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# Crop Productivity, Nutritional and Economic Benefits of No-Till Systems in Smallholder Farms of Ethiopia

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**Abstract:** Smallholder maize and wheat production systems are characterized by high drudgery. On-farm trials were run for three seasons in Ethiopia. The study assessed the effect of 2 WT direct seeding and growing season on (1) soil quality, and (2) maize and wheat productivity, energy and protein gains, and gross margins, on smallholder farms in Ethiopia. For the wheat crop, the effect of different soil types and agroecological conditions on productivity was assessed. The treatments in paired plots were (i) conventional ploughing practice and (ii) no-till (NT). Soil properties, crop yield, nutrition gains and gross margins were determined. No-till improved soil properties in the short term. No-till produced 1210–1559 kg ha$^{-1}$ grain, 18–29 GJ ha$^{-1}$ energy and 121–194 kg ha$^{-1}$ proteins, and generated 358–385 US$ ha$^{-1}$ more than the conventional practice in the maize system. In the wheat system, no-till treatment had 341–1107 kg ha$^{-1}$ grain, 5–16 GJ ha$^{-1}$ energy and 43–137 kg ha$^{-1}$ proteins, and generated 230–453 US$ ha$^{-1}$ more than conventional practice. No-till can be more productive and profitable in the Ethiopian maize and wheat-based cropping systems.

**Keywords:** energy; maize; mechanization; proteins; two-wheel tractor

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## 1. Introduction

Crop production in *Maresha*-based conventional systems of the Ethiopian highlands is characterized by low yields of the major cereal and legume food crops [1,2]. Maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.) yields have remained lower than the maximum potential in different parts of the Ethiopian highlands [2,3]. Currently, the yield gap for maize varies by an average of 28–30% in Ethiopia [1] while authors [4] report wheat yield gaps of 14–17% under farmer conditions. Maize and wheat productivity has remained below the potential yields due to poor soil quality including acidity and low organic matter, the use of inappropriate agronomic practices in cropping systems, and the use of retained seed of the major food security cereals [3,5]. Countrywide, the wheat deficit stands at 1.9 million tonnes per year [6] which feeds about 30% of the population. This is worsened by a gradual increase in the human population of 3.02% per annum [7]. Wheat and maize contribute 11 and 17% of the national calorie intake respectively [8,9]. Maize contribution towards food security remains lower than expected and this is attributable to various factors including low yields due to highly degraded soils, unreliable rainfall patterns, as well as a poor grain distribution network from surplus to deficit areas of the country [3].

Maize and wheat production systems in Ethiopia's smallholder farming sector are characterized by high drudgery. Field operations such as land preparation, fertilizer application and planting are carried out using human muscle power [10,11]. These field operations are carried out by both men and women [12]. Elsewhere, conservation agriculture-based farming systems that are being promoted in sub-Saharan Africa (SSA) have reportedly increased the workload on women farmers [11], who are already overwhelmed due to the multi-task nature of their roles at the smallholder farming family level [13]. It is imperative, therefore, that alternative technologies and innovations that reduce drudgery and reallocate family labour to other income-generating activities be explored in the smallholder farming sector [14].

Low horsepower (8–22 HP) two-wheel or walking tractors (2 WT) are an alternative technology that can reduce drudgery along the crop value chains and increase productivity on smallholder farms [15]. For the smallholder farmer, direct seeding into untilled soil substantially reduces costs and time for establishing a crop during the sowing window at the onset of the growing season [14,15]. Direct seeding increases precision in basal fertilizer placement and quantities applied during planting. Additionally, direct seeding allows timely planting and more efficient utilization of available soil moisture at the critical stage of crop establishment [10,16].

Two-wheel tractor direct seeding complements no-till (NT) based practices that are being promoted to improve soil and crop productivity in the smallholder farming sector [17,18]. No-till systems improve soil health by reducing erosion, increasing organic matter and soil biodiversity [19], as well as reducing soil acidity, which is one of the major crop production constraints in Ethiopia and other SSA countries [20–22]. For the acidic soils in Ethiopia [5], NT systems offer an opportunity for increasing the productivity of maize, wheat and other food security crops under the different agroecological conditions of the country. Crop yield gains from conservation agriculture-based cropping systems are well documented in studies from different parts of Eastern and Southern Africa [23–25]. However, there is still limited evidence on how 2 WT direct seeding influences the productivity of major food security crops such as maize and wheat compared with the traditional practices under smallholder farming conditions.

Successful promotion of cropping systems resilient to climate change and variability also hinges on income generated from crop production in the smallholder farming sector. The profitability of new and improved technologies is often a key incentive for smallholder farmers, and this has been demonstrated by conservation agriculture and integrated soil fertility management innovations promoted on smallholder farms [20,26–29]. Elsewhere, studies have also shown that NT systems are both productive and profitable compared with conventional practices [17]. Under smallholder farming conditions of SSA, there is still limited evidence on how profitable 2 WT direct-seeded cropping systems are compared with the various conventional practices that have been in use for many generations.

Direct seeding in untilled soil is one of the operations that are being mechanized on smallholder farms in Ethiopia using 2 WTs. The other farm operations performed by a 2 WT include harvesting and threshing of crops such as wheat and barley, maize shelling and water pumping for irrigating high-value horticultural crops [30,31]. This study was designed to assess the effect of 2 WT direct seeding on maize and wheat productivity, energy and protein gains, and gross margins on smallholder farms in Ethiopia. The study was guided by the three research questions: (1) What is the effect of no-till on soil health over time, (2) What is the effect of 2 WT direct seeding and growing season on maize and wheat yields compared with the conventional Maresha-based practice? (3) What is the effect of different soil types and agro-ecological conditions on wheat yields? (4) What nutritional gains for farming households are derived from using 2 WT direct seeding systems? (5) What is the effect of 2 WT direct seeding on gross margins from the maize and wheat systems in the Ethiopian highlands?

## 2. Materials and Methods

### *2.1. Description of Experimental Sites*

Trials were conducted at 15 farms in the maize-growing zone and 26 farms in the wheat-growing parts of Ethiopia. The on-farm trials were run for three growing seasons

(2018, 2019, 2020) in the sub-humid and semi-arid highlands of Ethiopia and the general location of trial sites are summarised in Figure 1.

