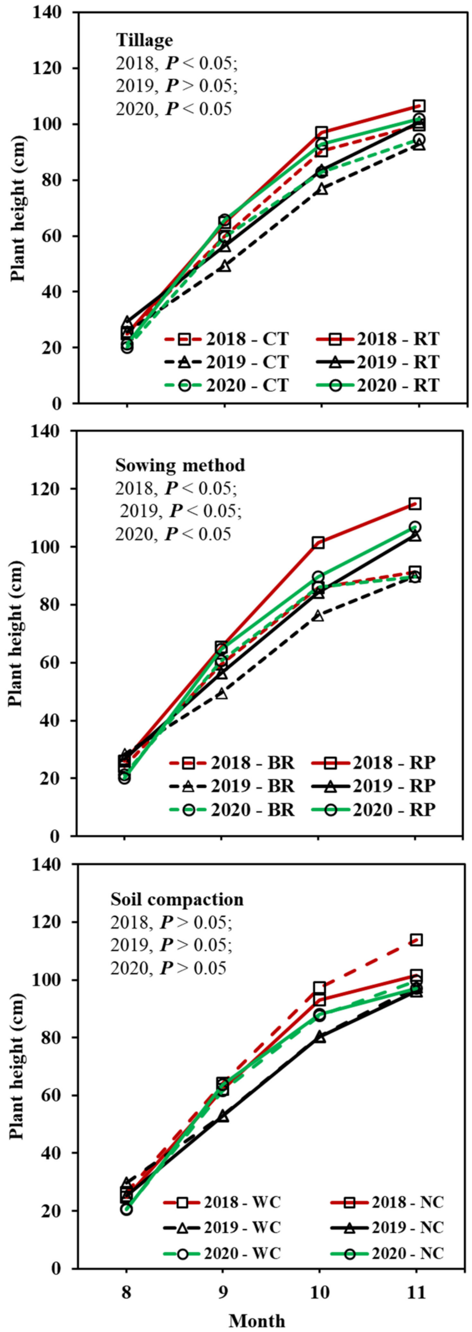

Figure 2. Mean teff plant height throughout the growing months (August to November) obtained with different tillage, sowing, and soil compaction practices. RT, reduced tillage; CT, conventional tillage; RP, row planting; BP, broadcast planting; WC, soil compacted; NC, soil not compacted. Means for plant height at maturity (November) were considered significantly different when $P < 0.05$.

Table 2. Effects of tillage, sowing, and soil compaction methods on panicle length of teff in 2018, 2019, and 2020.

	Panicle Length (cm)		
	2018	**2019**	**2020**
Tillage (T)			
CT	30.8 b	36.2 b	30.5 b
RT	37.0 a	40.3 a	39.6 a
F-value	11.5 **	16.0 **	40.9 **
Sowing (S)			
BP	33.7	35.1 b	32.5 b
RP	34.1	41.4 a	37.6 a
F-value	0.05 ns	38.1 **	12.4 **
Compaction (C)			
WC	30.5	38.6	35.8
NC	31.4	37.9	34.3
F-value	0.08 ns	0.5 ns	1.1 ns
Treatment combination (TRT)			
CT–BP–WC	30.2 c	35.1 b c	28.1 d
CT–BP–NC	30.1 c	32.2 c	27.6 d
CT–RP–WC	30.5 c	38.1 b	32.8 c d
CT–RP–NC	32.7 b c	39.3 b	33.5 c d
RT–BP–WC	34.2 a b c	37.6 b	38.6 a b c
RT–BP–NC	37.3 a	35.6 b c	35.8 b
RT–RP–WC	36.8 a	43.7 a	43.7 a
RT–RP–NC	36.7 a	44.6 a	40.3 a b
F-value	3.0 *	8.5 **	7.8 **
Interaction (*F*-value)			
T × S	0.6 ns	1.4 ns	0.03 ns
T × C	1.0 ns	0.02 ns	1.3 ns
S × C	0.8 ns	2.9 ns	0.01 ns
T × S × C	0.2 ns	0.1 ns	0.08 ns
Year (YR)		0.03 ns	
TRT × YR		1.3 ns	

RT, reduced tillage; CT, conventional tillage; RP, row planting; BP, broadcast planting; WC, soil compacted; NC, soil not compacted; T, tillage; S, sowing methods; C, compaction methods. Means with different letters are significantly different at the 0.01 (**) and 0.05 (*) probability levels. ns: not significant.

Table 3. Effects of tillage, sowing, and soil compaction methods on leaf area index at the tillering (September) and post-flowering (November) stages in teff in 2019 and 2020.

