Agriculture, Ecosystems and Environment 187 (2014) 146–154

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Weed growth and labor demand under hand-hoe based reduced tillage in smallholder farmers' fields in Zimbabwe

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A R T I C L E I N F O

Article history:
Received 11 February 2013
Received in revised form 3 October 2013
Accepted 7 October 2013
Available online 30 October 2013

Keywords:
Conventional tillage
Returns to labor
Planting basins
Weed growth

A B S T R A C T

Conservation agriculture based on hand hoe dug planting basins has been widely promoted for the last decade or two in the smallholder farming sector of southern Africa targeting resource constrained households without access to draft power. In Zimbabwe planting basins are used by about one hundred thousand households but on small plots (<0.5 ha) although most are unable to adopt soil surface mulching and crop rotation due to competing uses for crop residues as livestock feed and poorly developed markets for other crops, respectively. We report on the effects of reduced tillage based on hand-hoe dug planting basins (PB) on weed growth (20 farms), and labor demand and returns to investment (50 farms) compared with animal-drawn mouldboard plough based conventional tillage (CONV) in maize (*Zea mays* L.) fields, across selected districts located in contrasting agro-ecological zones in Zimbabwe. Weed growth was assessed through a survey conducted at the end of the 2009/10 and 2010/11 cropping seasons. Labor demand and returns to investment were measured on 50 farms across five districts using direct observations during the 2011/12 cropping season. The survey showed that farmers on average weeded their PB plots 2.7 times per season compared to 1.7–1.9 times in CONV plots ($P < 0.001$), and timing was often delayed in the former. Reduced tillage plots had 17% ($P < 0.001$) more weed ground cover and 9% ($P < 0.05$) more weed dry matter compared with CONV plots in the 2009/10 season, and differences in 2010/11 were not significant. Weed growth was highest in semi-arid areas (natural regions III and IV) compared with wetter sub-humid areas (natural region II) and arid areas (natural region V). Farmers planted their PB plots 12–23 days earlier, weeding frequency was 42.1–58.9% higher in PB plots, compared with CONV. Labor demand was more than double under PB (84.7 man days ha^{-1}, weeding 48.1 man days ha^{-1}) compared to CONV (38.6 man days ha^{-1}). However, returns to investment were 42.7% higher under PB (U$1.77) compared with CONV (U$1.24). Weed growth and labor demand remained high under PB tillage even after several years, interventions such as the use of alternative weed control methods need to be introduced to farmers to reduce labor demand and consequently increase its adoption both in terms of number of farmers and cultivated area in southern Africa.

1. Introduction

The lack of effective weed management strategies by resource-poor smallholder farmers in southern Africa may be one of the main constraints to increasing crop productivity through conservation agriculture (CA). The CA package currently being promoted in southern Africa comprises continuous minimum tillage, at least 30% permanent or semi-permanent organic soil cover and the cultivation of a wide range of crops in a spatial or temporal crop association/sequence/rotation (Kassam and Friedrich, 2011; Nyamangara et al., 2013). Manual minimum tillage systems, such as hand hoe dug planting basins (PB), that are currently being promoted in southern Africa as part of CA have been reported to increase crop yields by 30–120% on farmers' fields in Zambia (Haggblade and Tembo, 2003) and in Zimbabwe (Mazvimavi and Twomlow, 2009). However, farmers still have a larger proportion of their planted fields under conventional mouldboard tillage (CONV) (Baudron et al., 2007; Mazvimavi and Twomlow, 2009) and purportedly under CA; only the reduced tillage principle is followed by most farmers (Mazvimavi et al., 2008).

Labor limitations, especially for weeding, and low levels of mechanization for both land preparation and weeding have been

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0167-8809/$ – see front matter
http://dx.doi.org/10.1016/j.agee.2013.10.005

reported to lead to a reduction in the area under cultivation by up to 50% in sub Saharan Africa (SSA) (Kent et al., 2001; Bishop-Sambrook, 2003). It is, therefore, not surprising that minimum tillage systems such as PB are found on less than one hectare of most smallholder farming households in southern Africa (Baudron et al., 2007; Mazvimavi and Twomlow, 2009) despite their potential to increase and sustain crop yields. The PB method has been reported to increase returns to investment in labor by up to 40% compared with conventional tillage (CONV) (Mazvimavi et al., 2008). However, the use of planting basins often requires significantly higher investment in time in comparison with CONV for land preparation and hand-hoe weeding, especially in the first three years (Mazvimavi et al., 2008). In the first year, when the soil is still compacted, digging planting basins using the hand hoe has been reported to require up to 30 labor days per hectare (Mazvimavi et al., 2008) and this is coupled with over two-fold increase in weed biomass (Mashingaidze et al., 2012) compared with CONV. In the second year onwards the time required for preparing the planting basins can decrease by up to 16% probably as a result of farmers mastering the technique (Mazvimavi et al., 2008).

