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Weed dynamics in low-input dryland smallholder conservation agriculture systems in semi-arid zimbabwe

by

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DECLARATION

I , Nester Mashingaidze declare that the thesis, which I herby submit for the degree PhD Agronomy at the University of Pretoria, is my own work and has not previously been submitted by me at this or any other tertiary institution.

SIGNATURE: ……………………………………….

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Praise and glory to the Lord from whom all good things proceed!!

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LIST OF ABBREVIATIONS

AGRITEX	Zimbabwe Department of Agricultural, Technical and Extension Services
ANOVA	Analysis of variance
CA	Conservation agriculture
CIMMYT	International Maize and Wheat Improvement Centre
CONV	Conventional mouldboard plough tillage
FAO	United Nations Food and Agricultural Organization
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
GART	Golden Valley Research Trust
LSD	Least significant difference
MT	Minimum tillage
NGO	Non-Governmental Organisation
NR	Natural Region
OC	Organic carbon
PB	Planting basin
PRA	Participatory Rural Appraisal
REML	Restricted maximum likelihood model
RIV	Relative Importance Value
RT	Ripper tine
SED	Standard error of difference of means
WAP	Weeks after planting
ZCATF	Zimbabwe Conservation Agriculture Taskforce
ZFU	Zimbabwe Farmers' Union

ABSTRACT

The reported requirement for a higher weeding effort due to increased weed infestations under conservation agriculture (CA) relative to conventional mouldboard plough tillage is perceived by both smallholder farmers and extension workers as the main limiting factor to the widespread adoption of CA by smallholder farmers in southern Africa. However, proponents of CA argue that weeds are only a problem under CA in the initial two years and decline afterwards resulting in reduced labour requirements for weeding under CA. They further posit that weeds are only major problem where minimum tillage (MT) is adopted without crop residue mulching and diverse crop rotations. This thesis explores the effect of time under CA on weed population dynamics and crop growth under the recommended CA practices and actual smallholder farmer practice in semi-arid Zimbabwe.

Assessment of weed and crop growth on a long-term CA experiment at Matopos Research Station revealed that the MT systems of planting basins and ripper tine were associated with higher early season weed density and biomass than conventional early summer mouldboard tillage (CONV) in both the fifth (cowpea phase) and sixth (sorghum phase) years of CA. This increased weed infestation within the first four weeks after planting in CA necessitated early weeding to provide a clean seedbed and avert significant crop yield loss. Maize mulching only suppressed early season weed growth in sorghum mostly at a mulch rate of 8 t ha^{-1} which is not a mulching rate that is attainable on most smallholder farms. However, the lower maize residue mulch rate of 4 t ha^{-1} was consistently associated with increased weed emergence and growth as from the middle of the cropping season in both crop species. The increased weed infestations under the mulch were probably due to the creation of 'safe sites' with moist conditions and moderate temperatures. The high weed growth under the mulch contributed to the low sorghum grain yield obtained under mulched plots. In addition, maize mulching was also associated with a less diverse weed community that was dominated by the competitive *Setaria* spp. and difficult to hoe weed *Eleusine indica* (L.) Gaertn. However, the weed community under CA was similar to that under CONV tillage with no evidence of a shift to the more difficult to control weed species. The increased early season weed growth and high weed pressure under CA meant that it

was still necessary to hoe weed four times within the cropping season to reduce weed infestations and improve crop growth even after four years of recommended CA practices. Early and frequent weeding was effective in reducing weed growth of most species including *Setaria* spp. and *E. indica* demonstrating that on smallholder farms where labour is available hoe weeding can provide adequate weed control. The wider spacings recommended for use in CA contributed to the low cowpea and sorghum grain yields obtained under CA compared to CONV tillage.

On smallholder farms in Masvingo District, the MT system of planting basin (PB) was the only conservation farming (CF) component adopted by farmers. There was no difference in the total seedling density of the soil weed seed bank and density of emerged weeds in the field in PB and conventional mouldboard ploughing done at first effective rains (CONV tillage). However, the first weeding in PB was done at least 15 days earlier ($P < 0.05$) than in CONV tillage suggesting high early season weed growth in PB relative to CONV tillage. As weed density did not decline with time in PB, weed management did not differ with increase in years under PB. Shortage of inputs such as seed and fertiliser was identified by smallholder farmers as the most limiting factor in PB crop production with the area under PB was equivalent to the seed and fertiliser provided by CARE International for most farmers. On this small area, weeds could be managed by available family labour. Double the maize grain yield was obtained in PB (mean: 2856 kg ha^{-1}) due to improved weed management and soil fertility. However, the use of poorly stored composts was found to introduce weeds into some PB fields. The findings of this study demonstrated that weed pressure was still high and weed management were still a challenge under the practice recommended to smallholder farmers in Zimbabwe even in the sixth year of practice. There is, therefore, a need for research on the economic feasibility of using herbicides, intercropping and optimal crop density to ameliorate the high weed pressure under CA.