	Leaf Area Index in 2019		Leaf Area Index in 2020	
	September	**November**	**September**	**November**
Tillage (T)				
CT	2.7 a	-	1.7	4.6 b
RT	2.3 b	-	1.8	5.0 a
F-value	1.8 **		0.4 ns	2.1 *
Sowing (S)				
BP	2.8 a	-	1.6	5.4 a
RP	2.2 b	-	1.9	4.2 b
F-value	2.9 **		0.6 ns	2.2 *

Table 3. *Cont.*

	Leaf Area Index in 2019		Leaf Area Index in 2020	
	September	**November**	**September**	**November**
Compaction (C)				
WC	2.6	-	1.8	4.8
NC	2.4	-	1.7	4.8
F-value	0.4 ns		0.02 ns	0.1 ns
Treatment combination (TRT)				
CT–BP–WC	3.1 a	-	1.1	5.31
CT–BP–NC	3.0 a	-	1.6	5.60
CT–RP–WC	2.5 a b	-	2.3	3.75
CT–RP–NC	2.4 b	-	1.6	3.87
RT–BP–WC	2.6 a b	-	1.6	5.49
RT–BP–NC	2.5 a b	-	2.2	5.11
RT–RP–WC	2.3 b	-	2.1	4.55
RT–RP–NC	1.7 c	-	1.5	4.68
F-value	6.7 **		0.9 ns	1.0 ns
Interaction (*F*-value)				
T × S	0.01 ns	-	1.4 ns	0.9 ns
T × C	0.15 ns	-	0.001 ns	0.5 ns
S × C	0.11 ns	-	3.9 ns	0.1 ns
T × S × C	0.08 ns	-	0.00 ns	0.1 ns

RT, reduced tillage; CT, conventional tillage; RP, row planting; BP, broadcast planting; WC, soil compacted; NC, soil not compacted; T, tillage; S, sowing methods; C, compaction methods. Means with different letters are significantly different at the 0.01 (**) and 0.05 (*) probability levels. "-" data not recorded due to malfunctioning of the measuring instrument. ns: not significant.

Plant population: Table 4 shows the effects of tillage, sowing, and soil compaction on plant population at emergence and maturity. The plant population was comparable between CT and RT at both emergence and maturity in all three years, except for at emergence in 2018 where the plant population was significantly smaller with RT than with CT. In all three years, the plant population was significantly larger with BP than with RP at emergence ($p < 0.05$). However, at maturity, the plant population was significantly larger with RP than with BP in 2018, was comparable between the two treatments in 2019, and was significantly smaller with RP than with BP in 2020. The plant population was comparable WC and NC in all three years, except at emergence in 2018 when the plant population was significantly larger NC than WC. Both at emergence and maturity, no interaction effects on the plant population were observed (T × S, T × C, S × C, and T × S × C) except for T × S in 2018 at emergence ($p < 0.05$). The combined effects of T, S, and C on the plant population were significant for all years at emergence, but only for 2020 at maturity. The largest plant population at emergence was obtained with CT–BP–NC in 2018, with CT–BP–WC in 2019, and with CT–BP–NC in 2020; the smallest plant population was obtained with RT–RP–NC and CT–RP–WC in 2018, with CT–RP–NC in 2019, and with CT–RP–WC in 2020. At maturity in 2020, the largest plant population was obtained with CT–BP–NC and the lowest with CT–RP–WC.

Table 4. Effects of tillage, sowing, and soil compaction methods on teff plant population at emergence and maturity stages in 2018, 2019, and 2020.

	Plant Population at Emergence ($\times 10^6$ Plants^{-1} ha^{-1})			Plant Population at Maturity ($\times 10^6$ Plants^{-1} ha^{-1})		
	2018	**2019**	**2020**	**2018**	**2019**	**2020**
Tillage (T)						
CT	4.8 a	4.5	3.0	8.5	13.3	9.0
RT	3.0 b	4.7	2.9	8.5	10.9	8.9
F-value	30.6 **	0.6 ns	0.2 ns	0.001	0.6 ns	0.2 ns
Sowing (S)						
BP	5.7 a	5.3 a	3.7 a	7.6 b	12.7	9.7 a
RP	2.0 b	3.9 b	2.1 b	9.5 a	11.6	8.1 b
F-value	126.1 **	25.7 *	38.9 *	6.4 *	25.7 ns	38.9 **
Compaction (C)						
WC	1.9 b	4.7	2.7	9.4	12.6	8.7
NC	4.1 a	4.5	3.1	8.4	11.7	9.1
F-value	7.3 *	0.5 ns	2.3 ns	0.001	0.6 ns	2.3 ns
Treatment combination (TRT)						
CT–BP–WC	7.1 a	5.9 a	3.9 a b	9.5	13.7	9.9 a b
CT–BP–NC	7.4 a	4.8 a b c d	4.1 a	7.0	12.3	10.1 a
CT–RP–WC	1.9 c	3.8 d e	1.9 c	9.4	14.3	7.9 c
CT–RP–NC	2.3 c	3.4 e	2.0 c	10.5	13.0	8.0 c
RT–BP–WC	3.8 b	5.1 a b c	2.9 b c	7.8	12.9	8.9 a b
RT–BP–NC	4.0 b	5.4 a b	4.0 a	9.0	11.7	10.0 a
RT–RP–WC	2.0 c	4.0 c d e	2.2 c	8.4	9.3	8.2 c
RT–RP–NC	1.9 c	4.3 b c d e	2.4 c	8.9	9.8	8.4 c
F-value	45.0 **	4.6 **	6.7 **	2.2 ns	1.5 ns	6.7 **
T × S	16.2 **	1.3 ns	3.2 ns	2.6 ns	1.3 ns	3.2 ns
T × C	4.1 ns	3.2 ns	0.9 ns	2.6 ns	3.2 ns	0.9 ns
S × C	1.0 ns	0.4 ns	1.2 ns	1.0 ns	0.4 ns	1.2 ns
T × S × C	2.5 ns	0.4 ns	0.6 ns	0.4 ns	0.4 ns	0.6 ns
Year (YR)		11.3 **			0.008	
TRT × YR		6.2 **			3.068 **	