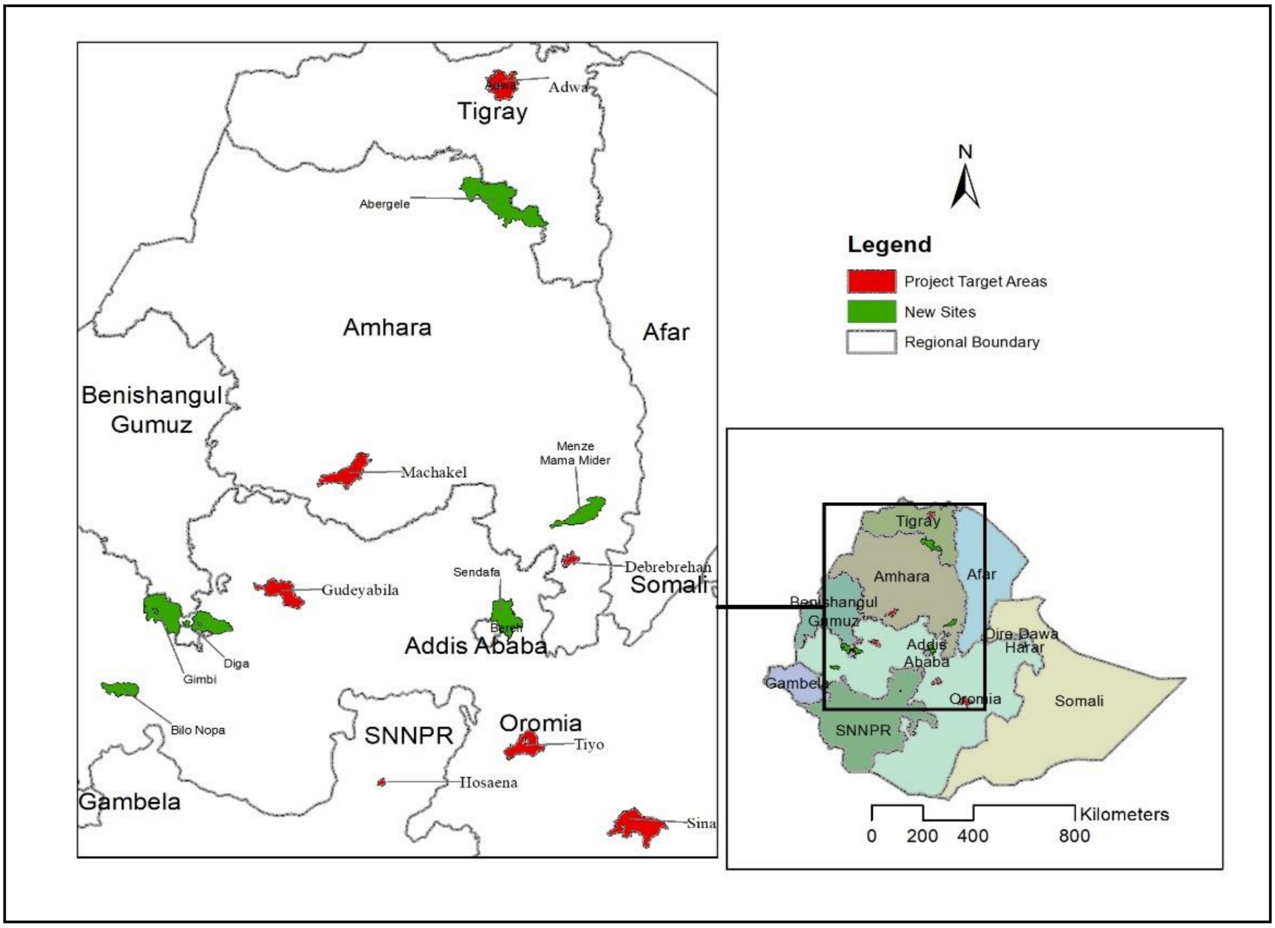

**Figure 1.** Map of Ethiopia showing parts of the country where two-wheel tractor-based small mechanization technologies are being promoted since 2015. Experimental sites were located Gudeya-Billa (maize), Machakel (wheat), Debre Birhan (wheat), Gimbichu (wheat) and Adwa (wheat) areas of Ethiopia.

In the predominantly maize-growing region, trials were in the Gudeya-Billa District of the Oromia region. Gudeya-Billa lies in the mid-altitude highland with a high potential for maize production [32]. Gudeya-Billa is characterised by a bimodal rainy season with a mean annual rainfall of 1300 mm. The average minimum and maximum temperatures are 13.3 and 29.9 °C [33]. The predominant soils in the region are well-drained *Alfisols* (*Udalf*) with a bulk density of 1.12 g $cm^3$, pH 5.6, soil organic carbon (SOC) of 14 g $kg^{-1}$ and 48% clay content [25,32].

In the predominantly wheat-growing area of the Oromia region, on-farm trials were run in the Gimbichu District which lies in the sub-humid highlands with soil characterized by clay content averaging 62%, 1.21–1.41 g $cm^3$ bulk density, pH of 6–7.5, and 2.3% organic matter [2]. The area receives about 1200 to 2200 mm per annum. The average minimum and maximum temperatures are 7 and 26 °C, respectively [34]. In the Amhara region, wheat trials were conducted in Goshe Bado (Debre Birhan) and Machakel (Debre Markos). Debre Birhan receives an average rainfall of 900 to 1200 mm per annum with minimum and maximum temperatures of 9 °C and 22 °C, respectively. The predominant soils are *Cambisols*, *vertisol* and *Nitosols*. The soils are moderately drained due to the relatively high clay content [35]. *Alfisols* are the predominant soil type in the Debre Markos area. They are moderately drained due to significant clay content [36]. The area receives a mean annual rainfall of 1308 mm and has an annual average temperature of 16 °C. In the Tigray region, wheat trials were conducted in Adwa, a semi-arid low altitude part of Ethiopia. The Adwa area receives at least 880 mm of rainfall per annum. The soils in Adwa are moderately drained *Leptosols*, *Cambisols*, *Vertisols*, *Fluvisols* and *Nitosols* [37]. The farming system at the trial sites is predominantly mixed crop-livestock with cropping systems involving cereals and legumes grown under rotation and intercropping practices.

### *2.2. Experimental Design and Treatment Description*

Trials were implemented on land volunteered by each host farmer. Each farmer offered 660 $m^2$ of land for hosting the trial in each growing season. Each farm had paired plots one for the conventional *Maresha* practice and another for NT treatment. Each experimental plot measured 30 m × 10 m and there was a 2 m pathway between the plots. The two treatments were:

i. Conventional practice (CP): land preparation involved ploughing 3–4 times using an ox-drawn *Maresha* traditional plough before the onset of the rains. The fifth ploughing operation was conducted at planting after receiving effective rains.
ii. No-till (NT): the soil was not tilled before planting the two test crops. Maize planting and basal fertilizer application were done using a two-row planter (model 2 CYF-2) that was powered by a 20 HP two-wheel tractor. The 2-BFG-100 (*Dongfeng brand*) planter was used for wheat direct seeding at all sites every growing season.

In both treatments, maize was planted at 75 cm × 25 cm giving 53,333 plants $ha^{-1}$. Wheat seed was drilled at 20 cm inter-row spacing giving 300,000 plants $ha^{-1}$. No crop residues were applied as mulch to the NT plot because farmers needed to use the residues for livestock feed and construction. Wheat trials were established in different agroecological regions of Ethiopia which had different soil types. This allowed the assessment of agroecological conditions and soil type effects on wheat yields to be conducted.

### *2.3. Experimental Management*

Maize and wheat were planted on the same day in both treatments at each farm at the onset of the growing season. Late maturing Shone maize variety was used in all seasons at the Gudeya-Billa trial sites. A white-grained Damfi bread wheat variety was grown at the trial sites in all seasons. The two treatments received the same amount of basal and top-dressing mineral fertilizers. Basal fertilizer (19% N, 38% $P_2O_5$, 7% S) was applied at 150 kg $ha^{-1}$ followed by urea (46% N) at 100 kg $ha^{-1}$ as topdressing to both maize and wheat crops at 5–6 weeks after emergence. Weed control in the conventional practice treatment was done manually using hand hoes. In the NT treatment, the first weed control was achieved by applying glyphosate [*N*-(phosphonomethyl) glycine] at 3.0 l $ha^{-1}$ (1.025 l $ha^{-1}$ active ingredient) at 5–7 days before seeding. Subsequent weed control in the NT treatment was done manually using hand hoes whenever necessary. Management of trials and the decision on when to weed the trial during the growing season was taken by the host farmer in consultation with the resident extension agent.

### *2.4. Data Collection*

#### 2.4.1. Soil Analysis

Soil samples were collected from the maize fields at on-farm sites in the Gudeya-Billa District in western Ethiopia that had been in use for four years. The soil samples were collected in December after harvesting. The purpose of soil analyses was to assess differences in soil quality indicators between conventionally ploughed and NT treatments. Soil samples were collected from the 0–15 cm depth in each treatment. Soil pH was determined using the water method (1:2.5 ratio) and soil organic carbon was measured using the Walkley-Black procedure [38]. Zinc, sulphur and phosphorus were extracted using the Mehlich 3 method [39] and determined by the atomic absorption spectrometer. Cation exchange capacity was determined using the ammonium acetate procedure. Soil samples were analysed by Horticoop Laboratory in Debre Zeit, Ethiopia.

