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Comparison of mechanized conservation agriculture and conventional tillage in Zambia: A short-term agronomic and economic analysis

Godfrey Omulo [a,*,1], Regina Birner [a], Karlheinz Köller [b], Simunji Simunji [c], Thomas Daum [a]

[a] Hans-Ruthenberg Institute of Agricultural Sciences in the Tropics, University of Hohenheim, Wollgrasweg 43, 70599 Stuttgart, Germany
[b] Institute of Agricultural Engineering, University of Hohenheim, Garbenstrasse 9, 70599 Stuttgart, Germany
[c] Department of Plant Science, School of Agriculture Sciences, The University of Zambia, P.O. Box 32379, Lusaka, Zambia

A R T I C L E I N F O

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A B S T R A C T

The rise of medium-scale farmers across sub-Saharan Africa (SSA) is offering Conservation agriculture (CA) a new perspective. Such farmers not only cultivate increasingly large land areas but also provide machinery services, share knowledge, and can act as role models to smallholders. Although mechanization may incentivize CA adoption in SSA, little research has focused on the performance of mechanized CA using four-wheel tractors (4WTs). This study explores the short-term agronomic and economic differences between mechanized conventional tillage and mechanized CA. An on-farm experiment was set up in a randomized complete block design in Zambia to compare 1) disc harrowing (DH) plus residue burning, 2) ripping tillage (RT), and 3) direct seeding (DS) plus soil cover. The experiment focused on maize and soyabean and covered two years, of which the first was more "dry" and the second more "wet". All treatments were replicated four times and crops were rotated in the subsequent season. All operations were performed using a 60 hp 4WT. For both maize and soyabeans, DS and RT treatments resulted in higher grain yields during the dry season than DH. However, in the wet season, DH and RT resulted in significantly higher yields than DS for maize, but not for soyabeans. RT and DS plots showed higher plant densities in maize and soyabeans at germination and maturity than DH plots. RT plots produced significantly higher maize vegetative biomass (5928 kg ha^{-1}) in the dry season while in the wet season DS recorded significantly higher biomass yields (7886 kg ha^{-1}). The cumulative time for all agronomic operations except harvesting for both maize and soyabean was significantly lower in DS while DH and RT treatments recorded no significant differences. Fuel-saving was significantly higher in DS and RT than in DH plots for the two crops. Maize gross margin was highest in DS plots (US$790 ha-1) in the dry season compared to US$746 ha-1 for DH and US$768ha-1 for RT. In the wet season, DH plots had the highest gross margins for maize (US$685 ha-1) as compared to US$576 ha-1 for DS and US$581 ha-1 for RT. Regarding soyabeans, DS treatments had the highest gross margins in both seasons, US$537 ha-1 and US$392 ha-1, respectively. The results of this short-term study demonstrate the potential of mechanized CA among small and medium-scale farmers in SSA.

1. Introduction

The practice of conservation agriculture (CA) has become widespread worldwide, being adopted by small, medium, and large-scale farmers alike (Kassam et al., 2019). CA is an ecosystem-friendly practice that combines the three interlinked principles of minimal mechanical soil disturbance, maintenance of soil mulch cover, at least 30%, and diversification of crops to improve soil, nutrient, and water management (FAO, 2016). Research has shown that CA can enhance yields (Mupangwa et al., 2019), improve economic gains (Lalani et al., 2017) and enhance soil and water conservation (Thierfelder et al., 2013). Most CA research, promotion, and adoption in sub-Saharan Africa (SSA) has focused on smallholder farmers, using manual labor (Mupangwa et al., 2019). Notably, most agronomic experiments in SSA are conducted on small plots at research stations or in farmers' fields (Thierfelder and Wall, 2009; Mupangwa et al., 2019). Emerging evidence shows that CA adoption is often undermined due to its high labor burden, i.e., when CA techniques such as planting basins are used (Thierfelder et al., 2016; Rusinamhodzi, 2015). This has led to calls for mechanized CA (Brown et al., 2018; Grabowski et al., 2014; Thierfelder et al., 2016; Umar et al.,

* Corresponding author.
E-mail address: godfrey.omulo@uni-hohenheim.de (G. Omulo).
[1] ORCID: 0000-0002-2501-3487.

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2014; Omulo et al., 2022). Mechanization can either be achieved using animal draught power, two-wheeled tractors or four-wheeled tractors. Thus, amidst various mechanization promotion attempts in SSA, the FASACI project has shown both the opportunities as well as constraints to use two-wheel tractors (2WTs) for scaling CA (Baudron et al., 2015, 2019). Despite the prospects offered by 2WTs, they have limited scope because of their low tractive capacity to operate under rainfed conditions in most SSA soils and less fragmented farms (Baudron et al., 2015). So far, limited research has focused on the role of four-wheel tractors (4WTs) to scale CA. Starting from a low level, 4WTs are on the rise in Zambia (Jayne et al., 2019). This is because medium-scale farmers are steadily growing in number and size in various African countries (Sitko and Jayne, 2014) and they are increasingly buying or hiring tractors for land preparation (Adu-Baffour et al., 2019; Omulo et al., 2022). Such medium-scale farmers (sometimes referred to as “emergent” farmers) in Africa cultivate between 5 and100 ha, and they often also offer mechanization services, thereby creating an impact beyond their farms (Sitko and Jayne, 2014; Adu-Baffour et al., 2019; Omulo et al., 2022).

Despite the growth of medium-scale farmers in African countries, limited research has investigated how their adoption of mechanized conservation agriculture (MCA) can influence agricultural productivity, socio-economic trade-offs and environmental footprints as opposed to mechanized conventional practices (Sitko and Jayne, 2014). Our study is the first to examine the economic and agronomic performance of MCA and conventional tillage in SSA on medium and large-scale plot experiments. As such, the perceived successes, and challenges of CA-based tillage practices over conventional farming practices require validation by medium-scale experiments that are relevant for mechanizing emergent farmers (Mupangwa et al., 2019). Further, it is important to understand the short-term agronomic and economic performance of MCA as this will shape the adoption decision of farmers who are seeking to hire mechanization services for their farming operations (Omulo et al., 2022).

To address this gap, we conducted a field trial involving the production of maize and soyabeans in Zambia. This is key, noting that Zambia is the country with the second-largest land area under CA in SSA due to its continued promotion and adoption (Kassam et al., 2019; Omulo et al., 2022). Maize is Zambia’s most important staple food, and the demand for the sustainable production of sufficient quantities to feed a growing population and combat food insecurity is high (Thierfelder et al., 2013). Conversely, soyabean is rapidly becoming a cash crop among small, medium, and large-scale farmers in Zambia, making it an economically viable crop since its price is relatively stable in comparison to maize (Mofya-Mukuka and Hichaambwa, 2018).