RT, reduced tillage; CT, conventional tillage; RP, row planting; BP, broadcast planting; WC, soil compacted; NC, soil not compacted; T, tillage; S, sowing methods; C, compaction methods. Means with different letters are significantly different at the 0.01 (**) and 0.05 (*) probability levels. ns: not significant.

3.2. Weed Infestation

Table 5 shows the effects of tillage, sowing, and soil compaction on the weed population. In all three years, the weed population was significantly larger with RT than with CT at both the first and second weeding ($p < 0.05$), except at the second weeding in 2019 when the weed populations in the RT and CT plots were comparable and in 2020 (CT > RT). At the first weeding, the weed population was significantly larger with RP than with BP in 2018 and 2019 ($p < 0.05$); in 2020, the weed populations were comparable between the two treatments. At the second weeding, no differences in weed population were observed. Similarly, a significant difference in the weed populations between WC and NC was observed only at the first weeding in 2018. The combined effects of T, S, and C on the weed population at the first and second weeding were significant in 2018 and 2020. The largest weed population across both the first and second weeding was obtained with RT–RP–NC in 2018. The largest weed population at the first weeding was obtained with RT–RP–NC and at the second weeding with RT–RP–NC, both in 2018. The smallest weed population across both the first and second weeding was obtained with CT–BP–WC, RT–BP–WC and RT–RP–WC in 2018. The largest weed population at the first weeding was obtained with RT–BP–WC and RT–RP–WC and at the second weeding with CT–RP–NC, in 2020. The smallest weed population was CT–BP–NC, CT–RP–WC and

CT–RP–NC at the first weeding and RT–BP–WC, RT–BP–NC, RT–RP–WC and RT–RP–NC at the second weeding.

Table 5. Effects of tillage, sowing, and soil compaction methods on weed population at first and second weeding in 2018, 2019, and 2020.

	Weed Population at 1st Weeding ($\times 10^{-6}$ ha^{-1})			Weed Population at 2nd Weeding ($\times 10^{-6}$ ha^{-1})		
	2018	**2019**	**2020**	**2018**	**2019**	**2020**
Tillage (T)						
CT	1.7 b	1.2 b	1.1 b	0.9 b	0.8	0.9 a
RT	1.9 a	1.4 a	1.8 a	1.2 a	0.8	0.6 b
F-value	22.9 **	1.3 ns	21.9 **	9.2 **	0.04 ns	30.8 **
Sowing (S)						
BP	1.7 b	1.2 b	1.0	0.9	0.8	0.7
RP	1.9 a	1.4 a	1.0	1.1	0.8	0.8
F-value	14.1 **	5.6 *	0.001 ns	3.3 ns	0.00 ns	3.1 ns
Compaction (C)						
WC	1.6 b	1.3	1.0	0.9	0.8	0.7
NC	1.8 a	1.3	0.9	1.0	0.9	0.8
F-value	4.9 *	0.07 ns	3.2 ns	0.07 ns	1.6 ns	2.3 ns
Treatment combination (TRT)						
CT–BP–WC	1.4 b	1.0	0.9 b c	0.7 b	0.8	0.7 b
CT–BP–NC	1.6 b	1.2	0.8 c	0.8 b	0.9	0.9 a b
CT–RP–WC	1.6 b	1.5	0.8 c	0.9 b	0.9	0.9 a b
CT–RP–NC	1.8 a b	1.3	0.8 c	0.9 b	0.8	1.1 a
RT–BP–WC	1.5 b	1.1	1.2 a	0.7 b	0.7	0.6 c
RT–BP–NC	1.8 a b	1.4	1.0 a b	1.0 a b	1.0	0.6 c
RT–RP–WC	1.8 a b	1.7	1.2 a	0.7 b	0.7	0.6 c
RT–RP–NC	2.1 a	1.4	1.1 a b	1.3 a	0.9	0.6 c
F-value	11.4 **	1.6 ns	4.2 **	3.4 *	0.4 ns	6.0 **
Interaction (*F-value*)						
T × S	3.5 ns	0.004 ns	2.8 ns	0.8 ns	0.01 ns	3.1 ns
T × C	2.1 ns	0.007 ns	1.1 ns	2.2 ns	1.06 ns	2.7 ns
S × C	0.9 ns	4.1 ns	0.6 ns	1.9 ns	0.37 ns	0.3 ns
T × S × C	1.1 ns	0.15 ns	0.02 ns	0.6 ns	0.008 ns	0.001 ns
Year (YR)		188 **			11.1 **	
TRT × YR		6.8 **			3.5 **	

RT, reduced tillage; CT, conventional tillage; RP, row planting; BP, broadcast planting; WC, soil compacted; NC, soil not compacted; T, tillage; S, sowing methods; C, compaction methods. Means with different letters are significantly different at the 0.01 (**) and 0.05 (*) probability levels. ns: not significant.