#### 2.4.2. Crop Productivity Variables

All crops were harvested at physiological maturity. The final maize plant population was measured from a 4 m × 4 m net plot where grain and stover yields were determined. Maize cobs and biomass from the net plot were weighed in the field before taking sub-samples for determining grain and biomass moisture content. Wheat grain and straw yield were also measured from a 16 $m^2$ net plot in each treatment. Wheat straw and spike samples were weighed in the field before taking sub-samples for air-drying and determination of final grain and straw yields. Grain and straw/stover sub-samples were air-dried for five weeks before determining dry grain and biomass weight. Grain moisture content was measured using the mini GAC® moisture tester (DICKEY-John, Auburn, IL, USA). The final maize and wheat grain yields were expressed per $ha^{-1}$ at 12.5% moisture content. Harvest index (HI) was determined as the proportion of maize or wheat grain to the total above-ground biomass. Hundred seed weight (HSW) of wheat grain was determined after air drying for 5 weeks.

#### 2.4.3. System Nutritional Value

Grain energy yield (GJ $ha^{-1}$) in each plot was calculated from the grain yield of either maize or wheat from each treatment. Maize and wheat grain protein yield (kg $ha^{-1}$) was expressed as a product of the seed protein content (g 100 $g^{-1}$) and grain yield (kg $ha^{-1}$). Grain energy and protein contents for both maize and wheat were obtained from the Food Nutrition Table database (http://www.foodnutritiontable.com/, accessed on 15 April 2021). Maize energy and protein contents were reported to be 353 kcal 100 $g^{-1}$ and 10 g 100 $g^{-1}$, respectively, while for wheat they were reported to be 329 kcal 100 $g^{-1}$ and 12.4 g 100 $g^{-1}$, respectively.

#### 2.4.4. Economic Analysis

A gross margin analysis was conducted to evaluate the economic benefit of the 2 WT direct seeding. The partial budgeting technique was used to compare the profitability of conventional planting with 2 WT-powered direct seedings. All costs including expenses on inputs (seed, fertilizer, herbicide and labour), fuel and oil for the tractor, and labour were collected from each plot. Plot level maize and wheat yield data (t $ha^{-1}$), variable costs of each farm (inputs, labour, equipment hire fee, and other related costs) and output prices of three years were used for the gross margin analysis. These variable costs were recorded using standardized protocols developed by CIMMYT [40]. The input and output prices were converted from the Ethiopian Birr to USD using the prevailing official exchange rate of the National Bank of Ethiopia.

### *2.5. Statistical Analyses*

In the analysis of maize data, treatment (conventional practice and NT) and season were the fixed factors and the experimental farm was used as a random factor. Multiple linear mixed models with the corresponding analysis of variance (ANOVA) were used to assess the effect of treatment (conventional practice and NT) and season on maize yield, HI, plant population, gross margins, protein and energy yield. The same multiple linear mixed models were used to assess the effect of treatment (conventional practice and NT), season, agroecology and soil type on wheat yield, HI, HSW, gross margins, protein and energy yield. The fixed factors were treatment, season, agroecology and soil type, and the experimental farm was used as the random factor in the analysis of wheat data. Agroecology (semi-arid and sub-humid) and soil type (vertisol, clay loam and loamy sand) were not part of the maize model since these fixed factors were only featured in the wheat dataset. Analysis was conducted using the lme4 package for linear mixed regression analysis and the ggplot2 package for plotting all the graphs in R [41]. The following formula [2] is a multiple linear mixed regression model used:

$$y = \beta_0 + \sum_{j=1}^{k-1} \beta_j \theta_{ij} + \beta_{\omega ij} \omega_j + \varepsilon_{ij} \tag{1}$$

where

$y$ = maize/wheat yield (kg ha$^{-1}$), wheat/maize energy (GJ ha$^{-1}$), wheat/maize protein (kg ha$^{-1}$), maize density (plants ha$^{-1}$), maize/wheat HI, wheat HSW (g), or gross margin (US$ ha$^{-1}$)

$\beta_0$ = model intercept that represents the grand mean

$k$ = number of factor variables categories e.g., (treatment: 0 = CP, 1 = No-till)

$\beta_j$ = the regression coefficient associated with the $j$th factor variable (treatment, season)

$\theta_{ij}$ = the numerical value assigned to subject $i$ in the $j$th factor variable (season = 2018, 2019 and 2020)

$\beta_{\omega ij}$ = the coefficient of the possible interaction of $j$th factor variable.

$\omega_j$ = the possible interactions of the factor variables e.g., (*treatment: season*)

$\varepsilon_{ij}$ = error term

## 3. Results

### 3.1. Soil Properties

Soil conditions improved when tillage was changed from conventional to direct seeding no-till using a 2-WT (Table 1). All measured soil parameters were higher in the NT treatment compared with conventional ploughing. Only the differences in zinc and sulphur content between treatments were significant ($p < 0.05$). The increase in soil pH over time with direct planting is important for reducing soil acidity which is prevalent in western Ethiopia and other similar environments in the country. Similarly, the increase in soil organic carbon over time will improve the physical, chemical and biological conditions of the soil, leading to increased crop productivity on the farms. The results also indicated an increase in zinc, one of the critical micro-nutrients required for human nutrition.

**Table 1.** Soil properties measured four years after introducing 2 WT direct planting in maize systems of the Gudeya-Billa District. Figures in brackets are the standard deviation of each mean.

| Soil Property | Conventional Practice | No-Till |
|---|---|---|
| pH | 5.6 (0.44) | 5.7 (0.92) |
| Organic carbon (%) | 3.4 (0.07) | 3.8 (0.45) |
| Phosphorus (mg kg$^{-1}$) | 4.7 (0.68) | 5.2 (0.09) |
| Sulphur (mg kg$^{-1}$) | 8.5 (2.74) | 10.7 (3.27) |
| Zinc (mg kg$^{-1}$) | 2.6 (0.29) | 3.5 (0.74) |
| Cation exchange capacity (mg kg$^{-1}$) | 26.2 (0.57) | 26.9 (0.81) |

### 3.2. Crop Productivity

#### 3.2.1. Maize Productivity

Maize plant population varied with season and in 2019, NT treatment had significantly higher crop density than CP (Table 2). Maize stover yield and harvest index were not influenced by the treatments tested. Maize grain production was not significantly influenced by Treatment × Season interaction (Supplementary Table S1). Direct seeding significantly influenced maize grain production within and across seasons compared with the conventional practice (Figure 2). The NT treatment had 1210, 1351 and 1559 kg ha$^{-1}$ more grain than the conventional practice in 2018, 2019 and 2020, respectively. Across growing seasons, the NT treatment had 1346 kg ha$^{-1}$ more grain than the conventional practice. Maize yield significantly varied with season. The 2018 growing season had higher grain yield compared with 2019 and 2020 across trial sites, regardless of the land preparation and seeding system used. In the 2018 season, 992 mm of rainfall was received compared with 1116 mm recorded in 2019 (Supplementary Figure S1).