The objectives of this study were (1) to investigate the agronomic and yield differences between maize and soyabean under three mechanized operations: residue burning and disc-harrowing (conventional practice), ripping (reduced tillage) and direct seeding (zero tillage); (2) to determine the socio-economic impacts of ripping and direct seeding compared to conventional disc-harrowing in terms of the operation time, hiring labor costs and fuel consumption; and (3) to analyse the overall profitability and economic viability of ripping and direct seeding compared to conventional disc harrowing.

We evaluated the three tillage options with regard to these objectives over two cropping seasons. It is well established in the literature that the agronomic and economic benefits of CA only occur in the long term, because the biological, chemical, and physical properties of the soil improve gradually and it may, therefore, take up to 15 years before yield effects occur (Corbeels et al., 2014: 160–161). However, short-term effects are still important from the farmers’ perspective. The first few years play a crucial role in determining whether farmers, who often have short-term needs and trade-offs, will or will not continue to practice CA (Corbeels et al., 2014; Grabowski et al., 2016). If one can show under what circumstances switching to mechanized CA practice does, at least, not have a negative economic impact in the early years of adoption, an important obstacle to the adoption of CA can be addressed. We assessed the costs and benefits of mechanized CA for a scenario where a farmer hires agricultural machinery services. Thus, our results are very relevant for smallholder and medium-scale farmers who can access mechanization services. The research findings are intended to generate evidence for farmers, policymakers, and development partners about the feasibility of mechanization in enabling CA adoption and ensuring sustainable agricultural mechanization in Africa, as demanded by the FAO and African Union (FAO and AUC, 2018).

2. Materials and methods

2.1. Study site description

The study was conducted in the Central Province of Zambia at the German-Zambian Agricultural Knowledge and Training Centre (AKTC) located within the Golden Valley Agricultural Research Trust (GART) in Chisamba district, 65 km north of Lusaka (Fig. 1). Central Province lies between latitude 11–15°S and longitude 25–31°E, within Zambia’s agricultural ecological zone IIa, which is characterized by fertile reddish-brown clay soils (Acrisols). The soils in the Chisamba district are erodible, acidic, and nutrient-deficient because of prolonged weathering processes (Simunji et al., 2018). Recurrent droughts and unpredictable rainfall patterns have been observed in this area, a trend observed throughout Zambia (Musonda et al., 2020).

The study area is characterized by annual precipitation of approximately 700–1000 mm. However, great variability has been recorded in the past two decades with the 2006/2007 and 2018/2019 seasons recording the highest (1206 mm) and the lowest (562 mm) rainfall amounts respectively (Fig. 2). The rainfall period spans from late October to the end of April, lasting for about 120–160 days. The daily rainfall data was measured using an automatic weather station on site. A total of 714 mm of rainfall, average air temperatures between 22 °C and 28 °C and relative humidity between 28% and 86% were recorded in the 2019/2020 season. In the second season, 2020/2021, a total of 1068.42 mm precipitation, average air temperature between 20 °C and 26 °C and relative humidity between 41% and 89% were registered.

2.2. Experimental design

A mechanized on-farm experiment was conducted for two seasons under a rain-fed farming system based on disc-harrowing (conventional option) and ripping and direct seeding (CA option) on 15 ha of land that had been fallow for three years. The farm was divided into two main plots: 8 ha for maize and 7 ha for soybeans based on the orientation and uniformity in soil properties. The two main plots were further subdivided into smaller experimental units, each factoring three treatments replicated four times, totaling 12 experimental units per crop. A disc harrow and a planter were used for conventional tillage, while a ripper and a no-till planter were used for conservation options. Treatments were based on three types of tillage: disc harrowing (DH), ripping tillage (RT), and direct seeding (DS). DH included prior burning of crop residues, whereas RT and DS plots had at least 30% residue retention (FAO, 2016; Kassam et al., 2019). The crop residue percentage was determined using the combination of photo comparison and meter stick techniques (ICM, 2002). The meter stick was thrown randomly across the plot and the crop residues occurring along the meter counted. If the residues occurred at marking more than 30 cm, the percentage of residue was taken as more than 30% and thus sufficient. With the aid of photos taken across the plots, residues were redistributed from areas with high cover (more than 50%) to less covered parts upon the determination by the meter stick technique (ICM, 2002).

Treatments within the blocks were assigned based on randomized complete block design to enable the establishment of tillage effects on agronomic factors, time use, fuel consumption, labor costs, and overall profitability (Thierfelder et al., 2013). DH was conducted at a depth of 20 cm, 1–2 weeks before planting. A two-tine ripper with a row spacing