3.3. Lodging

Figure 3 shows the effects of tillage, sowing, and soil compaction on lodging. Comparing RT and CT, there were no significant differences in lodging in 2018 and 2020; however, lodging was significantly higher with RT than with CT in 2019 ($p < 0.05$). Comparing planting practices, lodging was significantly lower with RP than with BP in 2018 and 2020 ($p < 0.05$), and was comparable in 2019. Comparing compaction treatments, there were no significant differences in lodging in 2019 and 2020; however, lodging was significantly higher NC than WC in 2018 ($p < 0.05$). The lodging percentage varied substantially across the years in the order of 2018 > 2019 > 2020 ($p < 0.05$). No interaction effects were observed for lodging (T × S, T × C, S × C, and T × S × C) (Figure 3).

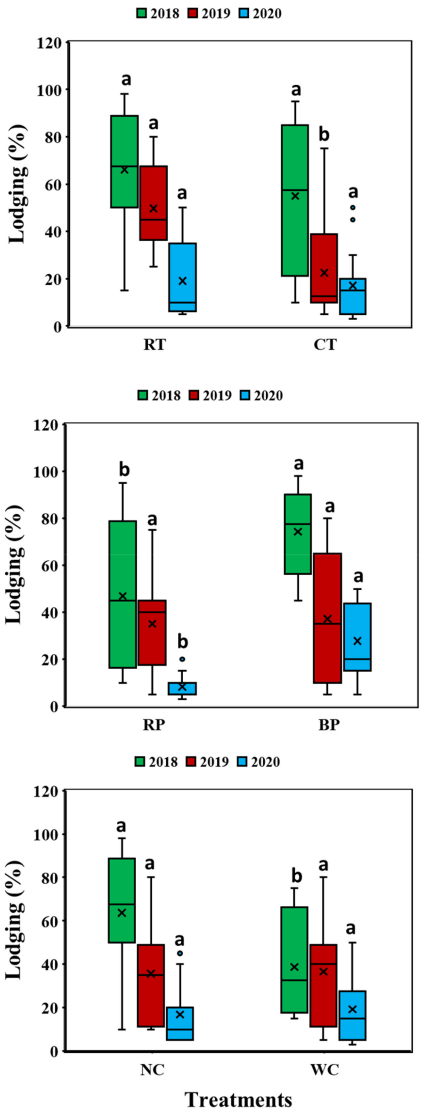

Figure 3. Effects of tillage, sowing, and soil compaction practices on teff lodging in 2018, 2019, and 2020. The top and bottom of each box represent the upper and lower quartiles, respectively; the horizontal line and the multiplication symbol (×) within each box represent the median and mean, respectively; whiskers represent variability outside the upper and lower quartiles. RT, reduced tillage; CT, conventional tillage; RP, row planting; BP, broadcast planting; WC, soil compacted; NC, soil not compacted. Within each year (similar color) across treatments, means with different letters are significantly different at $p < 0.05$.

3.4. Grain and Straw Yields

Table 6 shows the effects of tillage, sowing, and soil compaction on grain and straw yields. In all three years, grain and straw yields were significantly higher with RT than with CT ($p < 0.05$); except straw yields in 2018. The effects of S on grain yield were significant only in 2019 when RP gave a higher grain yield (2.2 t ha^{-1}) than did BP (1.6 t ha^{-1}) ($p < 0.05$). Straw yield was not significantly impacted by S ($p > 0.05$). Both grain yield and straw yield were not significantly influenced by C ($p > 0.05$). Grain yield was significantly impacted by the combined effects of T, S and C methods in all the years ($p < 0.05$). The highest grain yield was obtained with RT–RP–WC in 2018, and with RT–RP–NC in 2019 and 2020. The lowest grain yield was obtained with CT–RP–WC in 2018, with CT–BP–WC in 2019, and with CT–RP–NC in 2020. The highest straw yield was obtained with RT–RP–NC; the lowest was obtained with CT–RP–NC in 2020. No interaction effects were observed for grain yield and straw yield (T × C, S × C and T × S × C), except for grain yield in 2020 ($p < 0.05$). In addition, significant interactions between treatment combination and year were observed for both grain and straw yield. In general, grain and straw yield were both significantly increased year on year in the order 2018 < 2020 < 2019.

Table 6. Influences of tillage, sowing, and soil compaction methods on grain and straw yields of teff in 2018, 2019, and 2020.