**Table 2.** Maize plant population (plants ha$^{-1}$), stover yield (kg ha$^{-1}$), and harvest index (HI) across sites used in 2018, 2019, 2020 and across seasons.

| Treatment | 2018 | | | 2019 | | | 2020 | | | Across Years | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Population** | **Stover** | **HI** | **Population** | **Stover** | **HI** | **Population** | **Stover** | **HI** | **Population** | **Stover** | **HI** |
| CP | 41,172 | 11,458 | 0.39 | 30,982 $^{b}$ | 5639 | 0.37 | 35,500 | 5014 | 0.47 | 37,337 $^{b}$ | 9126 | 0.34 |
| NT | 45,391 | 9232 | 0.49 | 37,946 $^{a}$ | 6568 | 0.41 | 42,000 | 5439 | 0.55 | 43,087 $^{a}$ | 9410 | 0.37 |
| *p*-value | ns | ns | ns | 0.0005 | ns | ns | ns | ns | ns | 0.0034 | ns | ns |
| SE | 2403 | 1452 | 0.067 | 1025 | 387 | 0.040 | 2508 | 506.6 | 0.033 | 1324 | 652.2 | 0.0244 |
| CV (%) | 11.1 | 28.1 | 30.3 | 5.56 | 16.8 | 19.1 | 14.2 | 21.2 | 14.3 | 14.1 | 30.0 | 29.3 |

HI—harvest index; HSW—hundred seed weight; SE—standard error; CV—coefficient of variation. Ns—not significant; Letters a and b are for mean separation.

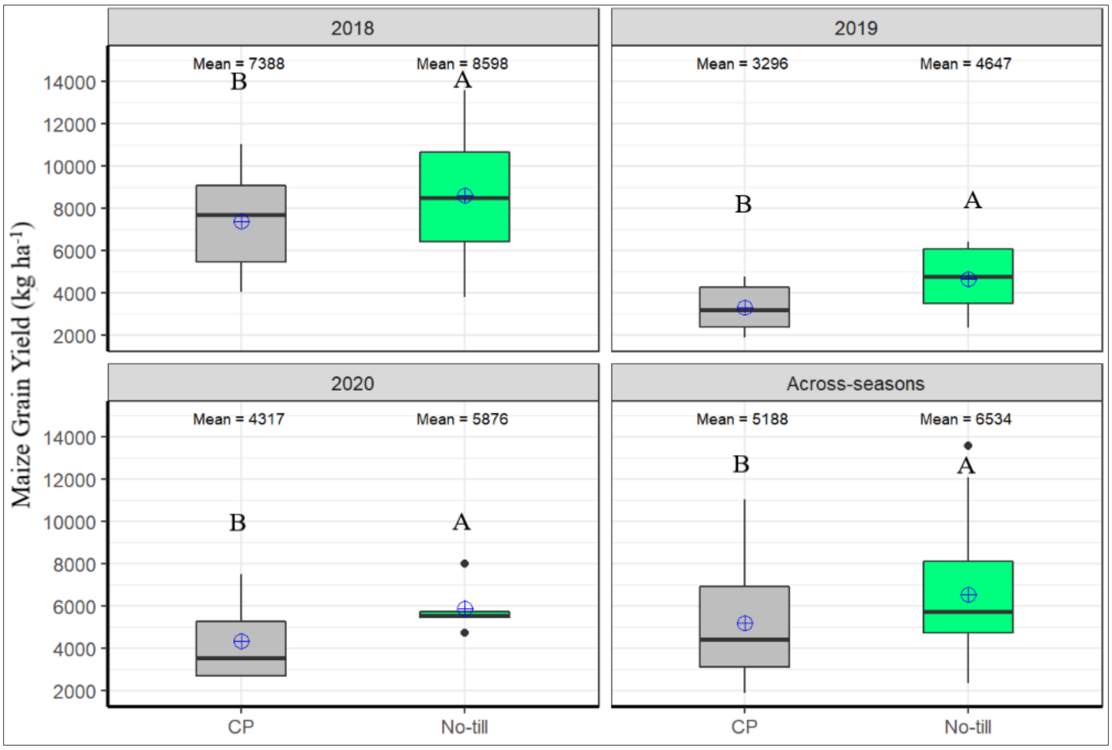

**Figure 2.** Maize grain yield from conventional practice and NT treatments in 2018, 2019, 2020 and across the growing seasons from experimental sites in the Gudeya-Billa district, Oromia, western Ethiopia. Means with different letters (A, B) in the same season are significantly different at $p < 0.05$. The blue dots within each box represent the mean yield while the horizontal line represents the median yield.

### 3.2.2. Wheat Productivity

The effect of NT and conventional treatments on grain yield was not dependent on soil type and agroecological conditions at the trial sites (Supplementary Table S2). Direct seeding significantly increased wheat grain production compared with the conventional practice (Figure 3). The NT treatment had 341, 722 and 1107 kg ha$^{-1}$ more grain than the conventional practice in 2018, 2019 and 2020 seasons, respectively. Across seasons, NT had 649 kg ha$^{-1}$ more grain than the conventional practice. Based on soil types, the NT treatment had a higher grain yield than conventional practice under clay-loam and vertisol soil (Figure 4; Supplementary Table S2). Under clay loam and vertisol, NT had 683 and 844 kg ha$^{-1}$ more grain than conventional practice, respectively. However, conventional and NT treatments had similar yields under loamy sands which were in semi-arid parts of Ethiopia. Wheat straw yield, HI and HSW varied with the season (Table 3). The NT treatment had a higher straw yield than conventional practice in 2018, contrary to the trend in the other two years. The NT treatment had higher HI than conventional practice, but the two systems had a similar effect on HSW.

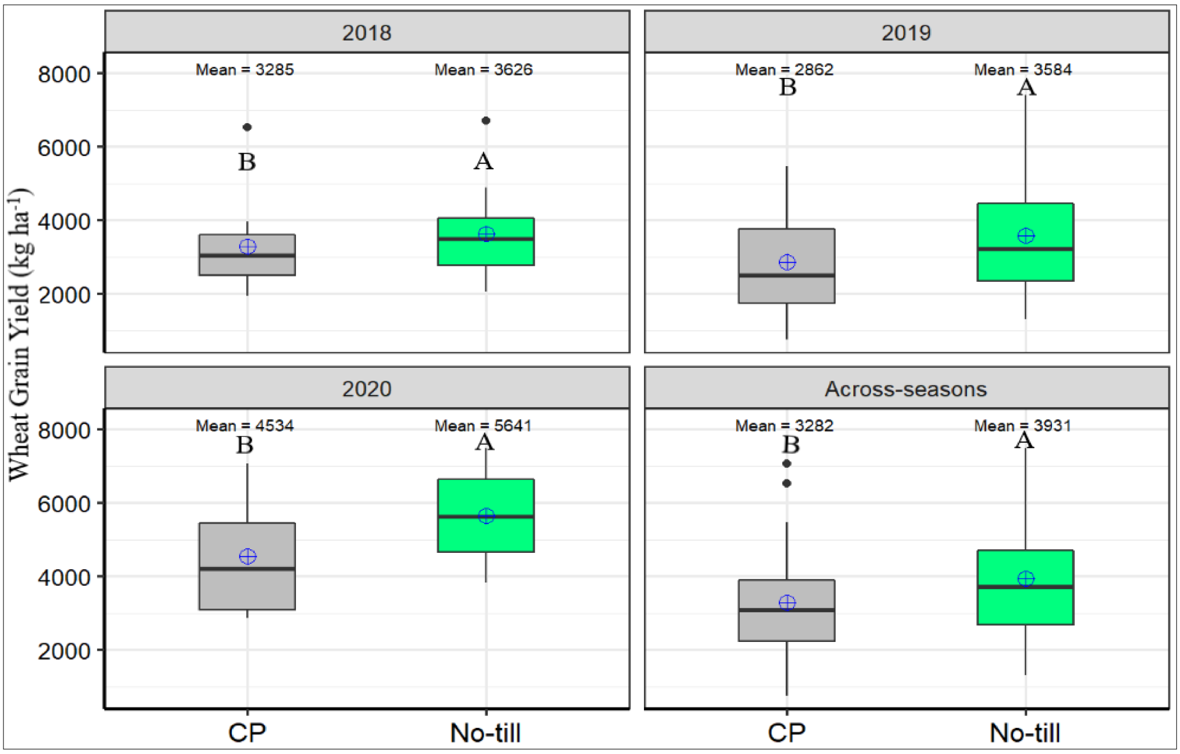

**Figure 3.** Wheat grain yield from conventional practice and no-till (NT) treatments in 2018, 2019, 2020 and across the growing seasons. Means with different letters (A, B) in the same season are significantly different at $p < 0.05$.