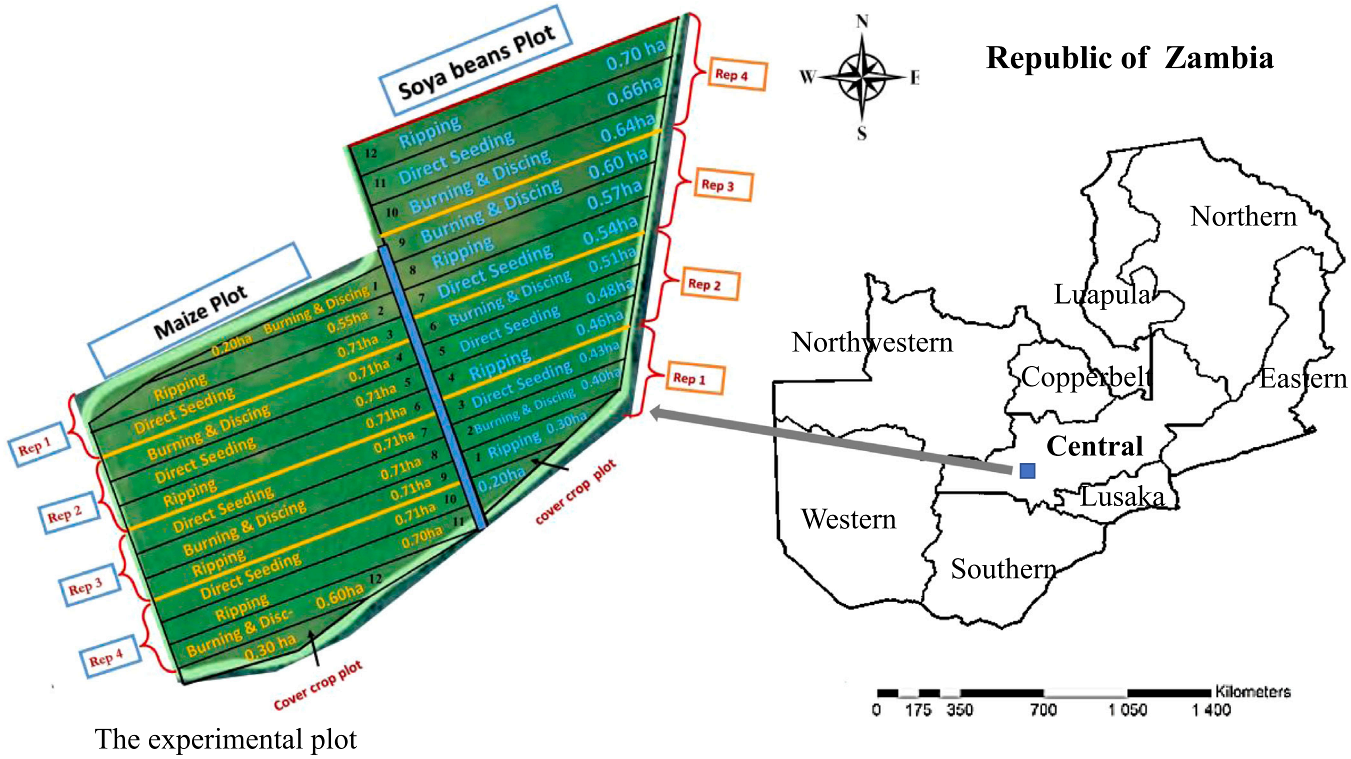

Fig. 1. Location of the study area, 14° 57′ 42″ S, 28° 04′ 53″ E, 1147 m above the sea level, Central Province of Zambia.

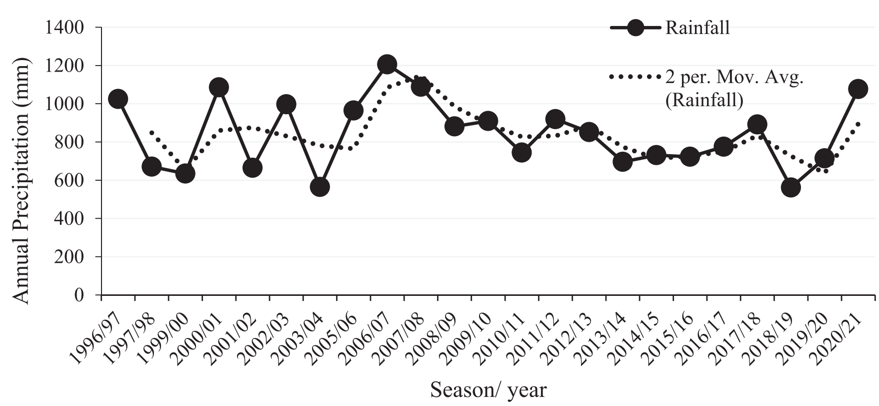

Fig. 2. Total annual rainfall plus two-period moving average comparisons in two decades.
Source: Data from AKTC and GART weather department.

of 75 cm was utilized 1–2 weeks before seeding, to rip at a depth of 15 cm for maize and 10 cm for soyabeans. A two-row no-till planter was used to plant both DS, RT and DH plots. The average experimental plot size for a maize plot was 24 by 270 m while the plot size for a soyabean plot was 24 by 220 m. Each replicate was separated by a 2-meter buffer zone, while the maize and soyabean plots were separated by a 6-meter buffer zone. Land preparation, planting, fertilizer application, weed-, fungi-, and pest- control were performed using specific implements mounted on a 4WT 60 hp tractor. In both seasons, planting was done shortly after the first substantial rainfall of about 90 mm. Table 1 summarizes the experimental management.

2.3. Soil sampling and analysis

Soil samples were collected at depths of 15–25 cm before the onset of every season and analysed based on the gamma-ray spectroscopy prediction method (Mahmood et al., 2013). Nitrogen content analysis was done using the Kjeldahl method (Parkinson and Allen, 1975). The soil texture, soil type, pH, soil carbon (C) and other soil minerals composition generated at the onset of the trial and after the first season's rotation are shown in Table 2.

2.4. Agronomic data collection

Maize and soyabean populations were measured two weeks after germination and at maturity. Lodged, inclined or plants with broken stalks were considered during the population data collection. Maize height (m) was established by measuring the above-ground height to the base of the tassel for 20 randomly selected plants per plot (Sime et al., 2015). The crops were harvested at physiological maturity and recommended grain moisture contents. The yields of both crops were measured using plot sample harvesting, then extrapolated per hectare. In each treatment, 10 points of 7.5 m^2 maize were harvested from two rows of five meters long, excluding two edge rows on both sides. Maize

Table 1
A summary of agronomic considerations for both maize and soyabeans for the two seasons.

Practice	Maize	Soyabean
Seed variety	SeedCo 633, medium maturing, 135–140 days to physiological maturity	SeedCo Safari, drought-tolerant, 100–125 days to physiological maturity
Seed rate (kg ha^{-1})	25	80
Seed treatment	None	Treated with RhizoFlo 5 bacterial inoculant at the rate of 400 ml/100 kg seeds
Spacing (cm)	75 × 25	75 × 5
Expected population per ha	53,000	266,000
Basal fertilizer application	36 $kgNha^{-1}$ 62 $kgP_2O_5ha^{-1}$, 43 kgK_2Oha^{-1} 1.5 $kgZnha^{-1}$, 0.3 $kgBha^{-1}$	15 $kgNha^{-1}$, 51 $kgP_2O_5ha^{-1}$, 53 kg K_2O ha^{-1} 4.5 $kgSha^{-1}$, 1.1 $kgZnha^{-1}$ 0.7 $kgBha^{-1}$
Topdressing fertilization	123 kgN ha^{-1}, 64 kgS ha^{-1}, 16 $kgCaha^{-1}$	Omni boost 0.36 $kgNha^{-1}$, 0.81 $kgPha^{-1}$
Weed management	Mixture of Glyphosate (2 l/ha) and 2,4D (500 ml/ha) for pre-emergent control, and Nicosulfuron (60 g/ha) and auxo (1.5 l/ha) for post emergent control	Mixture of Glyphosate (2 l/ha), dual (1.2 l/ha) and Metribuzin (700 ml/ha) for pre-emergent control, and Flex and Fomesafen (1 l/ha), Quizalofop-p-ethyl (1.5 l/ha) and Imazethapyr (700 ml/ha) for post emergent control
Insect control	Belt (200 ml/ha) for fall armyworm and Thunder (200 ml/ha) for cricket control	A mixture of the Belt (75 ml/ha) and Warrant power (175 ml/ha) for cricket control.
Fungi control	None	Nativo (500 ml/ha) for control of rust disease

cob weights from all sampled points were determined, then ten cobs were further sampled and shelled to obtain grain yields at a 12.5% moisture content dry matter basis. Maize stover was weighed at harvest, then sun-dried for 10 days before determining the biomass yield per hectare when no change in stover weight was observed (Mupangwa et al., 2016).