Without soil inversion in minimum tillage systems, most weed seeds are maintained at the soil surface where conditions are conducive for weed seed germination (Chauhan et al., 2006). However, with intensive management which includes eradicating weeds before they set seed, the weed population in CA will diminish over time as seed deposition into the seed bank lessens (Wall, 2007; Baraibar et al., 2009). The weed seed bank also declines as seed left near or on the surface is also lost through mortality caused by diseases, predators and aging (Baraibar et al., 2009; Schultz, 2011). With conventional tillage, especially mouldboard ploughing, redistribution of weed seeds occurs where they are either buried (as such the soil seed bank persists) or are brought to the surface (Baraibar et al., 2009) resulting in an initial weed flush at the start of the season. The Zimbabwean CA Taskforce recommends that fields be weeded as soon as weeds appear to prevent them from setting seeds and replenishing the soil weed seed bank (Twomlow et al., 2008). Similarly in Zambia, promoters recommend up to six operations using the hand hoes each cropping season to achieve timely weed control (Baudron et al., 2007). These operations include manual weeding before and after crop harvesting periods, during which the majority of smallholder farmers do not normally carry out weeding even if labor is available. There are, however, other options in weed management within CA such as crop rotations that suppress weed growth, smothering weeds by the use of green mulch cover crops and crop residue mulching and the use of herbicides have been used successfully in the region (Barberi, 2003; Ngwira et al., 2012).

From 2004 to 2011 the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) provided technical assistance to various non-governmental organizations (NGOs), the national extension service involved in the promotion of CA and based on the manual PB tillage system in Zimbabwe under the Protracted Relief Program (PRP). ICRISAT was also tasked by the PRP and Food and Agricultural Organisation of the United Nations (FAO) with assessing the impact of the input program. This was done by conducting annual panel surveys from 2006/7 to 2010/11 seasons and data collected included both biophysical and socio-economic challenges and opportunities faced by the households receiving inputs from the relief program. Each household was encouraged to establish paired PB and CONV plots so that they could compare the performance of the tillage systems in terms of crop establishment, growth and yield as well as qualitative weed growth and dynamics. The management of paired plots was greatly dependent on farmer resource endowments; however there were cases where farmers applied similar management to both plots and these farmers were selected for the study.

Table 1
Number of farmers with PB[a] and CONV[b] tillage fields that were under the same crop species during the 2009/10 cropping season in the 10 districts in Zimbabwe.

District	Natural region	Crop		Total number of farmers
		Maize	Sorghum	
Mt. Darwin	II	4	0	4
Chirumhanzu	III	1	0	1
Masvingo	III	3	0	3
Gokwe South	III	3	0	3
Binga	IV	0	3	3
Insiza	IV	1	1	2
Hwange	IV	2	0	2
Nkayi	IV	2	0	2
Chivi	V	3	0	3
Nyanga	V	1	0	1
Total		20	4	24

[a] Planting basin-based conservation agriculture.
[b] Conventionally tilled (animal-drawn mouldboard ploughing).

During 2009/10 and 2010/11 panel surveys, quantitative weed growth measurements in terms of ground coverage and dry matter yield were taken from the paired plots that compared the CONV and the PB systems. In 2011/12 larger plots were established in selected districts in order to measure labor demand by direct observations and returns to investment between the two tillage systems. The objective of this study was to assess weed growth between the two tillage systems in 2009/10 and 2010/11 cropping seasons, and labor demand and returns to investment in 2011/12 season using the panel survey data.

2. Materials and methods

2.1. Location

During March/April 2010 and May/June 2011, panel studies were conducted in 15 districts (450 households) in contrasting agro-ecological natural regions as part of the annual CA panel survey. In 2011, an extra five districts (150 households) were included in the survey in order to capture better endowed farmers who had been recently exposed to CA through other programs. However, because at the majority of households the paired PB and CONV plots did not have the same crops and that fertilizer rates were different, these were excluded in the weed data analysis. As maize (*Zea mays* L.) was the dominant crop grown, the study focused the weed and crop yields assessment on 20 paired plots (9 districts) in 2009/10 (Table 1) and 18 paired plots (8 districts) in 2010/11(Table 2) that were under maize.

Table 2
Number of farmers with PB[a] and CONV[b] tillage fields that were under the same crop species during the 2010/11 cropping season in 9 districts of Zimbabwe.

District	Natural region	Crop			Total farmers
		Maize	Sorghum	Pearl millet	
Guruve	II	1	0	0	1
Masvingo	III	4	0	0	4
Insiza	IV	1	0	0	1
Hwange	IV	3	0	0	3
Nkayi	IV	1	0	0	1
Zaka	IV	1	0	0	1
Mangwe	V	3	0	0	3
Nyanga	V	4	0	0	4
Chipinge	V	0	7	1	8
Total		18	7	1	26

[a] Planting basin-based conservation agriculture.
[b] Conventionally tilled (animal-drawn mouldboard ploughing).

Table 3
Management characteristics for PB[a] and CONV[b] tillage fields for weed and crop yield assessment under maize in the 2009/10 and 2010/11 cropping seasons.

	Plant density (plants m^{-2})	Basal fertilizer application rate (kg ha^{-1})	Top dressing fertilizer application rate (kg ha^{-1})
n	38	38	38
Mean	3.4	38.8	73.9
Standard error	0.2	9.3	14.1

[a] Planting basin-based conservation agriculture.
[b] Conventionally tilled (animal-drawn mouldboard ploughing).

Zimbabwe is divided into five agro-ecological natural regions mainly based on rainfall amount, distribution and reliability (Vincent et al., 1960). Natural region I receives the highest and most reliable rainfall (>1000 mm per annum) and is characterized by specialized agriculture such as horticulture and dairy. Natural region II is most suitable for arable cropping and is characterized by 750–1000 mm per annum rainfall which is relatively well distributed. Natural region III (650–800 mm per annum) is also suitable for arable cropping but the rainfall is less reliable. Natural regions II and III are dominated by maize based crop production with some livestock rearing, and the latter is important for tillage and provides manure for soil fertility improvement. Natural region IV is characterized by 450–650 mm rainfall per annum and extended mid-season droughts, which affect yields, are common. Rainfall is lowest and least reliable in natural region V (<450 mm per annum). In this region and most of natural region IV, livestock rearing is dominant and cropping is limited to drought tolerant crops such as sorghum (*Sorghum bicolor* L.) and pearl millet (*Pennisetum glaucum* L.). Frequent droughts often result in total crop failure and livestock deaths.