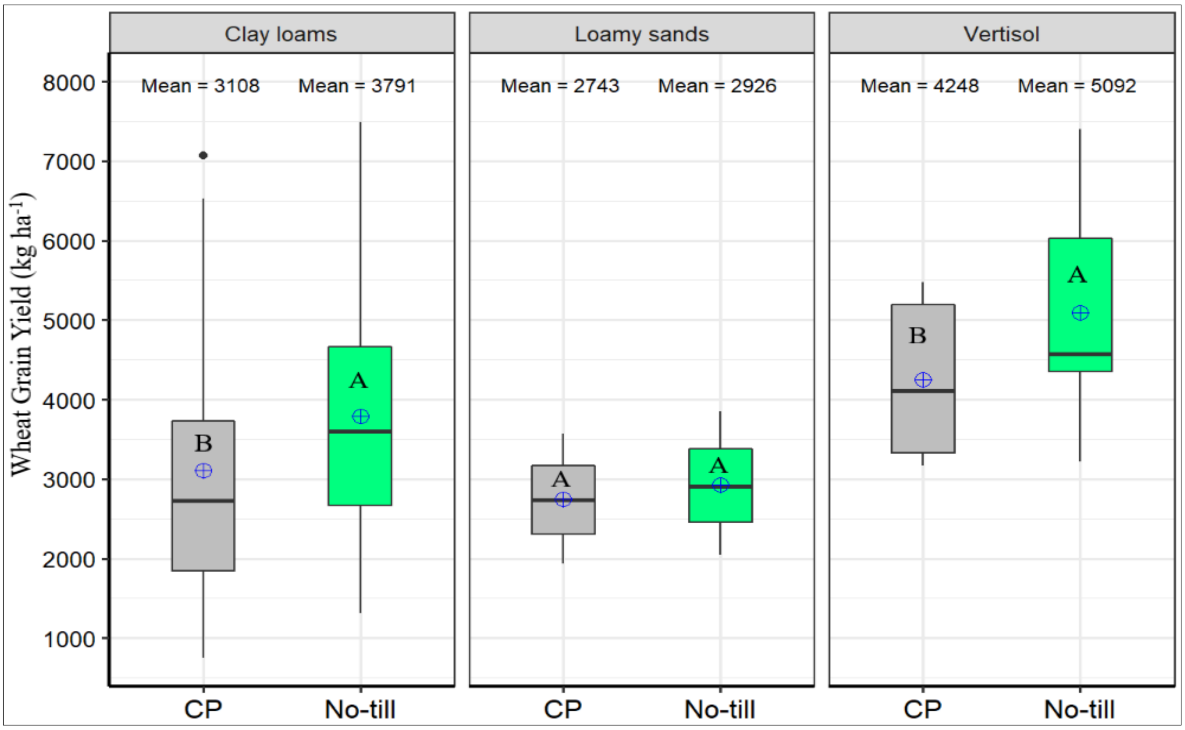

**Figure 4.** Wheat grain yield from conventional practice and no-till (NT) treatments from sites under clay-loam, loamy sands and vertisol across growing seasons. Means with different letters (A, B) under each soil type are significantly different at $p < 0.05$.

**Table 3.** Wheat straw yield (kg $ha^{-1}$), harvest index and hundred seed weight (g) in 2018, 2019, 2020 and across seasons.

| **Treatment** | **2018** | | | **2019** | | | **2020** | | | **Across Years** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Straw** | **HI** | **HSW** | **Straw** | **HI** | **HSW** | **Straw** | **HI** | **HSW** | **Straw** | **HI** | **HSW** |
| CP | 3 243 $^{b}$ | 0.47 $^{b}$ | 4.0 | 6 245 | 0.31 $^{b}$ | 3.2 | 2811 | 0.62 $^{a}$ | 3.28 | 3071 $^{b}$ | 0.51 b | 3.50 |
| NT | 4 149 $^{a}$ | 0.51 $^{a}$ | 4.2 | 6 862 | 0.34 $^{a}$ | 3.7 | 3759 | 0.60 $^{b}$ | 3.32 | 3897 $^{a}$ | 0.54 a | 3.78 |
| *p*-value | 0.0026 | 0.0318 | ns | ns | 0.0074 | ns | ns | 0.0198 | ns | <0.001 | 0.0094 | ns |
| SE | 228 | 0.012 | 0.23 | 378 | 0.010 | 0.213 | 305.7 | 0.0034 | 0.1196 | 112.1 | 0.007 | 0.105 |
| CV (%) | 14.4 | 7.9 | 12.0 | 15.8 | 8.8 | 16.7 | 20.8 | 1.26 | 8.10 | 15.4 | 6.36 | 14.8 |

HI—harvest index; HSW—hundred seed weight; SE—standard error; CV—coefficient of variation. Ns—not significant; Letters a and b are for mean separation.

### 3.3. System Nutritional Value

Energy and protein contributions from maize and wheat systems followed a similar trend demonstrated by the grain yields from the two treatments. The NT treatment had 18, 20, 29 and 21 GJ $ha^{-1}$ in 2018, 2019, and 2020, and across seasons, respectively, compared with the conventional practice in the maize system (Figure 5). Similarly, maize protein gains from NT were, respectively, 121, 135, 194 and 144 kg $ha^{-1}$ in 2018, 2019, and 2020, and across seasons (Figure 6). In the wheat system, NT had 5, 10, 16 and 9 GJ $ha^{-1}$ in 2018, 2019, and 2020, and across seasons more than the conventional practice, respectively, (Figure 7). The protein gains from NT were 43 kg $ha^{-1}$ in 2018, 89 kg $ha^{-1}$ in 2019, 137 kg $ha^{-1}$ in 2020 and 80 kg $ha^{-1}$ across seasons compared with the conventional practice (Figure 8).