	Grain Yield (kg ha^{-1})			Straw Yield (kg ha^{-1})		
	2018	**2019**	**2020**	**2018**	**2019**	**2020**
Tillage (T)						
CT	639 b	1640 b	728 b	6543	21,724 b	7933 b
RT	782 a	2161 a	1013 a	7158	27,083 a	10,693 a
F-value	6.9 *	9.5 **	9.8 **	1.3 ns	5.3 *	16.4 **
Sowing (S)						
BP	767	1629 b	846	7191	22,310	9443
RP	655	2172 a	894	6510	26,498	9182
F-value	4.2 ns	10.3 **	0.3 ns	1.6 ns	3.2 ns	0.1 ns
Compaction (C)						
WC	530	1827	874	5803	23,968	9434
NC	736	1974	866	7000	24,839	9191
F-value	0.7 ns	0.76 ns	0.008 ns	0.4 ns	0.14 ns	0.1 ns
Treatment combination (TRT)						
CT–BP–WC	664 b c	1313 d	850 a b c	6811	17,090	8665 a b c
CT–BP–NC	724 a b c	1609 c d	800 b c	7288	21,620	8338 b c
CT–RP–WC	530 c	2017 b c	703 c	5803	26,540	8085 b c
CT–RP–NC	579 b c	1622 b c d	558 c	5796	21,645	6643 c
RT–BP–WC	580 b c	1672 b c d	853 a b c	7516	23,589	10,135 a b
RT–BP–NC	809 a	1922 b c d	883 a b c	7094	26,940	10,635 a b
RT–RP–WC	1102 a	2306 a b	1093 a b	7440	28,655	10,850 a b
RT–RP–NC	755 a b	2744 a	1225 a	7221	29,150	11,150 a
F-value	3.1 *	3.6 **	2.6 *	1.3 ns	1.6 ns	2.8 *
Interaction (*F-value*)						
T × S	0.5 ns	1.19 ns	7.1 *	1.8 ns	0.05 ns	1.6 ns
T × C	1.1 ns	1.35 ns	0.9 ns	0.1 ns	0.20 ns	0.9 ns
S × C	0.9 ns	0.55 ns	0.001 ns	0.2 ns	1.75 ns	0.2 ns
T × S × C	0.8 ns	1.69 ns	0.3 ns	0.4 ns	0.50 ns	0.1 ns
Year (YR)		0.5 ns			0.3 ns	
TRT × YR		2.5 *			3.0 *	

RT, reduced tillage; CT, conventional tillage; RP, row planting; BP, broadcast planting; WC, soil compacted; NC, soil not compacted; T, tillage; S, sowing methods; C, compaction methods. Means with different letters are significantly different at the 0.01 (**) and 0.05 (*) probability levels. ns: not significant.

3.5. Profitability

Table 7 shows the results of a partial cost–benefit analysis conducted for the different combinations of farming practices. As expected, the labor costs for tillage were significantly higher for combinations involving CT than for those involving RT, for those involving RP than for those involving BP, and for WC than NC (all $p < 0.05$). Similarly, seed cost was significantly higher for combinations involving BP than for combinations involving RP ($p < 0.05$). Total variable cost was significantly different among the different combinations of T, S, and C ($p < 0.05$); CT–RP–WC incurred the highest total variable cost, and RT–BP–NC incurred the lowest total variable cost. Total gross benefit also significantly varied among the different combinations of T, S, and C ($p < 0.05$); RT–RP–WC afforded the highest total gross benefit (USD 2216) and CT–RP–NC afforded the lowest total gross benefit (USD 1235).

Net benefit significantly varied among the different treatment combinations ($p < 0.05$); RT–RP–WC afforded the highest net benefit (USD 1631).

Table 7. Partial cost–benefit analysis for the different tillage, sowing, and soil compaction practices.

Cost or Benefit (USD ha^{-1})	CT–BP–WC	CT–BP–NC	CT–RP–WC	CT–RP–NC	RT–BP–WC	RT–BP–NC	RT–RP–WC	RT–RP–NC
1. Labor cost								
Tillage	368 a	368 a	368 a	368 a	92 b	92 b	92 b	92 b
Compaction	78	–	78	–	78	–	78	–
Sowing	16 b	16 b	49 a	49 a	16 b	16 b	49 a	49 a
Weeding	375 a	376 a	460 a	453 a	378 a	399 a	358 a	397 a
2. Seed cost	20 a	20 a	8 b	8 b	20 a	20 a	8 b	8 b
3. Total variable cost	858 a b	780 b	963 a	878 a b	585 c	527 c	585 c	546 c
4. Total gross benefit	1427 a b	1253 b	1460 a b	1235 b	1764 a b	1447 a b	2216 a	1665 a b
5. Net benefit	569 b c	474 b c	498 b c	358 c	1179 a b	920 a b c	1631 a	1120 a b

RT, reduced tillage; CT, conventional tillage; RP, row planting; BP, broadcast planting; WC, soil compacted; NC, soil not compacted. Treatment means with different letters are significantly different at $p < 0.05$.