2.2. Paired plot selection criteria

The paired PB and CONV plots selected for the assessment were planted to maize, with field sizes of 0.15–0.4 ha and similar fertilizer application rates averaging 38.8 kg ha^{-1} for basal (NPK) and 73.9 kg ha^{-1} for top dressing (ammonium nitrate) fertilizer. The average planting density was 3.4 plants m^{-2} (Table 3). For the PB tillage system, basins were opened up using hand held hoes to prepare the position where the seeds were to be planted. The recommended dimensions of the basins are 15 cm in length, breadth and depth (Twomlow et al., 2008). The recommended inter-row and intra-row spacing is 90 cm and 60 cm respectively. Under the conventional tillage treatment the land was cultivated using an ox/donkey drawn VS 10 mouldboard plough. The ploughing depth in small-holder farming systems is often shallow (8–12 cm) (Grant et al., 1979; Nyengerai, 2010). Planting furrows are opened at a spacing of 90 cm.

2.2.1. Determination of weed growth

In each field, a 1 m × 1 m quadrat was randomly thrown three times and percentage weed ground cover estimated per quadrat. Weeds within each quadrat were cut at ground level and air dried at 60 °C to constant weight in order to determine dry matter yield.

2.2.2. Crop yields

Maize grain yields were determined from the selected plots from the farmers' harvests in 2009/10 and 2010/11 seasons. Maize cobs harvested from the PB and CONV plots where measured to the nearest half of a 50 kg grain bag. The grain bags were calibrated after Twomlow et al. (2010) and spot checks. A 50 kg bag of maize cobs contained 24.0 kg of grain and this was converted to yield (kg ha^{-1}).

2.2.3. Determination of labor requirements

The labor study was conducted in nine districts (Table 4). In each district, except for Gokwe South where two wards were selected, one ward was selected giving a total of ten wards. A total of 50 households (five households per ward) were selected based on socio-economic and demographic data collected during the 2010/11panel survey. Of the five households (farmers) in each ward, three established both PB and CONV plots while the other two established CONV plots only. In each ward, a Field Assistant (FA) was selected and trained by ICRISAT on data collection. The FA recorded the activities and the time taken to carry out operations within each plot. To reduce the error associated with poor farmer's recall, FAs visited farmers daily recording time taken by farmers to complete each field operation. Breaks taken by farmers during field operations were noted. A total of 80 record books were collected for analysis. Using the data collected, returns to labor were calculated by dividing the gross margin by the total labor days taken to manage a plot under each tillage treatment. Labor availability data for the districts, where direct observations were conducted, was obtained from the main panel survey data. Crop yields were determined by measuring the actual grain yield from the trial plots and correcting to 12.5% moisture content.

2.3. Statistical analyses

The percentage mean weed biomass data under the two tillage systems were square root transformed $\sqrt{(x+0.5)}$ to homogenize variances (Gomez and Gomez, 1984). All weed (cover and biomass) and crop (yield) data were analyzed using linear mixed models in GenStat 14th edition (VSN, 2011). The standard error of differences (SED) of the mean ($P < 0.05$) were used to separate means. A regression analysis was also conducted to assess the relationship between weed growth and the number of years the plot had been under the PB tillage. Regression analyses were also conducted to assess the correlation between grain yields and weed biomass.

Table 4
Household size and family labor in districts where real time PB[a] and CONV[b] labor studies were conducted in Zimbabwe (figures in brackets denote standard error of the mean).

District	Natural region	Average household size	Average fulltime labor	Average part time labor
Bindura	II	6.3 (1.39)	2.6 (0.55)	2.6 (1.08)
Murehwa	II	6.8 (0.85)	1.8 (0.49)	3.9 (1.03)
Masvingo	III	7.1 (0.43)	3.0 (0.71)	2.3 (0.85)
Kadoma	III	6.0 (0.76)	3.6 (0.75)	1.9 (0.84)
Nkayi	IV	6.6 (1.80)	5.5 (1.32)	0.5 (0.29)
Gokwe South	IV	5.7 (1.00)	2.3 (0.30)	1.8 (0.65)
Zaka	IV	5.8 (1.87)	3.8 (0.86)	1.2 (0.58)
Hwange	IV	8.9 (2.12)	3.5 (0.85)	4.0 (1.51)
Binga	V	6.7 (0.37)	3.2 (0.37)	0.8 (0.20)
Average		6.6 (0.44)	3.1 (0.24)	2.1 (0.32)

[a] Planting basin-based conservation agriculture.
[b] Conventionally tilled (animal-drawn mouldboard ploughing).