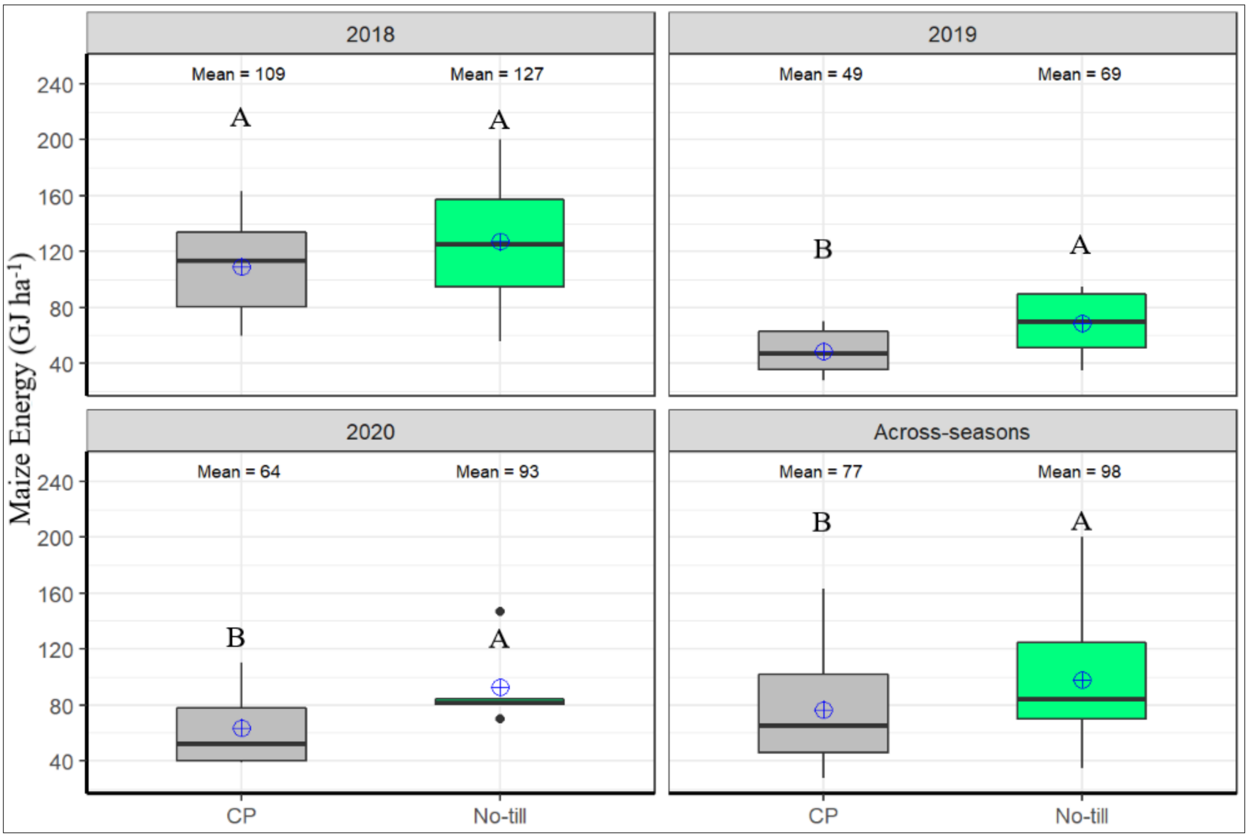

**Figure 5.** Energy contributions from conventional practice and NT treatments under maize cropping system in 2018, 2019, 2020 and across the growing seasons. Means with different letters (A, B) in the same season are significantly different at $p < 0.05$.

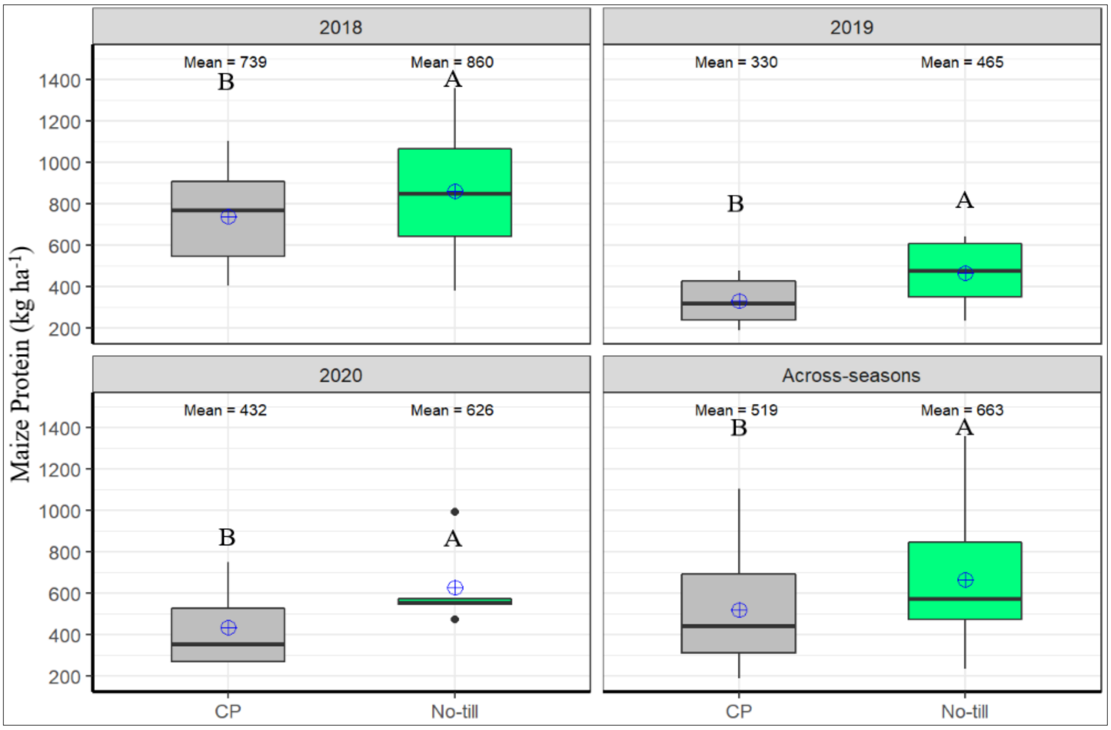

**Figure 6.** Protein contributions from conventional practice and NT treatments under maize cropping system in 2018, 2019, 2020 and across the growing seasons. Means with different letters (A, B) in the same season are significantly different at $p < 0.05$.

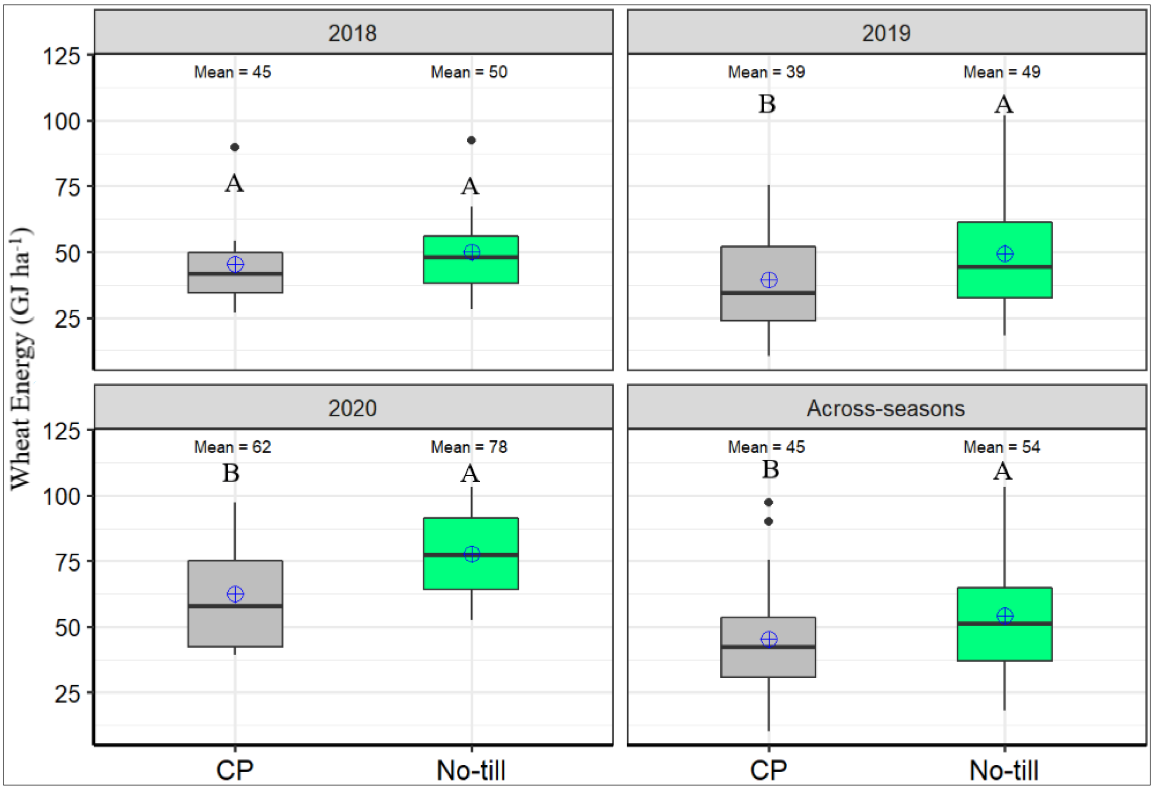

**Figure 7.** Energy contributions from conventional practice and NT treatments under wheat cropping system in 2018, 2019, 2020 and across the growing seasons. Means with different letters (A, B) in the same season are significantly different at $p < 0.05$.