Key words: Conservation agriculture, minimum tillage, maize residue mulching, hoe weeding intensity, weed density and biomass, weed species composition, cowpea (*Vigna unguiculata* (L.) Walp), sorghum (*Sorghum bicolor* (L.) Moench), maize (*Zea mays* L.)

CHAPTER 1

GENERAL INTRODUCTION

1.1 Background

The last 10 years has seen an increase in the promotion of conservation agriculture (CA) to smallholder farmers in sub-Saharan Africa by a large number of research and development organisations (Andersson & Giller, 2012). Conservation agriculture is believed to have great potential to sustainably improve crop productivity for smallholder farmers in the region especially those with limited access to draught animal power and external inputs (FAO, 2010). Conservation agriculture comprises the simultaneous application of minimum tillage (MT), provision of permanent soil cover and crop rotation practiced in tandem with good crop management. According to Derpsch & Friedrich (2009) CA is a universal technology from which benefits can be derived across climatic zones and farming systems. On large-scale mechanised farms, benefits associated with CA include savings in fuel, time, labour and improved conservation of soil and water (Kassam *et al*., 2009). Adoption of CA by smallholder farmers is reported to be increasing in South America due to labour and time savings, erosion control, increased crop yield and better incomes (Bolliger *et al*., 2006).

In sub-Saharan Africa, CA offers the potential benefits of early planting for smallholder farmers with limited access to draught animal power (Twomlow *et al*., 2008), labour savings with use of implements like the ripper tine (Baudron *et al*., 2007), yield stabilisation and improvements in soil and water conservation (Thierfelder & Wall, 2009). Grain yield of maize (*Zea mays* L.), teff (*Eragrostis tef* (Zuccagani) Trotter) and wheat (*Triticum aestivum* L.) have been reported to double under CA-based practices compared to conventional farmer practices in Ghana, Ethiopia, Tanzania and Malawi (Ito *et al*., 2007) , Kenya (Rockstrom *et al*., 2009) and Mozambique (Nkala *et al*., 2011; Grabowski, 2011). In southern Africa, CA mainly comprises dry season land preparation using handheld hoes, crop residues retention on fields to provide at least 30% soil cover at planting and three-year rotations of a cereal, legume and cash crop or small grain

(Baudron *et al*., 2007; Mazvimavi & Twomlow, 2009). In semi-arid southern Zambia, this hoe-based CA is reported to have yielded on average an additional 1 694 kg ha^{-1} of maize grain on smallholder farmers' fields (GART, 2008). The increased maize yield was attributed mainly to early planting (45%), timely weeding (26%), improvements in soil fertility (20%) and the remainder of yield benefits derived from rainwater harvesting.

However, there is an increasing amount of evidence that suggests that CA may be less compatible with smallholder agriculture compared to large and mechanised farm holdings. Derpsch (2008) reports that adoption of CA by smallholder farmers in South America has been slow compared to that on large and more mechanised farms. The smallholder farmers face challenges in practicing permanent no-tillage and diversified crop rotations as recommended in CA. The no-tillage fields are occasionally tilled in order to control troublesome perennial weeds and combat soil compaction (Ribeiro *et al*., 2005). Furthermore, cover crops with low market demand are excluded from crop rotations resulting in less diversified crop sequences. The suitability of CA for the majority of smallholder farmers in sub-Saharan Africa is also being questioned by a number of researchers (Giller *et al*., 2009; Gowing & Palmer, 2008; Baudron *et al*., 2012a). The majority of smallholder farmers reported to be practicing CA in southern Africa are in fact practicing minimum tillage (Baudron *et al*., 2007; Mazvimavi *et al*., 2011) due to shortages of crop residue for mulching and poorly developed markets for legumes and small grains (Ncube, 2007; Mutsamba *et al*., 2012). In the mixed crop/livestock farming systems common to smallholder agriculture in the region, crop residues are primarily used to feed livestock during the dry season. In much of southern America, additional organic matter is obtained through the growing of cover crops such as black oats (*Avena strigosa* Schreb) and lablab (*Dolichos lablab* L.) either in sequence or association with cash crops in CA (Ribeiro *et al*., 2005). This is, however, not possible in southern Africa where the harsh and long dry season and the use of fields as communal grazing areas after crop harvesting preclude the growing of cover crops in dryland smallholder agriculture.

According to Baudron *et al*. (2012a) most smallholder farmers are unlikely to adopt a technology that requires greater capital and / or labour than their current farming practice. The promotion of CA to smallholder farmers in sub-Saharan Africa was often tied to free or subsidised inputs of seed, fertilisers and to a lesser extent herbicides (Ito *et al*., 2007; Giller *et al*., 2009). This resulted in higher crop yields even where only MT was adopted by farmers than obtained under conventional farmer practice where little or no fertilisers were used (Rusinamhodzi *et al*., 2011). Research findings from on-farm studies in Zimbabwe suggest that without fertiliser, CA or MT systems result in slight or no crop yield increases (Twomlow *et al*., 2009; Rusinamhodzi *et al*. 2011). This requirement for fertilisers may be the reason for the lack of expansion of area committed to MT on smallholder farms in southern Africa despite the reported crop yield increases (Baudron *et al*., 2007; Mazvimavi & Twomlow, 2009, Grabowski, 2011). Furthermore, an increase in hoe weeding frequency that sometimes translated into doubling of labour requirements has been reported under CA as practiced by smallholder farmers (Haggblade & Tembo, 2003). On hoe-based CA farms in Zambia, additional maize grain yield was obtained when weeding was done timeously which in some cases translated to up to six hoe weedings per cropping season (Baudron et al., 2007; GART, 2008). Weed control has long been recognised as a major constraint to the widespread adoption of minimum tillage-based technologies such as conservation tillage and CA. Weeds are viewed by Andersson & Giller (2012) as the 'Achilles heel of CA' while Farooq *et al*. (2011) contend that weed management is the fourth principle of CA.