4. Discussion

4.1. Teff Growth

We observed a greater plant height and panicle length in RT plots compared with those in CT plots, which we attributed to lower soil disturbance and better organic matter accumulation [4] leading to better soil moisture availability (Figure 4). Our findings are consistent with those of [33], who reported that reduced tillage practices improved crop growth in teff. However, Gebretsadik et al. [15] have reported that tillage practices do not have an effect on crop growth components in teff. We also observed a greater plant height in RP plots compared with that in BP plots, which we attributed to better placement of resources (moisture, light, and nutrients) close to the root zone [34]. These findings are consistent with those reported by Mihretie et al. [16], [35], which have indicated that RP results in better teff growth compared with that obtained with BP.

With respect to LAI, we did not observe a clear impact of tillage across growth stages and years. LAI is a complex trait affected by a range of factors including leaf arrangement and orientation, and so it might not be directly influenced by tillage [34]. BP plots produced a greater LAI than did RP plots, probably due to efficient utilization of space (high plant population). On the other hand, one of the disadvantages of BP in cereals is that uneven distribution of stands results in poor light interception (low LAI) and higher intra-plant competition [36]. The present findings are in agreement with previous reports that LAI in BP crops is greater than that in RP crops in teff [4] and other cereals such as maize [37]. The impact of S on LAI is governed by several factors such as the type of crop, cultivars and the amount of nutrients applied [38].

With respect to LAI, we did not observe a clear impact of T across growth stages and years. LAI is a complex trait affected by a range of factors including leaf arrangement and orientation, and so it might not be directly influenced by tillage [34]. BP plots produced a greater LAI than did RP plots, probably due to efficient utilization of space (high plant population). On the other hand, one of the disadvantages of BP in cereals is that uneven distribution of stands results in poor light interception (low LAI) and higher intra-plant competition [36]. The present findings are in agreement with previous reports that LAI in BP crops is greater than that in RP crops in teff [4] and other cereals such as maize [37]. The impact of S on LAI is governed by several factors such as the type of crop, cultivars and the amount of nutrients applied [38].

With respect to the plant population, a larger plant population at emergence was observed in BP plots, which we attributed to the higher seeding density (25 kg ha^{-1}) than that used in the RP plots (10 kg ha^{-1}) [16]. However, the plant population at maturity was comparable or higher in the RP plots than in the BP plots despite some inconsistency in 2020 (BP > RP), probably because of rapid compensation in the teff stands through enhanced tillering [16,39]. We also attributed the high tillering observed in the RP plots to the presence of open spaces [4], better availability of resources around the root zone compared to that in the BP plots [40], and to the high tillering capacity of the teff cultivar (Quncho) used in the study.

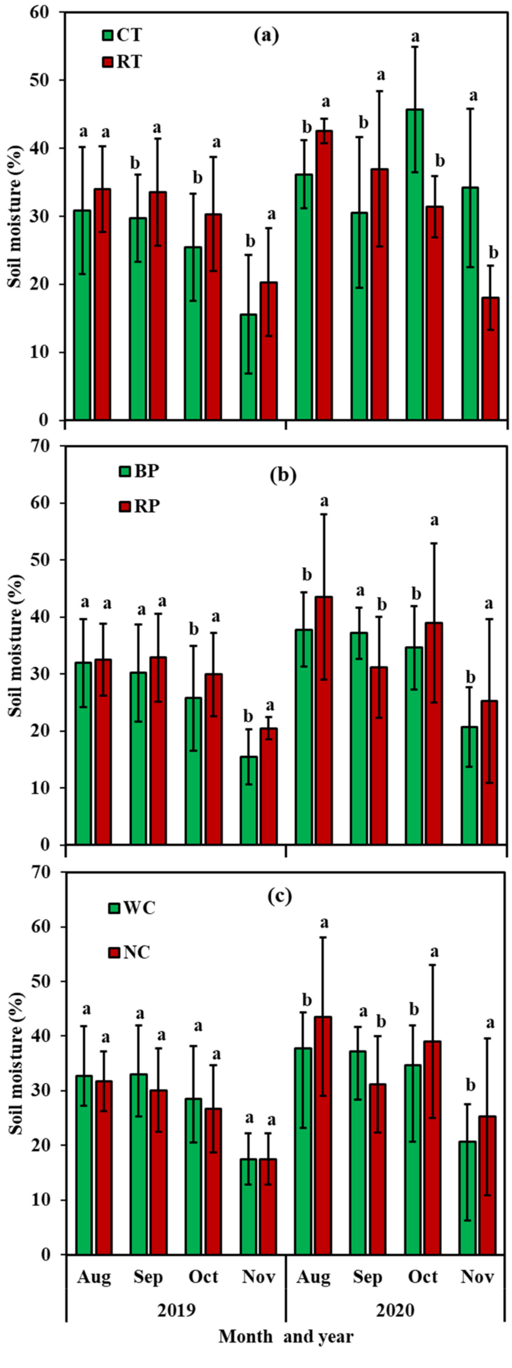

Figure 4. Average monthly soil moisture under different tillage (**a**), sowing (**b**), and soil compaction (**c**) practices in 2019 and 2020. RT, reduced tillage; CT, conventional tillage; RP, row planting; BP, broadcast planting; WC, soil compacted; NC, soil not compacted. In each month, bars labeled with different letters significantly differed at $p < 0.05$. Soil moisture data for 2018 were not recorded as the moisture sensor was not functional in 2018.