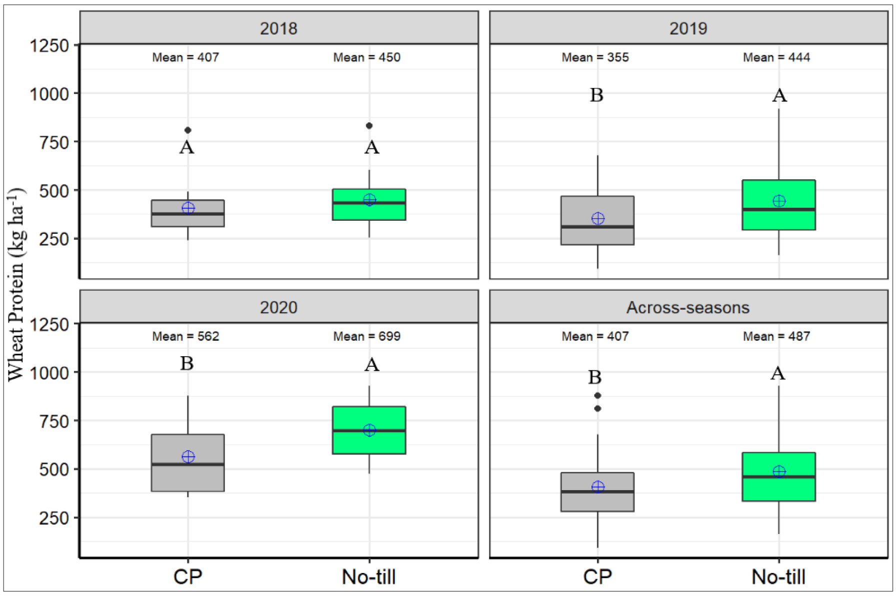

**Figure 8.** Protein contributions from conventional practice and NT treatments under wheat cropping system in 2018, 2019, 2020 and across the growing seasons. Means with different letters (A, B) in the same season are significantly different at $p < 0.05$.

### 3.4. Gross Margins from Maize and Wheat Cropping Systems

The NT treatment had higher ($p < 0.05$) economic returns than the conventional practice in both maize and wheat cropping systems (Figures 9 and 10). In the maize system, NT had 358, 385 and 156 US\$ ha$^{-1}$ more than the conventional practice in 2018, 2019 and 2020, respectively. Across seasons, NT outperformed the conventional practice by 317 US\$ ha$^{-1}$. As observed with the grain yield, gross margins varied with the season in the maize cropping systems of western Ethiopia. In the wheat system, NT treatment had 230, 453 and 692 US\$ ha$^{-1}$ more compared with the conventional practice in 2018, 2019 and 2020, respectively. Across seasons, NT had 412 US\$ ha$^{-1}$ more than the conventional practice.

**Figure 9.** Gross margins from conventional practice and NT treatments under maize cropping system in 2018, 2019, 2020 and across the growing seasons. Means with different letters (A, B) in the same season are significantly different at $p < 0.05$.

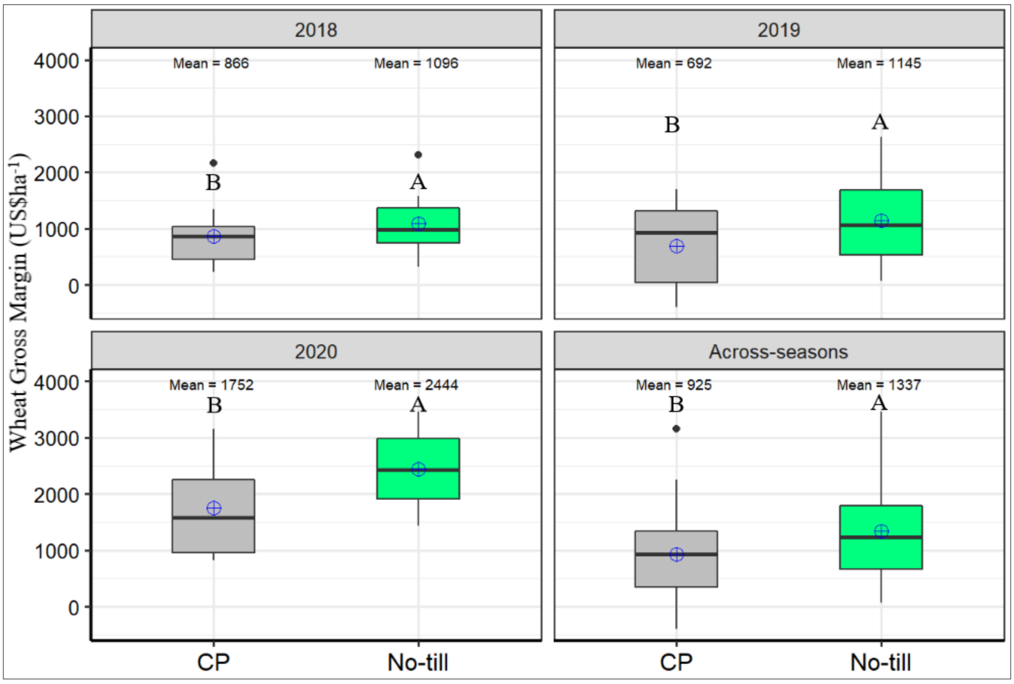

**Figure 10.** Gross margins from conventional practice and NT treatments under wheat cropping system in 2018, 2019, 2020 and across the growing seasons. Means with different letters (A, B) in the same season are significantly different at $p < 0.05$.

# 4. Discussion

## *4.1. Crop Productivity and Nutritional Gains*

### 4.1.1. Maize Productivity and Nutritional Gains

Higher maize productivity averaging 26% yield advantage was achieved from the NT-based 2 WT direct seeded system relative to the conventional practice. Maize yields across all sites were above the national average of 3230 kg ha$^{-1}$ for Ethiopia which therefore enhances food security [42]. The yield gain can be attributed to increased precision in NPS basal fertilizer placement close to the maize roots during crop establishment and the improvement in soil properties. The NPS basal fertilizer supplied 28.5, 24.5 and 10.5 kg ha$^{-1}$ N, $p$ and S, respectively. This promoted the early vigour of the maize plants during crop establishment, which ultimately resulted in higher yields. Phosphorus is required for root development [43] and with better root development the crop establishes faster, especially in soils low in P such as in the Gudeya-Billa area [5]. Ref. [44] indicated that efficient utilization of other production resources such as rainfall can be improved by more precise management of plant nutrients in the cropping system. Soils in Gudeya-Billa were inherently low in N and P, the critical nutrients that were supplied close to roots in NT-based direct seeded plots compared to the broadcast nutrients along the planting furrow in the conventional system. On the contrary, the limited nutrient use efficiency associated with conventional practices could have led to relatively lower maize yields in the conventional treatment. Maize yield differences between seasons can be attributed to rainfall patterns experienced during the three seasons. The 2019 and 2020 seasons had continuous rains during the June–July period, and this coincided with the vegetative stage of the maize crop in the trials. This could have led to excess soil water in both treatments which affected maize crop development in the vegetative phase, resulting in lower yield compared with the 2018 season which had a better distribution of rainfall. Maize yield differences between seasons could have been due to the unfavourable monocropping system that was used in the trials over the three years.

The 26% maize yield gain from the NT system can go a long way towards reducing the yield gap of this critical food security crop in Ethiopia and other SSA countries. The current yield gap has contributed substantially towards household food insecurity in the country. Reduction in the maize yield gap on smallholder farms has been attributed to the use of improved varieties, increased use of inorganic fertilizers and improved access to extension services [45] as well as agricultural technology [46]. Results suggest that the 2 WT direct seeded cropping systems have the potential of reducing the yield gap in maize production systems of the Ethiopian highlands. Good agronomic practices such as rotation and integrated soil fertility management combined with 2 WT direct seeding could further increase maize productivity thus reducing the yield gap in maize-based cropping systems on smallholder farms [20,47].