Tillage has long been used as an important method of weed control by farmers. Ploughing minimises weed infestations through burial of fresh weed seeds to depths from which germination and emergence is difficult (Chauhan *et al*., 2006a), buries any existing standing vegetation, disrupts growth of perennial weeds by exposing storage organs to dessication (Locke *et al*., 2002) and in this way prepares a clean seedbed for crops. In contrast, the CA tillage techniques of hand hoe-made planting basins and ripper tine being currently promoted in southern Africa leave over 80% of the soil area undisturbed (Thierfelder & Wall, 2009). Consequently, greater than 50% of fresh weed seeds are maintained near the soil surface where conditions are conducive for germination (Chauhan *et al*., 2006b). Weed infestations may, therefore, be higher under MT systems than conventional tillage. Research carried out in southern Africa reported higher weed biomass (Shumba *et al*., 1992; Vogel, 1994; Mabasa *et al*., 1998; Makanganise *et al*., 2001) and weed scores (Muliokela *et al*. 2001) under MT systems relative to convention mouldboard plough tillage. In addition, Vogel (1994) and Makanganise *et* *al*. (2001) observed the proliferation of perennial weeds such as *Cynodon dactylon* (L.) and annual weeds such as *Richardia scabra* L.in MT systems. The high weed growth associated with MT systems was identified by Nyagumbo (1999) as one of the main reasons for the low adoption of technologies such as no-till tied ridging and ripping by smallholder farmers in Zimbabwe.

However, promoters of CA argue that under the recommended practices weeds are only a problem during the first two years of adoption with weed infestations and labour requirements declining in subsequent years (FAO, 2012a; Thierfelder & Wall, undated). The improved weed management in CA is reported to be a result of the reduction in the soil weed seed bank due to use of practices that minimise weed seed return. Without access to herbicides, smallholder farmers in southern Africa are recommended to weed up to six times during the cropping season and also over the dry season when fields are un-cropped (Baudron *et al*, 2007; ZCATF, 2009) so as to reduce weed seed shed from existing vegetation. In addition, the CA practices of crop residue mulching and crop rotation are reported to aid in weed management. Crop residue mulches have been reported to suppress emergence and growth of weeds (Gill *et al*., 1992; Christoffoleti *et al*., 2007) while crop rotations can lead to greater weed mortalities than monocropping due to greater variability in the type and timing of soil and crop management (Cardina *et al*., 2002; Anderson, 2006). Under recommended CA practices, the cost of herbicides was reduced in sunnhemp (*Crotalaria juncea* L.) grown in a diversified rotation that included short duration green manure cover crops compared to monoculture in Paraguay (Kleuwer *et al*., 1998 cited in Derpsch, 2008). Furthermore, on some CA farms, herbicides were applied only before planting with the low weed infestation during the cropping season managed using only hand hoe weeding.

However, in contrast to the reported improvements in weed management with time under CA mostly observed on large scale farms, Bolliger *et al.* (2006) reports that CA is associated with increased herbicide use more than 20 years after its adoption by smallholder farmers in Brazil. As a result, herbicides are reported to present 11% of production costs in CA compared with between 2 and 5% in conventional tillage systems (Gowing & Palmer, 2008). A consequence of the increased weed pressure and prevalence of some troublesome perennial weed species observed under smallholder CA fields is the occasional ploughing or harrowing carried out in CA in order to effectively control weeds and reduce cost associated with use of herbicides (Ribeiro *et al.*, 2005; Gowing & Palmer, 2008). These findings, therefore, suggest that under sub-optimal CA practices weed management can still be serious issue even after more than 10 years of CA practice.

1.2 Rationale of study

Conservation agriculture is viewed by many to have the potential to sustainably increase crop productivity of smallholder farmers in semi-arid areas of southern Africa. The *in situ* water harvesting, early planting, the judicious use of limited fertiliser inputs and improved management associated with CA address the major constraints to crop production in smallholder agriculture in the region. As a result, CA has received increasing support for dissemination by international agencies, research organisations and has even been incorporated into the agriculture policy of NEPAD, AGRA and national agriculture programs in a number of countries in sub-Saharan Africa (Andersson & Giller, 2012). However, the suitability of CA for the majority of smallholder farmers in Africa is still a contentious among researchers and development practitioners. Practices such as crop residue mulching are incompatible with the prevalent use of crop residue as a livestock fodder during winter. Poor markets for legume seed and products limit the adoption of crop rotation. Due to these challenges, the earliest form of CA adoption by the majority of smallholder farmers in southern Africa has been minimum tillage with improved management. The higher level of management in MT has resulted in crop grain yield increases of over 100% compared to conventional mouldboard plough tillage in the short-term.