For the soyabean biomass and the number of pods measurements, five samples were randomly chosen from a row of 5 m length. The samples were cut at ground level at the full flowering stage, before leaf shading and then weighed. A total of three plant samples were randomly selected, and the number of pods containing beans was counted and weighed. Afterwards, the samples were air-dried for five days before being oven-dried at 80 °C for 48 h. At maturity, soyabeans were sequentially harvested from 10 points on two rows by five meters for all treatments. All the soyabean from the sample points were bundled, sun-dried, the pods shelled, and grain weight determined at a moisture content of 11%, before extrapolating per hectare basis. The moisture content of both maize and soyabean grains was measured at harvest using a moisture meter (Wile 78 Crusher) (TerAvest et al., 2015; Thierfelder et al., 2016). The remaining maize stover and soyabean residues were left as mulch on the CA plots and burned on the conventional plots.

2.5. Socio-economic data collection

The actual time spent performing all agronomic applications was recorded using a stopwatch. However, this excluded the time for harvesting and post-harvest operations. Fuel consumption of tractors for all operations was measured using a 'DUT-E S7′ fuel level sensor fitted to the tractor's fuel tank. The fuel sensors measure up to 99.75% accuracy and are fitted with automatic thermal correction for high and low temperatures (Technoton, 2020).

To calculate the costs of production, hiring costs for disc harrowing, ripping, planting, fertilizer application, weed control, pest and insect control were collected based on the prevailing local market rates as given by tractor service providers and local farmers (Appendix 1). These charges included the cost of equipment, fuel and operator; thus, the costs are also applicable for smallholder farmers who would hire these equipment. Since maize was harvested by hand and shelled by motorized sheller, labor and shelling costs were based on the daily wages and hiring rates of US$2.73 per person per day and US$0.34/50 kg bag, respectively. All the costs were then converted to US dollars each year based on the Zambian Reserve Bank exchange rate.

The economic evaluation of the treatments was based on the conventional enterprise budgeting techniques aimed at estimating the cost of production and net return (CIMMYT, 1988; Jat et al., 2019a,2019b). The objective was to evaluate and compare the potential net benefits of using conventional tillage and CA systems for soyabean and maize. Total Variable Cost (TVC) was estimated by factoring in machinery hiring charges (Appendix 1), labor hiring charges and all input costs (seeds, fertilizers, herbicides, pesticides, and fungicides) for each plot per crop for the two seasons. Hiring charges and machinery operation time records were kept for each of the three treatments per crop (land preparation, tillage, planting, fertilization, herbicide application, fungicide, pesticide application, harvesting, shelling, transport and bagging).

The Total Revenue (TR) was determined from yield (ton/ha) and the national grain prices. TR (US$/ha) earned from the two crops was calculated based on the unit buying price per kilogram of grain according to the Zambian Government rates and the crops yield in the two seasons. For the first season, the National Food Reserve Board's price for maize was US$0.20 kg^{-1} and US$0.35 kg^{-1} for soyabean, while in the second season, the price was US$0.14 kg^{-1} and US$0.43 kg^{-1} for maize and soyabean, respectively. The prices were computed from Zambian Kwacha/ ton to US$ /ton based on exchange rates provided by the Reserve Bank of Zambia for the two seasons. Thus, the Gross Margin (GM) for every tillage treatment was computed by the difference between TR and TVC (Jat et al., 2019).

Consequently, the net returns on production were determined based on the variable cost of production, hiring costs and labor. Labor and financial capital were taken as the most limiting factors to production (Sime et al., 2015). The return to labor for the various tillage systems was calculated based on the difference between the total revenue and the input costs, as depicted in Eq. (1). Further, the return on every dollar invested was determined by dividing the GM by the TVC as in Eq. (2) (Thierfelder et al., 2016).

$$\text{Returns to labour}\left(\$\right) = \frac{\text{Total revenue} - (\text{TVC} - \text{Labour costs})}{\text{Labour costs}} \quad (1)$$

Table 2
Soil nutrient components analysis at the beginning of 2019/2020 and 2020/2021 seasons.

Season	Plant available nutrients (mg/kg)										pH (KCl)		
	Ca	Mg	K	Mn	Fe	Na	S	P	Cu	Zn	ECEC	Ex. Ac	pH
2019–20	1542	657	73	43.8	23.7	9	8.18	4	2.9	1.9	13.4	0.04	4.8
2020–21	1496	602	104	42	22.7	5	16.8	14	3.2	2.2	12.8	0.14	4.6

Na: Sodium, Mg: Magnesium, K: Potassium, Ca: Calcium, Mn: Manganese, Fe: Iron, S: Sulfur, P: Phosphorus, Cu: Copper, Zn: Zinc, ECEC: Effective cation exchange capacity (cmol (+)/kg), and Ex. Ac: Exchangeable acid (me%/100 ml).

$$\text{Returns to TVC}\left(\%\right) = \frac{\text{GrossMargin}}{\text{TVC}} \times 100 \quad (2)$$

2.6. Data analysis

The statistical analysis was performed using Minitab 18.1 statistical software. The crop yields and other agronomic data were subjected to normality tests and analysis of variance (ANOVA) using the randomized complete block design for on-farm trials (Rzewnicki, 1992). The effect of season and tillage treatment on socio-economic variables, plant population, pods per soyabean, maize height, biomass yield and grain yield were evaluated using the F-test of significance. Fisher's least significant difference (LSD) was used to separate the significantly different means. The probability level at p-value ≤ 0.05 was used as the critical value for the F-tests and the Fisher's LSD (McConnell et al., 1993). Standard errors of the differences of the variable means are presented. The correlation between soyabean pods per plant, maize plant height, biomass and population density and crops yields across the three tillage treatments were considered at $p \leq 0.05$ for the two seasons (TerAvest et al., 2015).

3. Results

3.1. Effects of tillage on maize and soyabeans plant densities

Plant populations at germination and maturity for the two crops showed slight variation across the three tillage treatments (Appendix 2). No significant differences in the maize population at germination and maturity were observed in the dry season. Yet, maize plant population at germination was positively correlated with RT and DS plots yield. Additionally, the significantly higher maize population in RT at maturity in the wet season negatively correlated with maize yield (Appendix 3). For soyabean, DS and RT plots showed significantly higher population densities at germination ($p = 0.024$) and maturity ($p \leq 0.001$) compared to conventional DH plots in both seasons (Appendix 2). Soyabean population at germination was positively correlated with yield in RT and DS in the first and second seasons, respectively (Appendix 3).