A smallholder farming household of five people requires at least 1000 kg of maize grain per year [48,49] and smallholder yields can be as low as 100 kg ha$^{-1}$ [50]. Given the yield gain of 1346 kg ha$^{-1}$ from the 2 WT seeded system across seasons, direct seeding can be a good option for smallholders to increase productivity and food security in Ethiopia and SSA. Growing food legumes such as common bean (*Phaseolus vulgaris* L.) and faba bean (*Vicia faba* L.) which are adapted to western Ethiopia, can further enhance food and nutrition security in maize-based systems. The 27% energy gain from the NT system will go a long way in supplementing energy sources from other foodstuffs available in a farming household. Similarly, the 28% protein gain from the NT system will supplement other protein sources such as pulses for farming households.

### 4.1.2. Wheat Productivity and Nutritional Gains

Higher wheat yields from NT-based 2 WT direct seeding were consistently observed with a difference of 20% recorded compared with conventional practice. The average wheat yield achieved across all sites was greater than the national average of 2700 kg ha$^{-1}$ [4]. As with maize systems, the yield differences between treatments can be attributed to the precise placement of basal NPS close to the seed at planting. In addition, soil moisture was not limiting during planting and crop establishment stages, due to sufficient rainfall received, hence N and P from basal fertilizer were efficiently utilized for crop growth. Phosphorus is critical during the first five to six weeks of crop growth [43], and an adequate supply of the nutrient during that time often leads to an increased final yield. During that period, adequate P supply from the soil helps root development [43]) and the initiation tillers which contribute significantly towards final grain yield. Adequate basal fertilization combined with precise placement of the fertilizer in the root zone is therefore critical in increasing wheat yield. Basal fertilizer applied at planting supplied 28.5, 24.5 and 10.5 kg ha$^{-1}$ N, P and S during crop establishment. The P quantity from basal NPS fertilizer was adequate to potentially produce a crop of up to 6 000 kg ha$^{-1}$ grain yield [50].

The overall 20% wheat yield gain achieved by using 2 WT direct seeding represents a significant step in closing the yield gap currently experienced between what farmers are achieving and the potential for their regions in Ethiopia. Ref. [4] reported wheat yield gaps of 14–17% under farmer conditions in Ethiopia, and the 2 WT direct seeding system can therefore contribute significantly towards improving wheat productivity in the country. Technologies and innovations that reduce the current wheat deficit standing at 1.9 million tonnes per year in Ethiopia [4] are critical for enhancing food security, and this further emphasizes the role that small-scale mechanization can play in improving the productivity of wheat-based cropping systems.

In all soil types, NT had yield gains over the conventional practice, implying that the 2 WT direct seeding can be a viable option in different locations of the highlands with similar soil types. This helps in identifying appropriate niches based on soil type for the 2 WT direct seeding technology. One of the challenges with the promotion of the 2 WT-based technologies is finding the appropriate niche for each technology. The niches vary and could be based on topography, soil type, farmer demand, and crops grown, among other factors [15].

Field experience during direct seeding with the 2 BFG planter revealed challenges with planting in relatively wet vertisol during the recommended planting window for the Ethiopian highlands where wheat is grown. As in any other region, timely planting is critical in the wheat belt of Ethiopia and farmers are already operating following a recommended planting window developed through research. However, the current planting window coincides with relatively high rainfall activity that results in high moisture content in the vertisols. This in turn makes seeding on the flat with the 2 BFG difficult, as experienced during trial establishment. There is, therefore, a need to either adjust the planting window or modify the current design of the 2 BFG planter or combine two-wheel tractor direct seeding with the raised beds system or a combination of the three options in areas with heavy textured soils.

The daily average energy requirement of an adult human being is 2 410 kcal [48,49]. The energy gain attributed to the use of the direct seeding technique can supplement other energy sources used by farming households. The energy deficits can further be reduced by additional yield increases in the NT cropping systems through mulching and the use of crop rotations. Mulching increases yields through soil moisture retention [47,51]. The research work in Ethiopia acknowledges the shortage of mulch attributed to crop-livestock competition. Such a challenge can be addressed through the use of alternate sources of livestock feed such as forage legumes and grasses, and crop residues can be utilised for mulching [52]. Crop rotations involving adapted legumes such as faba bean, chickpea (*Cicer arietinum* L.) and lentil (*Lens culinaris* Medic.) can lead to improved soil quality which ultimately increases wheat yields. The inclusion of these food legumes in wheat cropping systems will further complement the protein contributions of wheat to the household diet.

### 4.2. Gross Margins from Maize and Wheat Systems

The NT-based 2 WT direct seeding cropping system was more profitable relative to the traditional Maresha-based practice which involves ploughing 4–5 times before establishing a crop. Higher returns from the NT system are attributable to reduced labour intake of the practice during land preparation and planting, as well as increased crop yields. The 2 WT direct seeding combined land preparation, seed and basal fertilizer placement, and covering in one pass, in one hand. On the other hand, in the conventional practice, fields were ploughed 3–4 times before manual basal fertilizer and seed placement and covering during the 4th–5th plough-planting operation. Manual labour was used to ensure seed and basal fertilizer are properly covered during the final plough-planting operation.

Studies on conservation agriculture cropping systems with minimum tillage combined with other practices demonstrated that higher net returns are achievable in smallholder systems relative to the conventional practices dominant in SSA [23,53,54]. With the improved maize and wheat yields from the NT system, direct seeding, therefore, increased family labour productivity on the smallholder farms. This can be an incentive for smallholder farmers who often aim at increasing the productivity of farming resources including available farm labour [55]. Reductions of 36–39 labour days per hectare have been reported where minimum tillage in CA-based practices are implemented [24,53,56]. Scaling out of labour-saving technologies such as 2 WT direct seeding need to be given more attention in future initiatives targeted at improving smallholder agriculture in SSA.

## 5. Conclusions

The study assessed the effect of no-till based 2 WT direct seeding on maize and wheat productivity, nutritional contributions and gross margins on smallholder farms. No-till direct planting improved the properties of the *Alfisols* over a four-year period across experimental sites. Direct seeding using 2 WT-powered planters increased maize and wheat yields in smallholder cropping systems. The increase in crop yield due to direct seeding was not influenced by the quality of the growing season, giving farmers a good option for producing the two food security cereals that are critical for the country regardless of the quality of the growing season. The use of the direct seeding system has great potential for contributing towards reducing yield gaps in the maize and wheat production systems of Ethiopia. With increased yields, energy and protein contributions also increased in maize and wheat systems, and this significantly addresses the nutritional needs of smallholder farming households. Two-wheel tractor-powered direct seeding generated higher gross margins than the conventional practice. Direct seeding with 2 WT planters, therefore, generate more income for smallholder farmers in the maize and wheat production parts of the Ethiopian highlands than the conventional practice. There is scope for widescale promotion of NT systems in maize and wheat-based systems of the Ethiopian highlands and similar environments. Future research work could assess the contributions of 2 WT-based NT systems on soil quality and land degradation under the highland conditions of Ethiopia and similar environments in SSA.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13010115/s1, Figure S1: Monthly rainfall received at Gudeya-Billa trial sites during experimentation in 2018 and 2019 seasons; Table S1: ANOVA output for grain yield obtained from maize cropping systems tested in western Ethiopia; Table S2: ANOVA output for analyses of grain and straw yield, gross margins, energy, and proteins from wheat cropping systems.

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**Informed Consent Statement:** Informed consent was obtained from all farmers involved in the study. The farmers granted the researchers permission to use their fields.

**Data Availability Statement:** The data that support the findings of this study are available from the corresponding author upon reasonable request.

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