However, most smallholder farmers are facing problems in managing weeds with a reported doubling of labour required for hoe weeding. Proponents of CA argue that weeds are only a problem in the first two years and decline with time when MT is practiced with the other CA principles of crop residue mulching and diversified crop rotations (FAO, 2012a). Although a few studies have been carried out on weeds in MT and conservation tillage (CT) systems, no information is available on weed population dynamics under the CA practices currently being promoted to smallholder farmers in southern Africa. There is, thus, no empirical evidence to support the assertion that weed pressure declines from the third year of CA adoption. The studies where weed management improved with time in CA involved the use of herbicides, permanent soil cover and diversified rotations that included cover crops with cropping done in both the winter and summer seasons (Bolliger *et al*., 2006; Derpsch, 2008).

The situation under smallholder agriculture in southern Africa differs quite markedly from that on farms in South America where CA is reported to have led to improved weed management. Most smallholder farmers have limited access to herbicides and rely mainly on manual hoe weeding to control weeds (Gianessi, 2009). Under smallholder CA in southern Africa, permanent soil cover is not possible with the recommended practice being the retention of crop residue as surface mulch to provide at least 30% soil cover at planting. Although crop residue mulching is reported to suppress weed growth (Christofolleti *et al*., 2007) and thus potentially reduce weeding burden in MT systems (Gill *et al*., 1992; FAO, 2010), the mulch thresholds for weed suppression are unknown under smallholder CA practices in southern Africa. Furthermore, the recommendation to use crop residues for mulching in CA conflicts with the traditional use of crop residues as an important feed source for livestock during the long, dry season (Giller *et al*., 2009). According to Mazvimavi *et al*. (2011) more than 80% of farmers practice maize monocropping on fields that are reported to be under CA in Zimbabwe. This partial adoption of CA in smallholder agriculture is likely to result in increased weed pressure and a shift to perennial weed species under MT systems which most smallholder farmers may not be able to cope with using their current weed control strategy of hoe weeding.

The aim of the study was to assess weed infestation, weed species composition and crop yield under recommended CA practices and smallholder farmer management in semi-arid Zimbabwe. Weed growth, weed community composition and crop yields under different maize mulch rates and hoe weeding intensities were studied in the fifth and sixth years of a long-term CA experiment. This experiment explored whether the frequency of hoe weeding and maize mulch rate needed for weed suppression could be reduced without any yield penalty after four years of CA. An observational study was done over one season on farmers' fields to study extent of adoption of CA by smallholder farmers, weed infestation and management in fields that had been under CA for different lengths of time and to determine what farmers viewed as the major constraint to CA adoption. Since other management practices can also influence weed infestations in fields (Swanton & Booth, 2002), cultural practices associated with CA that could potentially reduce or increase weed pressure in fields were also investigated.

The hypotheses to be tested in the study are:

1. Weed and crop growth do not differ among i) tillage systems ii) maize residue mulch rates and iii) levels of hoe weeding intensity after more than four years of CA.
2. There is no difference in the weed community composition under different tillage systems, maize residue rates and intensities of hoe weeding in the fifth and sixth years of CA.
3. Weed infestations and weed management do not differ with number of years field has been under CA on smallholder farms. As a result labour, especially for weed management, is the main production constraint in CA.
4. Weed infestations on CA fields are the result of other cultural practices besides tillage.

1.3 Research questions

This study was designed to determine weed infestation and community composition under recommended CA practices and actual smallholder CA conditions in semi-arid southern Zimbabwe and several issues were investigated.

1. What are the effects of tillage systems, maize residue mulch rates and levels of intensity of hoe weeding on weed and crop growth after more than four years of CA?
2. Does the weed community differ with tillage system, maize mulch rates and level of hoe weeding intensity in the fifth and sixth years of CA?
3. Which of the three principles of CA have been adopted by smallholder farmers in semi-arid Zimbabwe? Do weed infestations differ with number of years a field has been under CA as practiced by these farmers? What is viewed by farmers as the main constraint to widespread CA adoption?

4. Are there any cultural practices that can ameliorate or increase weed infestations in CA under smallholder farming systems?