To summarize our findings related to growth performance, the present data indicate that RT and RP resulted in better teff growth performance compared with that obtained with CT and BP, respectively. In addition, the application of soil compaction was found to have little to no impact on teff growth.

4.2. Weed Infestation

Tillage in the dry season (April–June) creates not only a favorable ground for teff seeds to germinate but it also damages and exposes the weed plant (seed, stem, and root) to desiccation by sunlight [41]. Not unexpectedly then, we found that the weed population in RT plots (plowed one time) was higher than that in CT plots (plowed four times). Indeed, greater weed density has been reported in RT plots than in CT plots in teff [4], wheat [42], and maize [43]. It is well known that reduced tillage practices are most effective when accompanied by appropriate weed management practices such as mulching and the use of pre- and post-emergent herbicides. Despite RP allowing better access to applied N and *p*, the weed population is usually higher than that in BP plots due to the open spaces between rows [44]. In addition, during the first weeding (approx. 30 days after sowing), when tillering is not yet properly started, the plant population was lower (Table 4) in the RP plots due to the low seeding rate (10 kg ha^{-1}), which might have allowed weeds to flourish more than in the BP plots where a higher seeding rate (25 kg ha^{-1}) was used. These findings highlight the fact that the agronomic benefits from planting teff in rows can only be maximized when coupled with appropriate weed control practices.

4.3. Lodging

The significant reduction in lodging observed in the RP plots compared with that in the BP plots was attributed to the growth of strong stems as a result of better nutrition [45]. Our findings are consistent with those of Mihretie et al. [4] and Vandercasteelen et al. [18], who have also reported reduced lodging when teff is planted in rows. One of the reasons teff is highly susceptible to lodging is due to its weak stems [46]. The high tillering potential afforded by RP may promote the formation of crown roots [47], and because lodging in teff is partly caused by failing from the root [46], crown roots may provide better root anchorage [48]. However, the stronger stems may make the resultant teff straw less palatable to animals, preventing it from being used as livestock feed [49]. Indeed, in addition to high labor costs, poor-quality straw has been cited as one of the reasons for the slow adoption of row planting in teff [35]. As long as an alternative feed is provided to the farmers, row planting could be one strategy to reduce lodging in teff production.

4.4. Teff Grain and Straw Yields

The better teff growth (Figure 2) and soil moisture conditions (Figure 4) afforded by RT resulted in greater grain and straw yields compared with those obtained with CT. The lower soil disturbance caused by RT may have reduced the removal of soil organic matter and applied fertilizer in runoff, which would have provided an immediate advantage for RT over CT in terms of soil nutrition [50]. It is surprising that our use of RT resulted in greater teff yields in the short term, which is in contrast to several studies (e.g., Büchi et al. [51]) showing that RT requires a longer timeframe (>5 years) before marked effects on crop yield are observed as a result of improved soil qualities. The short-term impact of RT on teff in our study might be linked to the immediate benefits afforded by improved soil moisture compared to that obtained with CT (Figure 4) because one of the major bottlenecks of rain-fed teff production is the shortage of moisture immediately after planting and at flowering time [52]. In agreement with our present findings, Gezahegn et al. [53] and Desta et al. [54] have both reported that RT increased crop yield in the short term. However, others have reported a reduction in crop yield in the first 2–3 years of using RT [55].

Without considering the tillage and weeding costs, our study suggests that RT improved teff yield in the short term. Traditionally, more than 90% of the teff biomass is removed as an economic product; we suggest that future studies investigate the impacts of mulching or residue incorporation as part of a reduced tillage approach because this is something we did not consider in the present study.

The greater grain yield obtained with RP than with BP in 2019 was attributed to better growth (Figure 2), better soil moisture (Figure 4), and reduced lodging (Figure 3). Mihretie et al. [16] have suggested that RP may offer a 30% yield advantage when practiced with optimum seeding density and row spacing. In addition to the yield advantage, RP saves teff seed and makes farm operations easier [16]. However, the impact of RP on grain yield is highly impacted by several factors such as the type of cultivar used, soil type, seeding density, and row spacing [56,57]. In addition, this practice has a high labor requirement and produces a low-quality straw, resulting in poor adoption among smallholder farms in Ethiopia [35]. Additionally, some studies have reported that RP has no impact on teff grain yield and sometimes might even afford a lower yield than BP when a local cultivar with a low tillering capacity is used [4]. In the present study, we found that that RP improved (2019) or had comparable (2018 and 2020) grain yield but had no impact on straw yield compared with BP.