3.2. Effects of tillage on the crops' physiological characteristics

Marginal differences in maize plant heights were observed at maturity across the three tillage treatments in the two seasons. Maize plant heights were positively correlated with yield in RT and DS in both seasons and DH in the second season (Appendix 3). In contrast, a significantly greater number of soyabean pods per plant was reported in the DH plots than DS and RT treatments (Table 3). However, soyabean pods per plant were only positively correlated with yield in DS in the second season (Appendix 3). RT plots produced significantly more maize biomass than DH plots ($p \leq 0.001$ and $p = 0.04$) in both seasons, and DS plots only in the first season. Conversely, biomass yields of soyabean across the three tillage treatments did not differ statistically in either season (Table 3). Overall, maize and soyabean biomass yield tended to be higher in the 2020/21 season compared to the 2019/20 season.

3.3. Effects of tillage on maize and soyabean grain yields

The two CA practices, RT and DS, resulted in significantly greater soyabean yields in the first season ($p = 0.005$) compared to DH. However, there were only marginal differences in maize yield across the three tillage treatments ($p \geq 0.05$) in the first season (Table 4). In the second season, the conventional DH and RT plots had a significantly higher maize yield ($p = 0.004$) as compared to DS plots, while no significant yield differences were recorded in soyabean treatments. Overall, soyabean yields in the second season were lower than in the first season, but maize yields were higher (Table 4).

Table 3
Maize and soyabeans' physiological trait variations per treatment in the two seasons.

Season	Tillage type	Soyabean		Maize	
		Pods/plant	Biomass (kg/ha)	Plant height (m)	Biomass (kg/ha)
2019/20	DH	58^{b}	3007^{a}	2.630^{a}	4861^{a}
	RT	45^{a}	2803^{a}	2.660^{a}	5928^{b}
	DS	46^{a}	2586^{a}	2.649^{a}	4532^{a}
	p-value	0.007	0.503	0.078	< 0.001
	SED(n)	4.55 (20)	358(20)	0.013(120)	361(40)
2020/21	DH	37^{b}	3014^{a}	3.026^{a}	7689^{a}
	RT	32^{ab}	3235^{a}	3.008^{a}	6996^{ab}
	DS	30^{a}	3443^{a}	2.999^{a}	7886^{b}
	p-value	0.001	0.324	0.827	0.046
	SED(n)	2.64 (60)	282(20)	0.044(120)	372(40)

For each crop, the means followed by the same letter in the same column are not significantly different at $p \leq 0.05$ according to F and Fisher's LSD tests. Key: DH: disc-harrowing; RT: ripping tillage; DS: direct seeding; SED: standard error of difference.

Table 4
Maize and soyabean grain yield (kg ha^{-1}) differences between tillage treatments in 2019/20 and 2020/21 seasons.

Crop	Tillage type	2019/20	2020/21	Mean across years
Maize	DH	7792^{a}	$10{,}688^{b}$	9240^{a}
	RT	7873^{a}	$10{,}018^{ab}$	8946^{a}
	DS	7802^{a}	9751^{a}	8777^{a}
	p-value	0.969	0.004	0.116
	SED(n)	348(40)	285(40)	224(40)
Soyabean	DH	2848^{a}	2678^{a}	2763^{a}
	RT	2991^{ab}	2669^{a}	2830^{a}
	DS	3109^{b}	2634^{a}	2872^{a}
	p-value	0.005	0.893	0.243
	SED(n)	79.2(40)	78(40)	64.8(40)

For each crop, the means followed by the same letter in the same column are not significantly different at $p \leq 0.05$ according to F and Fisher's LSD tests. Key: DH: disc-harrowing; RT: ripping tillage; DS: direct seeding and SED: standard error of difference.

3.4. Time and fuel comparisons between the tillage treatments

The time and fuel consumption for various agronomic operations between maize and soyabean tillage treatments, excluding harvesting and post-harvest handling operations, varied greatly (Table 5). DS significantly saved time and fuel consumption during land preparation for both crops in the two seasons ($p \leq 0.001$). No significant difference was observed in operation time and fuel consumption during planting, fertilizer, herbicides, insecticides and fungicides control among the three treatments for the two crops. The cumulative time (hr) needed to produce both maize and soyabeans to maturity per hectare under DH and RT was significantly higher than under DS in both seasons ($p \leq 0.05$). Similarly, cumulative fuel consumption was significantly higher in DH followed by RT and DS plots, respectively for both crops in two seasons ($p \leq 0.001$). Overall, DS requires almost half as much energy and time as DH and RT to produce maize and soyabeans per unit area, which implies a reduced carbon footprint (Table 5).

3.5. Economic assessments of the tillage treatments

Since the crops' unit selling prices were the same for all treatments, the total revenues shown in Tables 6 and 7 reflect the yield differences described above. Accordingly, total maize revenues for RT, DS and DH tillage treatments were higher in the first than in the second season (Table 6). In contrast, soyabeans' DS treatment recorded the highest

Table 5
ANOVA of operation time and fuel consumption of various agronomic activities between maize and soyabeans in the 2019/20 and 2020/21 seasons.

Crop	Operation time (h/ha)									Fuel consumption (l/ha)							
	Activity	LP		P		FHIF		Total		LP		P		FHIF		Total	
	Tillage	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
Maize	DH	1.21^{a}	1.49^{a}	1.13^{a}	1.24^{a}	0.88^{a}	0.90^{a}	3.21^{a}	3.62^{a}	12.05^{a}	11.06^{a}	6.27^{a}	5.46^{a}	4.30^{a}	3.59^{a}	22.61^{a}	20.12^{a}
	RT	1.27^{a}	1.36^{a}	1.23^{a}	1.26^{a}	0.85^{a}	0.94^{a}	3.35^{a}	3.55^{a}	7.06^{b}	7.10^{b}	6.80^{a}	4.26^{a}	4.40^{a}	3.60^{a}	18.26^{b}	14.95^{b}
	DS	0^{b}	0^{b}	1.17^{a}	1.23^{a}	0.80^{a}	0.98^{a}	1.97^{b}	2.20^{b}	0^{c}	0^{c}	6.47^{a}	5.31^{a}	4.35^{a}	3.59^{a}	10.81^{c}	8.90^{c}
	SED	0.12	0.102	0.042	0.198	0.072	0.044	0.173	0.267	0.757	0.936	0.505	0.946	0.144	0.011	0.828	1.00
	p-value	0.000	0.000	0.110	0.984	0.575	0.297	0.000	0.001	0.000	0.000	0.583	0.416	0.79	0.649	0.000	0.000
Soyabean	DH	1.53^{a}	1.22^{a}	1.07^{a}	1.35^{a}	1.62^{a}	1.17^{a}	4.22^{a}	3.74^{a}	12.54^{a}	13.43^{a}	7.80^{a}	6.42^{a}	5.69^{a}	4.78^{a}	26.02^{a}	24.63^{a}
	RT	1.29^{b}	1.45^{a}	1.21^{a}	1.50^{a}	1.47^{a}	1.00^{a}	3.97^{a}	3.95^{a}	7.30^{b}	5.60^{b}	8.37^{a}	5.30^{a}	5.46^{a}	4.73^{a}	21.12^{b}	15.63^{b}
	DS	0^{c}	0^{b}	1.28^{a}	1.44^{a}	1.50^{a}	0.95^{a}	2.78^{b}	2.39^{b}	0^{c}	0^{c}	8.73^{a}	5.81^{a}	5.39^{a}	4.69^{a}	14.12^{c}	10.51^{c}
	SED	0.0848	0.151	0.129	0.162	0.121	0.185	0.202	0.355	0.764	0.787	0.632	1.380	0.150	0.465	1.230	1.580
	p-value	0.000	0.000	0.302	0.669	0.472	0.477	0.000	0.003	0.000	0.000	0.368	0.729	0.163	0.98	0.000	0.000