1.4 Outline of thesis

The thesis is organised into seven chapters beginning with Chapter 1 where the background, rationale, objectives and an outline of the thesis are given. The second chapter consists of a review of literature on CA, its associated benefits and constraints to adoption, weed population responses to tillage, crop residue mulching and crop rotation, and weed management in CA. Chapter 3 is based on a long-term CA field experiment designed to measure weed and crop growth under different maize mulch rates and hoe weeding intensity in the fifth and sixth years. A detailed description of the weed community composition under the long-term CA experiment is presented in Chapter 4. Results from an observational study on weed and maize growth under farmers' fields are given in the fifth chapter. Chapter 6 presents the findings on weed seed viability in composts applied by farmers on CA fields. The seventh chapter is a synthesis of chapters 3 to 6 where overall conclusions and practical recommendations of the entire study are given.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Introduction

Although conservation agriculture is currently being widely promoted to smallholder farmers in sub-Saharan Africa as a sustainable means to increase and stabilise crop yields, the actual benefits that can be obtained from the practice under typical smallholder conditions remains a highly debated issue. This is because according to the body of knowledge on CA, maximum benefits are obtained when the three pillars of CA - minimum tillage (MT), permanent soil cover and crop rotation - are applied simultaneously and in conjunction with good management. Although smallholder farmers in southern Africa have realised improved crop yields, increased weed pressure and high prevalence of perennial weed species have also been reported in these fields. Promoters of CA attribute the reported adverse weed changes to partial adoption of CA by smallholder farmers and argue that under recommended CA practices weed pressure and related management begin to decline from the third year of CA adoption. Smallholder farmers in southern Africa eke out a living on marginal agro-ecosystems and with limited capital to invest in agriculture to improve productivity. These farmers often face problems in adopting and adapting CA to their farming systems. This review of literature presents the benefits and challenges associated with each CA component and the full CA package based on findings from around the world. Weeds are the focus of this study as weed management is recognised by many as the major constraint to the widespread adoption of CA throughout the world and for resource-limited smallholder farmers in sub-Saharan Africa in particular.

2.2 Smallholder agriculture in sub-Saharan Africa

2.2.1 Constraints to crop production

The key to reducing hunger and poverty in developing countries is believed by many to lie in increasing productivity in smallholder agriculture (Zhou, 2010). However, smallholder farmers face multiple constraints related to their socio-economic and environmental conditions. In sub-Saharan Africa, smallholder farms are characterised by low land areas of less than 5 ha although this is usually not the primary factor limiting crop production (Giller *et al*., 2009).The majority of smallholder farmers often fail to meet their subsistence food requirements due to limited access to financial capital and farming implements, dependence on manual labour and lack of information on appropriate technologies (Wall, 2007; Mudhara *et al*., undated). The inherently infertile soils and lack of resources to purchase inputs such as fertiliser have resulted in low yields under smallholder farms of less than 1 t ha^{-1} for cereals including the staple maize crop (Twomlow *et al*., 2006) and 0.4 t ha^{-1} for legumes (Ncube, 2007).

A number of technologies have been promoted to smallholder farmers to address the problem of low crop productivity. The promotion of hybrid maize was one of the successful technologies with the majority of smallholder farmers buying and planting improved maize seed each year. Rohrbach (1988) attributes the high adoption rate of maize hybrid to increased yields, drought tolerance and good yield stability under adverse conditions. However, less than 5% of smallholder farmers in semi-arid areas use fertilisers at the recommended rates (Rusike *et al*., 2003) with farmers citing the high risk of crop failure due to dry spells and droughts in semi-arid areas (Twomlow *et al*., 2009). Therefore, smallholder farmers will only invest their limited resources in a technology if the expected returns are higher than those obtained from current practices and the risk of failure is low. Smallholder agriculture in southern Africa is based on cropping systems combined with livestock production on communal rangelands and fallow land (Masikati, 2010). Livestock complement cropping through the provision of manure for fertility management, draught power for ploughing and cultivation, and as a source of cash for the purchase of inputs. Other benefits obtained from livestock include their use as an important investment, insurance against risk, source of milk production and for transportation (Bossio, 2009). On the other hand, crop residues that are a by-product of the cropping system provide feed for livestock during the dry season when fodder is limited in smallholder agriculture (Nyathi *et al*., 2011). In particular maize residues are an important livestock feed during the dry season when they are either grazed *in situ* or harvested and transported to cattle pens (Masikati, 2010). Consequently, any new innovation on crop production should also consider the livestock component as smallholder farms are commonly managed as mixed crop/livestock systems if it is to be widely adopted by smallholder farmers.

2.2.2 Crop production in the semi-arid tropics

Smallholder agriculture in sub-Saharan Africa is characterised by wide variation in resource availability with the lowest productivity usually observed where agriculture is done in marginal areas. Among the marginal areas used in smallholder agriculture are semi-arid areas which account for more than 15% of the crop production area in southern Africa (Vivek *et al*., 2005). Zimbabwe's population is dominated by smallholder farmers of whom 75% reside in semi-arid areas (Chuma & Haggmann, 1998; Bird & Shepherd, 2003). Semi-arid areas are defined by Fischer *et al*. (2009) as regions where the length of the crop growing period is between 75 and 180 days. The remainder of the year is unsuitable for crop growth as precipitation is less than potential evaporation. The areas are typified by high temperatures of between 30 and 45 ^{0}C during the hottest months and low erratic rainfall of up to 800 mm per annum. The rainfall is highly variable in time resulting in drastic yield reductions every 2 to 4 years and total crop failure every 10 years (Rockström *et al*., 2002).