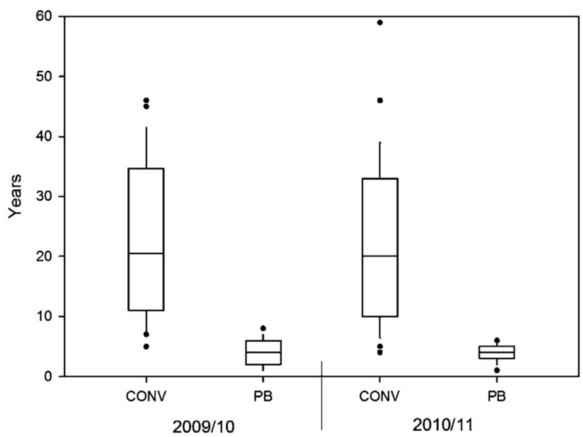

Fig. 1. Distribution of the period the target fields have been under PB or CONV tillage in the selected districts in Zimbabwe, 2009/10 and 2010/11 seasons (CONV – conventionally tilled and PB – planting basin-based conservation agriculture).

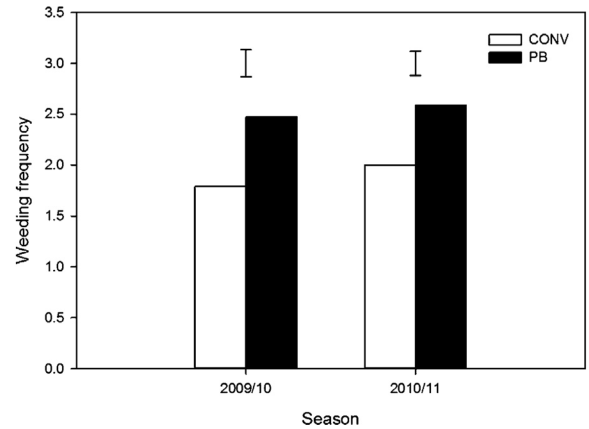

Fig. 3. Distribution of frequency of hand-hoe weeding in two tillage systems practiced by farmers across 20 districts in Zimbabwe during the 2009/10 and 2010/11 seasons (CONV – conventionally tilled, PB – planting basin-based conservation agriculture).

3. Results

3.1. Characteristics of tillage systems

The majority of fields were under maize (83% in 2009/10 and 69% in 2010/11 seasons), followed by sorghum (17% and 27% for 2009/10 and 2010/11 respectively) and pearl millet (4% in 2010/11) (Tables 1 and 2). In the 2009/10 season the small grains were grown in both tillage systems only in the driest areas (natural region IV and V), during the 2010/11 season 17 farmers produced small grains and only 2 of these were located in the wetter parts of the country (natural region II) the rest were in natural regions IV and V. Small grains are recommended in the semi arid areas of the country but farmers in these areas prefer growing maize which is less labor demanding in terms of bird scaring and harvesting.

On average, farmers' fields had been under PB for 4 years in 2009/10 and 5.6 years in 2010/11 seasons. Over 50% of the fields had been under PB for between 3 and 6 years in 2009/10, in 2010/11 over 60% were under PB for 4–7 years (Fig. 1). The mean length of time the fields had been ploughed was 26 and 26.5 years in 2009/10 and 2010/11 respectively.

In 2009/10 the mean planting date in PB plots was the 3rd of November 2009, with the planting period spreading over a period of 64 days, from the 1st of October to the 3rd of December 2009 (Fig. 2). The mean planting date for CONV was 21st November 2009, 18 days difference to PB. The CONV planting period was spread over 148 days, from the 8th of September 2009/10 to the 3rd of February 2010 (Fig. 2). In 2010/11 season, a similar trend was observed in planting time where the mean planting date under PB was 12 days earlier (20th of November 2011) than for CONV (1st of December 2010). Relative to the previous season, the planting period was longer under the PB spreading over109 days. Under CONV the planting period of the 2010/11 season spread over 129 days.

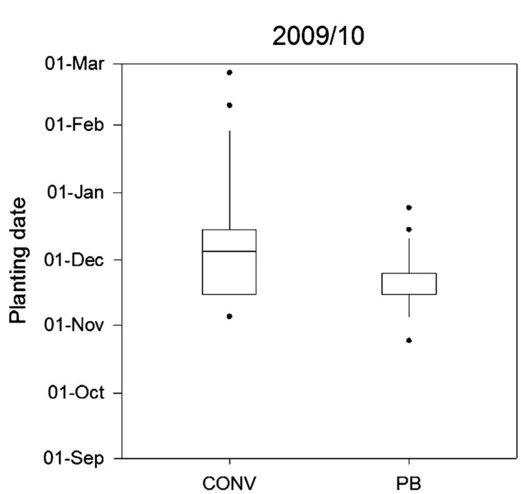

Fig. 2. Distribution of planting dates in CONV and PB tillage systems during the 2009/10 and 2010/11 cropping season in the selected districts in Zimbabwe.

3.2. Weed growth under different tillage systems

3.2.1. Tillage effects on weeding frequency

In both seasons the frequency of hand-hoe weeding was significantly different ($P < 0.05$) between the two tillage systems (Fig. 3). Fields under PB received an average of 2.5 and 2.6 post-planting hand-hoe weeding operations in the 2009/10 and 2010/11 seasons respectively compared with 1.8 and 2.0 operations under CONV fields in 2009/10 and 2010/11 seasons respectively. Although some farmers carried out more than three post-planting hand-hoe weeding operations in PB, the majority was unable to do so on time owing to labor constraints.