For each crop, the means followed by the same letter in the same column are not significantly different at $p \leq 0.05$ according to F and Fisher's LSD tests. Key: S1: 2019/20 season; S2: 2020/21 season; DH: disc-harrowing; RT: ripping tillage; DS: direct seeding; LP: land preparation; P: planting; FHIF: fertilizer, herbicides, insecticides & fungicides control; and SED: standard error of difference.

total revenue in the first season but DH treatment in the second season (Table 7). The input costs were the same across all treatments. The machinery hiring costs majorly differed in land preparation while the subsequent operation costs were similar across the treatments (Tables 6 and 7). No land preparation costs were incurred in DS treatments; yet, on average, one-third of costs were saved in RT land preparation compared to DH for the two crops. Overall, machinery hire and labor costs for maize and soyabean production were lower in DS and RT than in DH treatments across the two seasons. Consequently, the low variable costs in DS and RT compared to DH for both maize and soyabeans were due to the cost-saving in land preparation.

While maize's RT and DS treatments demonstrated higher profitability (gross margins) in the dry season (US\$768 ha^{-1}; US\$790 ha^{-1}), DH treatments produced higher gross margins (US\$685 ha^{-1}) in the wet season (Table 6). On the other hand, DS and RT's soyabeans gross margins were higher than DH in both seasons despite the marginal significant differences between the treatments. The low soyabean gross margins in the dry season were due to the low unit selling price compared to the second season. Returns to labor and returns to TVC were highest in DS treatments followed by RT and DH respectively, for both maize and soyabeans for the two seasons (Tables 6 and 7). Even though the returns to labor and returns to TVC were slightly higher in maize' and soyabeans' DS treatments, the difference in RT and DH for both seasons was marginal. This minimal difference in returns between CA's RT and DS practices compared to conventional DH was attributed to comparable crops yields. The gross margin analysis has shown that economic benefits are not lower in CA's RT and DS practices for both crops in the first two years of adopting MCA, even if a farmer hires machinery for all operations.

4. Discussion

4.1. Plant population, physiological characteristics and biomass responses

The high maize and soyabean plant populations in CA plots at germination can be attributed to sufficient soil moisture retention. However, the reduction in maize and soyabean populations observed in DH plots may be due to insufficient soil moisture and high soil temperatures during dry spells in the first season leading to failures (Simunji et al., 2018). The low crop populations in DH plots in the second season despite the same seed variety used and higher rainfall could indicate the negative impacts of soil compaction in DH plots than in RT and DS plots (Thierfelder et al., 2013).

Higher maize plant height at maturity in the wet season compared to the dry season showed the influence of soil moisture on plants' physiological growth besides agronomic management aspects and tillage type. This is affirmed by the positive correlation between maize plant height and yield in RT and DS plots in the dry season and DH plots in the wet season. The high number of pods per soyabean plant on the DH treatments did not result in significant yield differences as compared to RT and DS treatments across two seasons. These findings concur with Kumar et al. (2020), who also reported higher soyabean pods per plant under mechanized conventional tillage than the mechanized minimum and no-till practices in India.

Further, high maize biomass yields across treatments compare with Komarek et al. (2019) results in Chanje, Zambia based on a similar maize cultivar (SC627). Maize biomass yield increased with higher rainfall in the second season, highlighting the impact of soil moisture on maize vegetative growth and biomass accumulation. The significant positive correlation between biomass and maize yields in DH and RT plots and soyabean DS in the second season confirms this fact. Thus, the high biomass yield in the wet season could imply sufficient crop residues for mulching while the excess can be used for economic gains, for example, feeding livestock. However, the maize and soyabean biomasses generated were sufficient to provide the 2–4 tonnes of residue per hectare that is recommended for RT and DS plots (TerAvest et al., 2015; Mupangwa

Table 6
Total revenue, total variable costs, gross margin and returns to labor for maize under different tillage treatments for 2019/20 and 2020/21 seasons.

Item	Unit Price (US$)	2019–2020 season			Unit Price (US$)	2020–2021season		
		DH	RT	DS		DH	RT	DS
1. Revenue								
Grain yield (kg/ha)		7790	7870	7800		10690	10020	9750
Total revenue (US$/ha)	0.20	1558	1574	1560	0.14	1443	1353	1316
2. Variable costs (VC)								
a. Input costs								
Seed (US$/ha)	2.31	60	60	60	1.92	52	52	52
Basal fertilizers (US$/ha)	0.64	184	184	184	0.60	179	179	179
Topdressing fertilizer (US$/ha)	0.97	238	238	238	0.42	220	220	220
Pre-emergent herbicides (US$/ha)	7.94	23	23	23	0	0	0	0
Post-emergent herbicides (US$/ha)	26.57	19	19	19	26.85	62	62	62
Insecticides (US$/ha)	116.17	49	49	49	49.47	21	21	21
Total input costs		573	573	573		534	534	534
b. Machinery hiring costs								
Land preparation (US$/ha)		44	31	0		44	31	0
Planting cost (US$/ha)		27	31	31		28	31	31
Fertilizer application (US$/ha)		27	27	27		26	26	26
Weed control (US$/ha)		27	27	27		26	26	26
Insect control (US$/ha)		14	14	14		13	13	13
c. Labor costs								
Land clearance & demarcation (US$/ha)		7	7	7		7	7	7
Harvesting & shelling (US$/ha)		65	68	65		72	71	70
Transport & storage (US$/ha)		26	28	26		34	33	32
Total hiring & labor costs (US$/ha)		239	233	197		252	238	206
Total VC (US$/ha)		812	806	770		786	772	740
3. Returns								
Gross margin (US$/ha)		746	768	790		685	581	576
Returns to labor (per US$)		4.13	4.30	5.01		3.61	3.44	3.80
Returns to TVC (%)		91.95	95.32	102.56		83.71	75.28	77.91

Note: DH: Disc harrowing, RT: Ripping tillage, DS: Direct seeding.

Table 7
Total revenue, total variable costs, gross margin and returns to labor for soyabean under different tillage treatments for 2019/20 and 2020/21 seasons.