Zimbabwe is divided into five agro-ecological regions, also known as natural regions, based mainly on the mean annual rainfall, soil quality and vegetation (Fig. 2.1). Natural regions (NR) III, IV and V are classified as semi-arid in Zimbabwe (Moyo *et al*., 2012). The semi-arid areas have relatively high temperatures with mean annual rainfall of less than 800 mm that declines from NR III to V. Mupangwa *et al*. (2011) reported a coefficient of variation of 34 to 44 % in annual rainfall in semi-arid Zimbabwe. False starts to the rainy season and occurrence of intra-seasonal dry spells were also identified as factors that reduced crop establishment and crop yields in semi-arid Zimbabwe. The crop growing period is short ranging from 70 to 135 days. Soils are sandy textured with low pH, levels of N, P and S, and due to low organic matter cation exchange capacity is low in these soils (Nyamapfene, 1991). As a result, smallholder crop production in these semi-arid areas is highly risky with NR IV and V more suited to livestock rather than crop production.

However, on most smallholder farms cereals such as maize (*Zea mays* L.) and legumes including groundnuts (*Arachis hypogea* L.) and cowpeas (*Vigna unguiculata* (L.) Walp.) are grown for subsistence in semi-arid areas in Zimbabwe. The yield of crops is low because most smallholder farmers have limited income to invest in purchasing inputs such as fertilisers and lime that would increase crop yields (Bird & Shepherd, 2003). Furthermore, the majority of the smallholder farmers have limited access to draught animal power which results in delayed planting (Riches *et al*., 1998). In semi-arid Zimbabwe, a delay of a week in planting resulted in 48 kg ha^{-1} loss in maize grain yield (Mugabe & Banga, 2001) highlighting the importance of early planting in these areas where maize yields are often less than 1 t ha^{-1}.Therefore, improving productivity in these semi-arid areas is central to sustainable development in Zimbabwe and in the region (Makanda *et al*., 2009). Modeling work done by Fischer *et al*. (2009) indicated that use of high inputs and improved soil and water management had the potential to more than double crop yields in semi-arid tropics.