3.2.2. Tillage effect on weed growth

Differences in weed biomass between PB and CONV in both the 2009/10 and 2010/11 seasons were not significant ($P > 0.05$). When compared with CONV, PB had between 6.7 and 27.4% more weed biomass in the 2009/10 season. Although not significant, the weed dry matter in 2009/10 season was found to be positively correlated ($R^2 = 0.18$; $P > 0.05$) to the years the field had been under PB tillage. The correlation was, also not significant ($P > 0.05$) in the 2010/11 season. Weed ground cover was, however, significantly different ($P = 0.02$) between the two tillage treatments only in the 2009/10 season (Table 5).

3.2.3. Weed growth in different agro-ecological zones

There was no significant interaction between tillage and natural region on weed ground cover and dry matter yield in both seasons. However, weed cover significantly differed under different natural regions in 2009/10. Annual monocot weed species including the *Setaria* spp. group dominated fields in the semi-arid areas (natural region IV) whereas annual dicots such as *Richardia scabra* L. and *Leucas martinicensis* (Jacq.) r. Br. predominated in the wetter districts. Natural region II had the highest weed cover, with lower weed cover observed in natural region V in the 2009/10 season (Fig. 4). Though not significant a similar trend was observed in 2010/11. Weed biomass significantly ($P < 0.001$) varied with natural region in 2009/10, with natural region III having the highest weed dry matter under PB tillage (Fig. 5). There was no difference in weed biomass in the second season (2010/11).

3.2.4. Effect of weed biomass on crop yields

In the 2009/10 season, maize grain yields were higher with PB in all natural regions although differences were not significant (Table 6). The differences in yield were not significant across natural regions in both seasons. There was a weak correlation between weed biomass in PB and grain yields in both seasons ($R^2 = 0.009$ in 2009/10 and $R^2 = 0.013$ in 2010/11). The relationship was not significant in both seasons ($P > 0.05$).

3.3. Labor demand under different tillage systems

3.3.1. Labor requirements

Labor availability is a challenge in smallholder farming areas as shown in Table 4, where full time labor ranged from 22 to 47% of the average household size. Results from direct observation labor studies showed that generally, more man days were required to carry out operations in fields under PB compared with CONV (Table 7). Mean total man days required for PB, and CONV were 84.7 and 38.6, respectively (Table 7). It took a mean of 16.9 days for an average person to dig basins on one hectare compared to 2.7 days for ploughing a CONV plot of the same area. The average number of man days required in planting was less for CONV compared to PB (24.1%). Weeding in PB plots took 41.5 man days compared with 24.8 days for CONV.

Table 5
Effect of tillage system on percentage weed ground cover and dry matter yield at the end of the 2009/10 and 2010/11 cropping season across 9 contrasting districts in Zimbabwe.

Tillage	Weed growth			
	Weed ground cover (%)		Weed dry matter (g m^{-2})	
	2009/10 (n = 20)	2010/11 (n = 18)	2009/10 (n = 20)	2010/11 (n = 18)
PB	54.7	26.3	118.0	344.0
CONV	37.9	18.7	76.0	280.0
P value	0.02	0.19	0.09	0.42
SED	6.9	5.7	23.9	77.2

PB – planting basin; CONV – animal-drawn mouldboard ploughing.

Table 6
Effect of tillage system on maize crop yields in the 2009/10 and 2010/11 cropping seasons across 9 contrasting districts in Zimbabwe.

Natural region	2009/10		2010/11	
	CONV	PB	CONV	PB
II	787.5	1042.3	–	–
III	506.3	1060.6	2310	747
IV	330.6	384.7	1035	1091
V	0.0	106.7	1292	1183
***P* values**				
Tillage	NS		NS	
NR	NS		NS	
Interaction	NS		NS	
SED				
Tillage	237.7		499.4	
NR	347.1		634.3	
Interaction	490.7		898.3	

PB – planting basin; CONV – animal-drawn mouldboard ploughing; NS – not significant.

3.3.2. Grain yield

In the 2011/12 season, PB had 61.8% higher maize yields compared to CONV plots (Table 8) despite the higher weed pressure. The differences in yield between PB and CONV were significant in six of the nine districts.

3.3.3. Returns to labor

The cost associated with PB was higher compared with CONV (Table 9). Total variable cost for PB averaged US$368.82 per hectare compared with US$260 per hectare for CONV. Labor cost per kg of grain was lower and gross margin higher for PB and this was attributed to the higher yield (Table 8). Returns to labor were also higher ($0.44 per man day) for PB compared with CONV ($0.17 per man day) (Table 9).

4. Discussion

4.1. Farming system characteristics

Generally, farmers who used PB planted earlier when compared with CONV and therefore crops under the former benefited from the conditions at the start of the rainy season which favor early crop establishment and growth (Twomlow et al., 2006). Farmers who use PB do not have to wait for the first rains to soften the soil before they can plough and then later plant (Baudron et al., 2007; Mazvimavi and Twomlow, 2009). In addition, the planting period under PB was shorter than for CONV and incidences of late planting were much higher under CONV (Fig. 2). PB has been reported to conserve more soil moisture compared to CONV early in the season in semi-arid Zimbabwe (Mupangwa, 2009) because of the harvesting of the first rains in the planting basins. All these factors contribute to higher crop productivity under PB compared with CONV. To increase the chances of production and spread the risk of crop failure, farmers staggered planting dates throughout the cropping season hence planted over long durations. This is done so that the growing crop will receive enough moisture from subsequent rains ensuring some harvest. Similar observations were made in a semi arid region in Mozambique where farmers planted on up to eight separate occasions per season (Milgroom and Giller, 2013).