With respect to the impacts of soil compaction on grain and straw yields, we found no differences between whether soil compaction was used or not, indicating that the choice of whether to use soil compaction has relatively little importance in teff production. Despite finding no impacts on grain and straw yield, we found slightly reduced weed infestation and lodging and slightly improved teff growth and yield, although this latter finding was not statistically significant (Table 5) and the responses were not consistent across the study years and were not strong enough to contribute to the final harvest (grain and straw yields). These findings support the farmers' perception that soil compaction locks in soil moisture by preventing surface drying, resulting in better root anchorage [58]. In contrast, Mihretie et al. [4] and Amare et al. [21] have suggested that sealing the soil surface by compaction might reduce the infiltration of rain water and aggravate soil loss by runoff. In general, because the mechanisms of how soil compaction influences soil properties and teff root development are not fully understood, further studies are required to explore its impact in different soil types and at different compaction levels, as well as the effects of different approaches to soil compaction (human, animal, or tractor).

To summarize our findings regarding the effects of the different combinations of farming practices, combinations containing both RT and RP (RT–RP–NC in 2019 and 2020; RT–RP–WC in 2018) afforded greater grain and straw yields due to better growth, better soil moisture, and reduced lodging. Moreover, the differences in teff yield performance across the study years (2019 > 2020 > 2018) are attributed to the greater rainfall and distribution of rainfall throughout the growing season in 2019 than in 2020 and 2018. The occurrence of high rainfall during maturity (Nov) in 2018 and 2020 might have induced lodging, resulting in a drastic loss in teff yield. Indeed, one of the major driving factors that triggers lodging is unexpected rainfall during physiological maturity, which also induces teff plant failure and seed shattering, and causes panicles to develop mold [45].

4.5. Profitability

Despite the RT plots producing a higher yield than the CT plots, the RP plots producing a higher yield than the BP plots, and soil compaction not influencing teff yields, the associated costs of labor and seed will likely be the main determinants of the uptake of these practices by farmers. The low total variable cost and higher net benefit of RT–RP–WC and RT–RP–NC are a result of the lower cost of labor for plowing and the higher grain and straw yields (Table 7) compared to the high total variable cost and the lower net benefit of the combinations containing CT (high cost of labor for plowing and lower grain and straw yields). CT in teff production is labor intensive and RT might offer an economic advantage by minimizing plowing costs [4], even when there is little to no yield advantage over CT. However, the implementation of RT is more economical and effective when integrated with other crop intensification options such as crop residue management, crop rotation, and proper weed management [59].

In our study, RP had a high cost for sowing that could be compensated for through lower cost of seed and high yields compared to BP. In agreement with our study, Mihretie et al. [16]

have shown that RP improves teff yields and reduces seed costs, which balances the labor costs of sowing. Our present findings suggest that WC combined with RT and RP could be of benefit due to higher grain and straw yields, even with the additional high costs of labor. It should be noted here that farmers normally use cattle for tilling and soil compaction in teff cultivation; however, in the present study we used human labor because it was difficult to operate animals in the small experimental plots. Although our study clearly indicated comparative differences in costs and benefits among tillage, sowing, and soil compaction practices, quantification of the real costs associated with cattle tillage and trampling in a larger plot size is required. In traditional teff production systems, farmers are highly constrained by the availability of oxen for plowing and trampling. As men are usually the ones who perform the plowing operation in Ethiopia [60], oxless and widow female farmers face difficulties and might be forced to share their teff produce in exchange for oxen [61]. Even those farmers who can afforded to own oxen will incur additional costs for providing feed, shelter, and healthcare for the animals, and these animals could be one of the factors driving overgrazing and land degradation [62]. In addition, frequent plowing is a major cause of soil loss and land degradation in Ethiopia [4,63]. Therefore, RT may be a promising approach for resource-poor farmers who do not have access to oxen or whose land has degraded. Overall, we found that RT–RP–WC and RT–RP–NC were the most economical combinations of treatments for teff production in the study area. Since there was no significant difference among the two in net benefit, we recommend the use of RT–RP–NC, especially for farmers who have limited access to labor or animals for soil compaction.

5. Conclusions

Here, we found that alternative tillage and sowing practices could have a substantial impact on the agronomic and economic performance of teff cultivation. Reduced tillage significantly improved teff growth and yield, mainly through better soil moisture availability and reduced cost of production compared with conventional repeated tillage. However, the greater weed population that results from reduced tillage calls for effective weed control strategies. The grain yield with row seeding was significantly higher compared with that with broadcast sowing due to good tillering and efficient use of moisture and nutrients. However, row planting incurred a high cost of labor for sowing and weeding, and requires the use of small-scale labor-reduction technologies. Despite slight improvements in soil moisture, teff growth, and yields, soil compaction should be discouraged due to the high cost of labor. Overall, we conclude that reduced tillage, row seeding, and sowing without soil compaction are promising alternative practices for improving teff productivity by reducing the cost of production and pressure on soil resources.

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