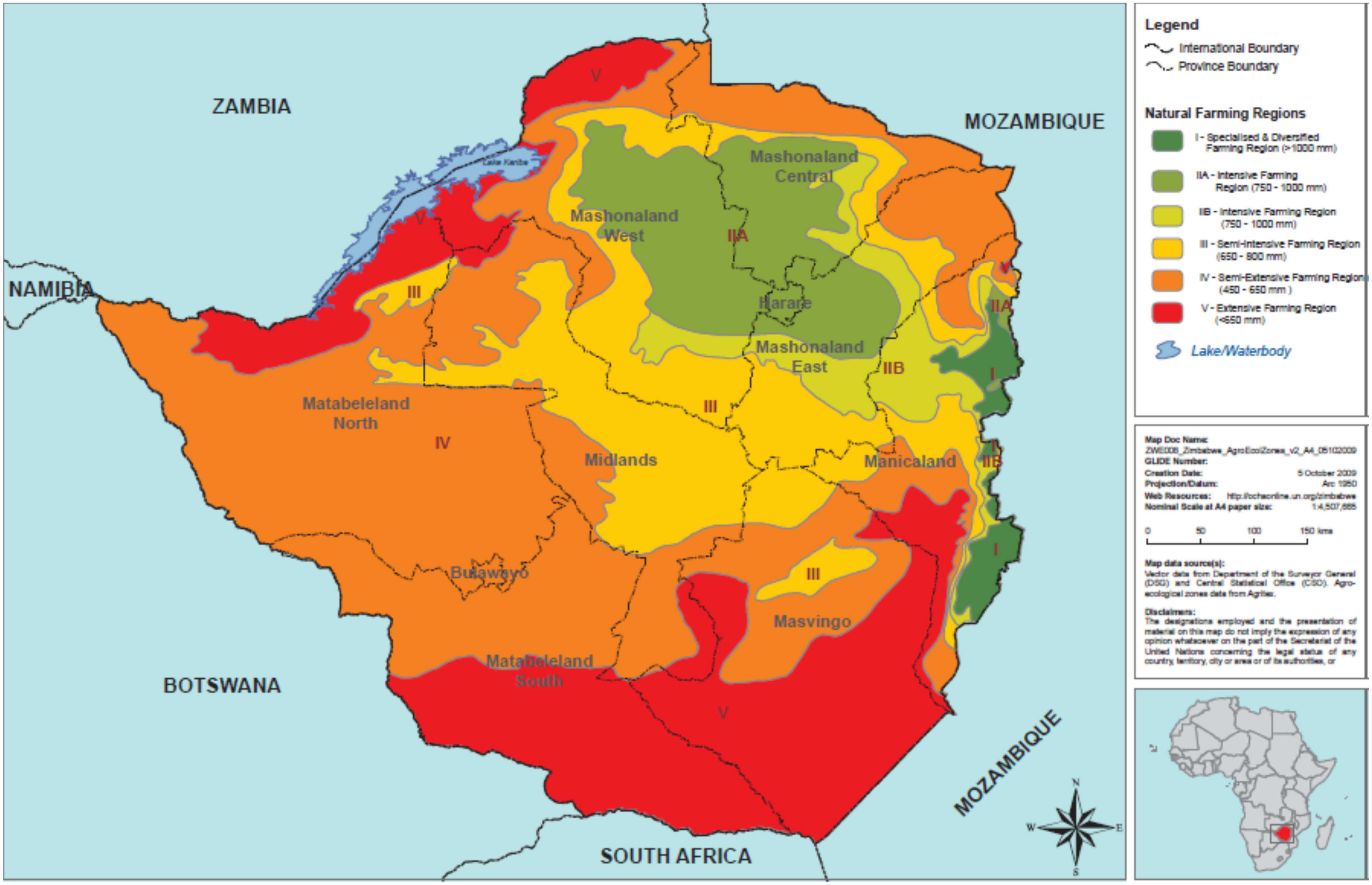


Fig. 2.1 The Natural Regions (NR) of Zimbabwe (Adopted from OCHA, 2009)

2.3 Conservation agriculture

A number of technologies have been promoted to reverse the trend of declining crop production in smallholder agriculture in sub-Saharan Africa. Of these, conservation agriculture (CA) is viewed by many as the most promising and sustainable technology to increase crop productivity (Rockström *et al*., 2009; FAO, 2010; Nkala *et al*., 2011).

2.3.1 Principles of CA

The term 'conservation agriculture' was adopted during the First World Congress on CA that was organised in 2001 by the FAO and the European Conservation Agriculture Federation in Spain (Kassam *et al*., 2009). Conservation agriculture is a means of agricultural production that is resource-efficient and based on the integrated management of soils, water and biological resources in combination with external inputs (FAO, 2010). The main aims of CA are to optimise resource use, increase profitability while minimising practices that result in land degradation (Wall, 2007; Marongwe *et al*., 2011). A suite of technologies comprise CA which when practiced simultaneously are reported to yield the highest long-term economic and environmental benefits (Ekboir, 2002; Kassam *et al*., 2009). The three main principles of CA are continuous minimum tillage, provision of permanent soil organic cover and crop rotations practiced in tandem with a high level of management (Derpsch & Friedrich, 2009; FAO, 2010). Timely crop management and judicious use of external inputs such as improved seed, fertilisers and pesticides are recommended to ensure high crop yield and profitability in CA.

2.3.1.1 Minimum tillage

Modern agriculture has long been associated with conventional tillage which involves inversion of the topsoil to at least 20 cm or more using the plough. Conventional tillage encompasses primary tillage operations carried out using different types of ploughs followed by secondary tillage operations whose aim is to break up soil clods and control weeds. On large mechanised farms conventional tillage includes multiple operations using implements such as the moudboard, disc and / or chisel plough followed by several harrowing and in-crop cultivations.

The number of tillage operations and depth of tillage vary depending on the type of implement used, number of passes, soil type and intended crop. Under smallholder agriculture in sub-Saharan Africa, conventional tillage for farmers with access to draught animal power is characterised by the use of the animal-drawn mouldboard plough for primary tillage followed by harrowing and cultivation during the cropping season for weed control (Koza, 2004). For smallholder farmers without access to draught animal power, conventional tillage is still based on hand hoe cultivation in sub-Saharan Africa (Thierfelder *et al*., 2013).

The advent of the mouldboard plough in the latter part of the 20th century facilitated the expansion of the cropped area and increased food production worldwide (Lal, 2009). This is because ploughing prepares a clean seedbed for the crop, increases short-term soil fertility, incorporates fertilisers and agrochemicals, controls weeds, increases water infiltration, alleviates soil compaction and is aesthetically pleasing (Bolliger *et al*., 2006; Gowing & Palmer, 2008; FAO, 2010). For smallholder farmers in southern Africa, ploughing is associated with increased short-term crop yields even without addition of fertiliser (Lal, 2009) and reduces the need to control weeds early in the cropping season when labour is often in short supply (Baudron *et al*., 2012b). In the Ethiopian Highlands, frequent ploughing is reported to improve water infiltration, minimise runoff, reduce evaporation and break soil crusts resulting in increased crop yield (Temesgen *et al*., 2008).