4.2. Weed growth

The significantly higher weed biomass and cover observed under PB in the 2009/10 indicated that weed pressure was still high even though farmers had used the tillage technique for up to six

Table 7
Time taken to do agronomic operations in field under PB[a] and CONV[b]. Figures in brackets denote standard error of the mean.

Operation	Time (man days per hectare)		
	PB	CONV	
		Separate ploughing and planting	Combined ploughing and planting
Winter weeding	6.58 (1.95)	–	–
Digging basins	16.86 (2.35)	–	–
Ploughing	–	2.68 (0.24)	–
Ploughing and planting	–	–	5.93 (1.16)
Planting	5.14 (0.67)	3.34 (0.48)	–
Manure application	8.11 (1.48)	2.84 (1.47)	2.84 (1.47)
Basal application	4.06 (1.45)	2.95 (1.06)	2.95 (1.06)
Top dressing	2.49 (0.59)	1.92 (0.34)	1.92 (0.34)
1st weeding	18.47 (2.19)	12.92 (1.10)	12.92 (1.10)
2nd weeding	12.30 (1.05)	11.92 (1.42)	11.92 (1.42)
3rd weeding	10.72 (1.53)	–	
Summation of average time for all operations	84.73	38.57	38.48

[a] Planting basin-based conservation agriculture.
[b] Conventionally tilled (animal-drawn mouldboard ploughing).

Table 8
Maize grain yields obtained in fields under reduced (PB) and conventional tillage (CONV) in the 2011/12 season. Figures in brackets denote standard error of the mean.

Natural region	District	Average yield (kg ha^{-1})		P value
		PB	CONV	
II	Bindura	1203 (159)	1150 (181)	NS
	Murehwa	2437 (168)	1860 (201)	0.03
III	Masvingo	2031 (186)	1043 (140)	0.00
	Kadoma	2059 (134)	1170 (197)	0.00
IV	Nkayi	1496 (247)	897 (165)	0.05
	Gokwe South	1558 (162)	1059 (125)	0.02
	Zaka	1402 (150)	607 (105)	0.00
V	Binga	1266 (433)	1328 (220)	NS
	Hwange	957 (152)	1145 (220)	NS
Average		1603 (50)	991 (40)	

NS – not significant.

years. It, however, has been estimated that yield, soil characteristics and weed population only reach an equilibrium when a management regime has been established for four to ten years (Clements et al., 1996). In our study, there were no significant differences in both weed cover and biomass in the 2010/11 season although the former was higher under PB. Mashingaidze et al. (2012) reported similar findings from on-station trials that had be run for four years. In our study, weed biomass was high in PB despite the fact that PB plots received 42% and 59% more weeding than CONV plots during the 2009/10 and 2010/11 seasons, respectively.

Weed species composition varied between areas probably reflecting the differences in agroecology and soil type. Our study showed a dominance of annual monocot weed species in fields in the semi arid areas (Natural region IV) whereas annual dicots were predominant in the wetter districts (natural region II and III). Previous studies at Matopos Research Station (Mashingaidze et al., 2012) and on farmers' fields in Masvingo (Mashingaidze, 2013) provided some evidence of association of small-seeded weed species such as *Portulaca oleracea* L. with minimum tillage practices, however this trend was not consistent over seasons or crops. Other annual monocot weeds such as *Cynodon dactylon* that are predominant in fields under CA are only effectively controlled with the use of herbicides such as glyphosate [N-(phosphono-methyl)glycine] (Steiner and Twomlow, 2003). Glyphosate has been used successfully to control weeds in Malawi although this is associated with high capital costs (Ngwira et al., 2012).

Although farmers are advised to mulch their fields using crop residues and practice crop rotations, in compliance with all CA principles and also to control weeds, the panel surveys indicated that crop residues were preferentially fed to livestock. Although legumes such as groundnut (*Arachis hypogaea*) and cowpea (*Vigna unguiculata*) were grown by some farmers, none of the farmers had paired PB and CONV fields under these legumes in both seasons. In fact, legumes were observed mainly on very small portions under CONV tillage and rarely on PB. The nature of crop production in SSA favors the production of cereal crops over legumes with relatively small areas allocated to legumes (Nhemachena et al., 2003). Lack of viable markets for other crops and food security concerns meant that most farmers grew maize, the staple crop.

In a review of research on the effect of tillage systems on soil weed distribution Chauhan et al. (2006) reported that minimum tillage concentrated weed seeds in the upper soil surface layer whereas with mouldboard ploughing weed seeds were distributed uniformly throughout the ploughing depth. The implication of weed seeds being maintained in the upper soil surface layer in tillage practices such as the PB is that environmental conditions in this layer are more conducive to weed germination and emergence compared to deeper soil layers. Ploughing buries some of the weed seeds at depths where seed dormancy is induced resulting in low weed seedling recruitment. It is likely that weeds seeds at the soil surface in PB fields in this survey were probably stimulated to germinate as the cereal crop canopy became more open toward the end of the season (Mashingaidze, 2004). Based on the planting dates (Fig. 2) most of the crops had reached physiological maturity and weed/crop competition for resources such as available water and nutrients was probably low allowing the weeds to grow (Kruepl et al., 2006).

4.3. Weed growth in different natural regions

Although the weed biomass was not defined by weed type in our study, the weed biomass was higher in the semi arid regions, nat-

Table 9
Returns to investment for fields under reduced tillage (PB) and conventional tillage in selected districts in Zimbabwe.