Item	Unit Price (US$)	2019–2020 season			Unit Price (US$)	2020–2021season		
		DH	RT	DS		DH	RT	DS
1. Revenue								
Grain yield (kg/ha)		2850	2990	3110		2680	2670	2630
Total revenue (US$/ha)	0.35	998	1047	1089	0.43	1152	1148	1131
2. Variable costs (VC)								
a. Input costs								
Seed (US$/ha)	1.30	122	122	122	1.07	98	98	98
Basal fertilizers (US$/ha)	0.68	152	152	152	0.63	141	141	141
Topdressing fertilizer (US$/ha)	1.20	12	12	12	9.15	11	11	11
Pre-emergent herbicides (US$/ha)	13.73	50	50	50	11.26	23	23	23
Post-emergent herbicides (US$/ha)	11.76	53	53	53	8.26	53	53	53
Insecticides (US$/ha)	108	21	21	21	0	0	0	0
Fungicides (US$/ha)	42	20	20	20	33.5	23	23	23
Total input costs		430	430	430		348	348	348
b. Machinery hiring costs								
Land preparation (US$/ha)		44	31	0		44	31	0
Planting (US$/ha)		27	31	31		28	31	31
Fertilizer application (US$/ha)		14	14	14		13	13	13
Weed control (US$/ha)		55	55	55		52	52	52
Insect & fungi control (US$/ha)		23	23	23		13	13	13
Harvesting & cleaning (US$/ha)		120	120	120		120	120	120
c. Labor costs								
Land clearance & demarcation (US$/ha)		7	7	7		7	7	7
Transport & storage (US$/ha)		12	12	13		8	8	9
Total hiring & labor costs (US$/ha)		306	296	266		287	275	246
Total VC (US$/ha)		736	727	696		635	624	594
3. Returns								
Gross margin (US$/ha)		261	320	392		517	525	537
Returns to labor (per US$)		1.85	2.08	2.47		2.80	2.91	3.18
Returns to TVC (%)		35.49	44.03	56.32		81.42	84.13	90.33

Note: DH: Disc harrowing, RT: Ripping tillage, DS: Direct seeding.

et al., 2019).

4.2. Tillage practice and maize and soyabean performance

DS and RT yields for both maize and soyabean in the first season were not significantly higher than DH, a deviation from other research outputs based on animal traction and medium-rainfall, which have shown that ripping and direct seeding recorded higher yield compared to conventional practices right from the first two seasons (Mupangwa et al., 2016). Further, the fact that RT and DS practices recorded relatively lower crops yield in the wet season than the conventional DH practice concurs with findings by Thierfelder et al. (2017), who also noted that high rainfall amounts may lead to low crop yield in CA plots due to waterlogging. Thus, for this mechanized trial, the high maize yield in DH treatments in the second season compared to RT and DS could be attributed to the increased soil moisture effect compared to the dry season. This conforms with previous predictions that have shown that greater maize yield stability is experienced in conventional tillage practices considering agroecological zones with more rainfall (Mupangwa et al., 2016). In contrast, soyabean yields did not record a positive yield increase when rotated with maize despite the high rainfall amounts recorded in the second season. This can be attributed to the fact that maize residues have immobilized N thus reducing N available for soyabean in the soil (TerAvest et al., 2015), this was not the case when soyabean was not rotated in subsequent seasons (Mupangwa et al., 2016). The increased maize yields upon rotation with soyabeans in the second season may be due to accumulated nitrogen from soyabean crops in the previous season, fertilizer-use efficiency and improved soil moisture (TerAvest et al., 2015; Mupangwa et al., 2019). These findings relate with Ncube et al. (2007) who also reported up to 200% increase in sorghum yield in wetter seasons when rotated with various grain legumes in Zimbabwe.

Maize and soyabean yields from this experiment were higher than previous research records and the Zambian national yield averages (Thierfelder and Wall, 2009; Thierfelder et al., 2013; Mupangwa et al., 2019; Mulenga et al., 2020). This may be due to differences in soil conditions, plant densities, as well as the crop protection and fertilization regimes, considered. According to Mulenga et al. (2020), maize and soyabean yield averages for small and medium-scale farmers in 2020 were 2 ton/ha and 1.29 ton/ha, respectively. Results of a related experiment conducted at Monze, Zambia, indicated maximum yields of 4,877kgha^{-1}, 5,141kgha^{-1}, 5,240kgha^{-1}, and 6,220kgha^{-1} for conventional ploughing, direct seeding, basin planting and direct-seeded rotation, respectively (Thierfelder and Wall, 2009). In other research by Thierfelder et al. (2013), conventional tillage plus fertilization yielded 5,843kgha^{-1}, no-till plus residues and fertilization 5,904kgha^{-1} whereas no-till plus residues plus fertilization and herbicides 4, 828kgha^{-1}. Under medium rainfall conditions in Zambia, direct seeding produced the highest yields (3,483kgha^{-1}) followed by ripping (3, 115kgha^{-1}) and conventional tillage (2,142kgha^{-1}) (Mupangwa et al., 2019). Consequently, unlike the previous small-scale plot experiments research based on hand tools and animal traction, this mechanized study using 4WT and associated implements has shown that DS and RT record stable maize and soyabean yields in the dry season, despite the non-significant yield difference in maize DH treatments. Nonetheless, in the wet season, maize DH and RT practices showed significantly higher yields compared to DS, even though the differences were not large.

4.3. Tillage types and operation time and fuel consumption

To calculate the costs for economic analysis, we used imputed values for hired machinery. In addition, we measured actual operation time and fuel use. These findings are relevant as time and labor constraints continue to limit agricultural productivity among small and medium-scale farmers in SSA (Johansen et al., 2012). Timeliness is key in land preparation, planting and competing with the shorter rain seasons to minimize crops' yield (González-Sánchez et al., 2018). No time was incurred in DS' land preparation compared to RT and DH operations which recorded relatively similar operation times. However, despite the comparable operation time across other agronomic applications, DS still registered significantly higher cumulative timesaving up to 39% and 41% relative to RT and DH without harvesting operations. Yet, even though minimum tillage and no-till have been reported to save time in crop establishments besides increased yield prospects (González-Sánchez et al., 2018; Johansen et al., 2012), in this study mechanized RT did not show any significant time difference from DH in all agronomic operations. The high operation time in RT can be attributed to the tractor's low speed and the uniform ripping depth requirements during land preparation.