Item	Unit	Price per-unit (US$)	PB plot		CONV plot	
			Quantity (kg)	Cost (US$)	Quantity (kg)	Cost (US$)
A Revenue	Maize grain (kg)	0.275	1603	440.83	991	272.53
	Total revenue			440.83		272.53
B Variable costs	Maize seed (kg)	2	25	50	20	40
	Basal fertilizer (kg)	0.58	107.51	62.36	132	76.56
	Top dressing (kg)	0.72	130.26	93.79	96.33	69.36
	Total inputs costs			206.14		185.91
	Labor (day)	1.92	84.73	162.68	38.6	74.11
	Total variable costs			368.82		260.03
C Returns	Gross margin (US$/ha)			72.00		12.50
	Cost per kg (US$/kg)			0.23		0.26
	Returns to labor (US$/day)			0.44		0.17
	Labor productivity			18.92		25.67

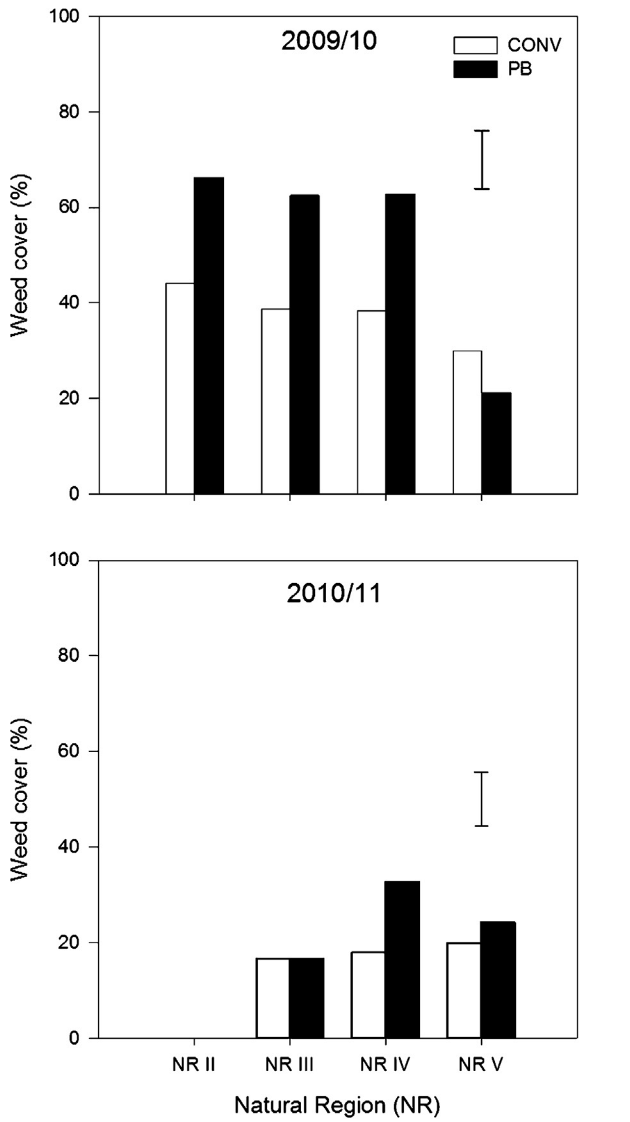

Fig. 4. Percentage weed ground cover measured in PB and CONV at the end of the 2009/10 and 2010/11 cropping season in different agro-ecological zones in Zimbabwe. Bars represent ±SED.

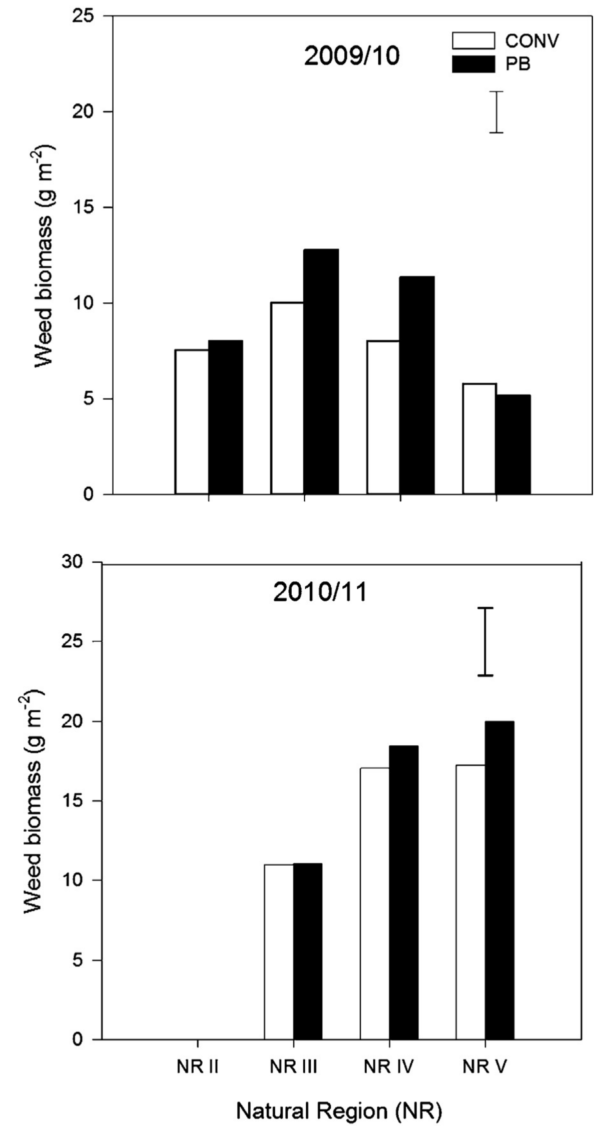

Fig. 5. Weed dry matter yield in PB and CONV at the end of the 2009/10 and 2010/11 cropping season in different agro-ecological zones in Zimbabwe. Bars represent ±SED (weed dry matter square-root ($\sqrt{(x+0.5)}$) transformed).

ural region III and IV in the 2009/10 season and in natural regions IV and V in the 2010/11 season. Vigorously growing crops in natural region II due to more rainfall form a full crop canopy early in the season that reduces the amount of light reaching the soil surface resulting in inhibition of weed seed germination (Kruepl et al., 2006). Such a crop community has the potential to reduce the amount of weeds that reproduce and replenish the weed seed bank. In the drier natural regions III, IV and V lower rainfall amounts imply that full crop canopy cover occur much later in the season, if it occurs, and therefore weeds easily germinate and establish. Dry spells in natural region V are frequent causing moisture stress therefore also may have affected weed growth in the 2009/10 season.

4.4. Effect of weed biomass on maize yields

Although a high weed biomass and cover was observed in PB compared with CONV, the weed pressure had no significant effect on crop yields. The weed assessment was conducted at the end of the cropping seasons, a time when the late season weeds had emerged. Weeding, in smallholder farms, is done at periods deemed critical for the growing crop and when the labor force is available. In our study, PB plots were weeded at least twice per season, the majority of smallholder farmers in Zimbabwe weed their maize crop once or twice in a season depending on weed infestation, crop growth stage and labor availability (Vogel, 1994; Rambakudzibga et al., 2002). Late season weeding is hardly carried out due to labor limitations, after the crop has set seed and up to harvesting. Late season weed infestations have been shown not to reduce crop yields as much as early weed competition (Rambakudzibga et al., 2002). However, the lack of weed control toward the end of the cropping season results in weeds setting seed in the fields and replenishing the weed seed bank (Mashingaidze, 2013). If weeds could be effectively controlled during the initial years of PB tillage in low-input agriculture systems, the weed seed bank may be reduced, eventually decreasing the potential for serious weed infestation.

4.5. Labor investment

Labor investment in most operations was higher under PB compared with CONV (Table 7). Labor investment is a critical determinant of technology adoption as most households have limited labor supply as shown in Table 4. Although investment in land preparation under PB was the highest between the two tillage treatments (Table 7), the time invested was over 50% less than that observed during the 2007 panel survey, i.e. within the first three years of the initiation of the program. This strongly supports the hypothesis by Mazvimavi et al. (2008) that over time the digging of basins becomes easier as the farmer gains experience. Mechanical tillage in CA using rippers has been recommended from previous panel studies but their use by the target group is still minimal. The farmers targeted for the weed assessment were resource-poor farmers targeted for input assistance by NGOs under the Protracted Relief Program. These farmers usually practice subsistence farming, thus hardly have surplus produce for income generation. This has undermined the investment in technologies like rippers and use of herbicides which have the potential to reduce time invested in PB.

In both the panel surveys and the labor study there was a higher frequency of weeding under the PB system; this is necessitated by the higher rate of weed growth under the systems of reduced tillage (Gianessi et al., 2009). Mashingaidze et al. (2012) reported that to achieve similar levels of post planting weed control between PB and CONV there was need to increase the number of man hours contributed to weed control by over 50–100% in the former tillage system. Mabasa et al. (1998) reported that the seedbed under plough was weed-free for up to four weeks after the ploughing operation and this reduced the need for early weed control and gave crop a head start with limited weed competition. Reduced tillage systems in Zimbabwe such as PB have been observed to have greater early season weed growth (Mabasa et al., 1998; Mashingaidze et al., 2012) and therefore require earlier and more frequent weeding than CONV tillage fields. However, with low household labor available for on-farm activities (Table 4), it is unlikely that PB plots will be expanded and that the frequency of hand-hoe weeding will increase.

4.6. Returns to investment

Though being more labor intensive, PB tillage was observed to have higher returns to investment. This was attributed to higher yields realized under PB (Table 8). Besides water harvesting and early planting benefits, PB enables farmers to increase nutrient use efficiency through precision application of fertility resources in the planting basins. Similar results have been reported by Mazvimavi et al. (2008). However it has been reported that increased returns to investment foster adoption in technologies where output is market driven and benefits are realized in terms of income improvements (Zeller et al., 1998). Therefore there is need to extend PB systems to more high value crops with ready markets. This would enable farmers to have an incentive and ability to invest in CA, use rippers, purchase herbicides for weed control, pay for hired labor and be able to practice crop rotation as they transition from CONV to CA.

5. Conclusions

Despite a higher frequency of weeding practiced by the smallholder farmers across contrasting agro-ecological conditions, fields under PB were generally associated with higher weed growth compared with CONV. A positive correlation between weed growth and number of years fields have been under PB as currently practiced by farmers implies that there is no reduction in weed pressure as expected. There is need to explore the use of herbicides, mulch and or cover crops as part of an integrated weed management package in order to reduce labor demand and enable farmers to benefit from higher crop yields and labor investment under PB.

Acknowledgements

The authors gratefully acknowledge financial assistance from the Protracted Relief Program funded by a Consortium of International Donors and the Food and Agriculture Organisation of the United Nations.

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