Up to 100% and 58% of fuel-use per hectare for land preparation was saved in DS and RT respectively to produce both crops compared to DH. Further, based on cumulative fuel-use for all agronomic operations excluding harvesting operation, DS and RT significantly saved fuel up to 57% and 37%, respectively, relative to DH. These findings compare with Pratibha et al. (2015) who also noted a high percentage of fossil fuel use in conventional tillage (34%) and ripping tillage (26%) compared to zero tillage (16%). Further, the low fossil fuel consumption in DS treatments conforms to findings in Kenya among large-scale farmers who noted reduced fuel consumption from 25 l/ha in conventional practice to 8 l/ha under CA (Araújo et al., 2020). The significantly lower fuel use in DS compared to RT and DH is one major reason why most large-scale farmers in South African countries prefer DS systems (Johansen et al., 2012). Yet, these findings could also influence the decision-making of small and medium-scale farmers who may want to shift to mechanized CA but are keen on profit maximization and risk-averseness (Mupangwa et al., 2016). Based on their low fuel use, DS and RT can further minimize the atmospheric CO_2 emission footprints making them more environmentally friendly compared to conventional DH practice (Pratibha et al., 2015).

4.4. Economic comparisons between conventional and CA tillage systems

The high maize and soyabeans gross margins in DS and RT treatments across the two seasons are suggestive of positive economic benefits of MCA in the short-term (first two seasons) even if all machinery services are hired (Fig. 3). This is critical noting that negative short-term economic benefits have been cited as among the predominant reasons for CA's disadoption in SSA (Giller et al., 2009; Grabowski et al., 2016). Overall yield and grain selling prices influenced the high maize gross margins in DH plots in the wet season while the soyabean's DS and RT treatment remained more profitable than DH in both seasons. These findings corroborate those of Sime et al. (2015) who also noted higher gross margins on conventional tillage practices than the minimum and no-tillage practices due to yield differences among small-scale CA farmers in Ethiopia. In contrast, Umar (2014), reported higher profit margins among small-scale CA ripping and hand-basin methods compared to conventional hand-hoe and ploughing practices in Zambia based on field assessments and farmers' perceptions. In this study, the slightly high gross margin in the maize DH plot in the second season was due to increased yields despite the low grain selling price (US $0.14 kg^{-1}) compared to the first season (US$0.20 kg^{-1}). However, Mupangwa et al. (2019) also noted that rotating maize and soyabean in mechanized CA systems brings greater net profits, subsequently making CA rotations the best bet for the risk-averse smallholder farmers as opposed to conventional practices. Contrarily for soyabeans, despite the low yield in the second season, high grain selling price (US$0.43 kg^{-1}) compared to the first season (US$0.35 kg^{-1}) and a saving on insecticide application impacted its overall profitability in the second season (Fig. 3).

The low machinery hiring charges in DS and RT contributed to labor savings compared to DH for the two crops. These findings compare with labor savings under rice strip-tillage using 2WTs in South Asia which

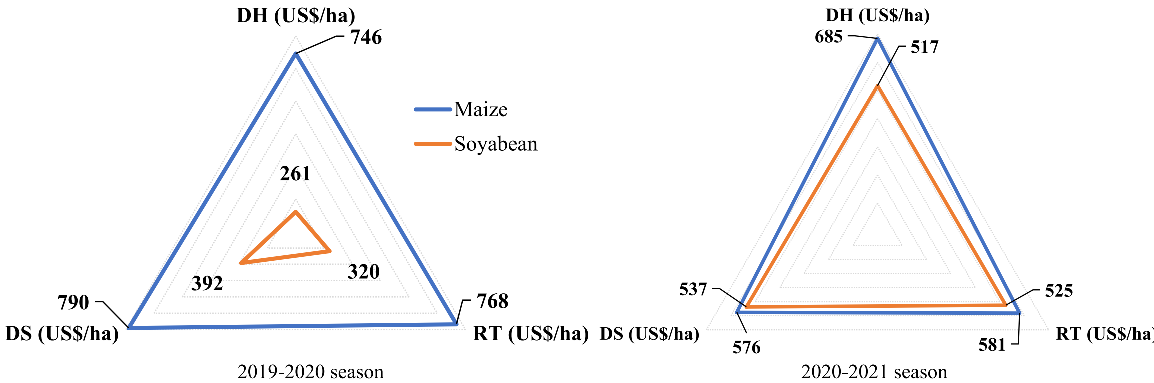

Fig. 3. Profitability (gross margin) comparisons of three tillage treatments and crops for the two seasons.

resulted in up to 30% fewer labor costs compared to conventional practices (Johansen et al., 2012). Overall, the difference in production costs for the crops were marginal across the three treatments. Yet, apart from land-preparations, labor savings in MCA's DS and RT treatments (also true for planting basins and animal ripping), labor charges for fertilizer application, weed, insects, fungi, and pest control as well as harvesting were relatively like mechanized conventional DH practice. This is different from the findings of small-scale CA research. Mupangwa et al. (2019) reported higher labor-saving costs in CA animal traction ripping and direct seeding practices, especially at planting and weeding stages. In contrast, this mechanized CA research reveals that RT and DS practices also incur higher labour costs, especially during planting and weed control. This is due to the recommended low tractor speeds (6–8 km/hr) during RT and DS to ensure the desired seed placement depths and to prevent blockages of seed metering chutes, in comparison to DH and its subsequent planting operations, which are accomplished at relatively higher speeds (10–12 km/hr). As such, the high cost of labour associated with minimum and no-tillage practices was also reported among smallholder farmers using ox-drawn minimum tillage and direct planting using dibble sticks, even if herbicides were not used (Sime et al., 2015). Nonetheless, the high returns to labour in DS and RT treatments for the two crops still indicate their risk-aversion and suitability for medium-scale farmers who are profit-oriented, particularly during dry seasons compared to DH. This corroborates Umar (2014) who noted high returns to labour on CA's ripping and basin practices in Zambia as compared to conventional hand-hoe and ploughing practices. Therefore, the two-year field experiment demonstrated that mechanized CA options can lead to promising economic benefits compared to conventional practices in the first two years of adoption, and farmers do not incur losses.

5. Conclusions

In light of recent climatic fluctuations experienced across SSA, our study shows that mechanized CA is profitable even if all machinery is hired. However, smallholder farmers would need access to capital markets to hire the machinery and buy the inputs. Further, feasible approaches such as mechanization service provision, which will enable most small and medium-scale farmers to access mechanization services across Zambia, are required. Based on the first two years, the economic benefits of MCA (RT and DS) are not lower than that of conventional practice (DH) – when considering a wet and a dry year and when considering the two typical crops – maize and soyabean. This is important as it does not discourage farmers from adopting CA, even though the real benefits (higher yields) may only occur much later. These findings provide an agronomic and profitability outlook for mechanized agriculture with a focus on small and medium-sized farmers who can access tractor hire services. Furthermore, these findings offer guidance to policymakers on the potential of MCA for both small and medium-scale farmers across SSA. Nevertheless, there is a need for further research. In particular, when ripping and when direct seeding is better, requires further research.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2022.105414.

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