However, repeated ploughing is associated with problems that include long-term reduction in soil organic matter, accelerated soil erosion, soil compaction and reduction in biodiversity (Kassam *et al*., 2009), non-point source pollution, widespread problems of land degradation and deforestation (Lal, 2009) . The damaging effect of intensive tillage on bare soil was observed as severe wind erosion during the Dust Bowl in mid-western United States in the 1930s (Hobbs *et al*., 2008) and as land degradation in most parts of the world. This led to the promotion of reduced tillage which encompasses management practices that reduce tillage intensity either through the exclusion of at least one major cultivation practice or minimising the depth of tillage operations (Locke *et al.*, 2002). The reduction in the level of soil inversion results in increased plant residue of between 15 to 30 % under reduced tillage compared to less than 15% under conventional plough tillage. Conservation tillage (CT) developed from reduced tillage and aims at maintaining a soil cover of at least 30% after planting so as to maximise soil and water conservation (Hobbs, 2007). A number of practices have been promoted under CT including ridge till, mulch till and no-till / zero till. Although terminology and practices describing the various CT practices tend to vary with regions (Hobbs et al., 2008) no-till is generally believed to be the ideal form of CT where soil disturbance is limited only to planting stations such that less than 25% of the soil area is disturbed from planting to harvesting and with a soil cover of 80% or more (FAO, 2012a). In South America, no-till also includes crop diversification through rotations of both cash and cover crops (Bolliger *et al*., 2006)

Conservation agriculture as defined by FAO (2010) is a practice that is fairly close to no-till as practiced in the Americas (Derpsch & Friedrich, 2009). In this text no-till as practiced in North and South America will be used interchangeably with CA. In CA, minimum tillage (MT) consists of the preparation of a planting furrow or trench that is less than 15 cm wide or disturbs 20% or less of the cropped area (FAO, 2010). Minimum tillage in CA can be achieved through manual, animal- and tractor based seeding equipment (FAO, 2012a). For farmers with limited l access to draught power, seeds and fertilisers are added to planting stations made using dibble sticks or hand held hoes. Animal-traction based CA uses ripper tines, chisel and coulters whereas in more mechanised holdings tractor-drawn no-till planters are used. These can be in the form of single or double furrow openers, single disc coulters and no-till direct seeders. Equipment for managing crop residue and weeds under CA includes rollers, mulch slashers and straw spreaders.

The benefits associated with MT systems include reduced erosion, and savings in fuel and time costs on mechanised farms, (Hobbs et al., 2008; FAO, 2010). In Zambia, use of the Magoye ripper reduced the time for land preparation in maize compared to mouldboard ploughing (Haggblade & Tembo, 2003). Tshuma *et al*. (2011) reports that labour for digging planting basins using handheld hoes in Zimbabwe reduced over time on farmers ‘fields. In planting basins labour is spread over the dry season to reduce labour bottlenecks early in the season (ZCATF, 2009). The MT systems of direct seeding are reported to increase *in situ* water harvesting resulting in improved rainwater productivity in semi-arid areas (Rockström *et al*., 2009; Thiefelder & Wall, 2009). Under smallholder agriculture in sub-Saharan Africa, MT allows farmers with limited access to draught animal power to plant early and improve crop yields without the need for ploughing (Baudron *et al*, 2007; Ito *et al*, 2007; Marongwe *et al*., 2011). This is achieved through the use of MT practices such as hand-made planting basins or jab planters for farmers without access to animal draught power and the ripper tine for farmers with limited access to animal draught power (Twomlow *et al*., 2008; ZCATF, 2009).

2.3.1.2 Provision of permanent soil cover

Minimum tillage systems are associated with minimal incorporation of plant material into the soil during land preparation. In contrast, mouldboard ploughing retains less than 10% of plant residues on the soil surface (Lal, 2007) resulting in bare soils that are more prone to erosion. Maintenance of permanent soil cover either through the use of cover crops and / or crop residues to achieve at least 30% soil cover at planting is a key component of CA. This component is regarded by many as the key practice in CA as it is directly linked to most of the benefits derived from CA (Erenstein, 2002; Wall, 2007; Kassam *et al*., 2009). Permanent soil cover in CA is achieved through the growing of cover crops and / or retention of residue of the previous crop.

A cover crop is a crop grown to provide soil cover either in pure stand or in association with the main crop during all or part of the year (FAO, 2010). Cover crops grown in CA include black oats (*Avena strigosa* Schreb), rye (*Secale cereal* L.) and hairy vetch (*Vicia vilosa* L.) that are grown during winter and summer cover crops such as lablab (*Dolichos lablab* L.), sunnhemp (*Crotalaria juncea* L.) and cowpea (Derpsch, 2008). Benefits derived from cover crops include additional fodder for livestock in mixed crop/ livestock systems (Ribeiro *et al*., 2005), N fixation when green manure cover crops are included in cropping systems , more efficient utilisation of resources, buffering the soil against compaction, facilitation of weed management and disruption pest and disease cycles (Bolliger *et al*., 2006). In South America, cover crops are either planted following the harvest of preceding crop and desiccated using burndown herbicides such as glyphosate (N-(phosphonomethyl) glycine) and paraquat (1.1'dimethyl-4.4'-bipyridinum) before or at planting of the next crop. In Zambia green manure cover crops such as black or red sunnhemp, velvet bean (*Mucuna pruriens* (L.) DC.), cowpea and field bean (*Phaseolus vulgaris* L.) are recommended for intercropping with maize in CA (GART, 2008). However, benefits such as increased soil fertility and weed suppression reported on trials conducted on research station are rarely attained under the sub-optimal management common on most smallholder farmers' fields. Baudron *et al*. (2007) report that, although widely promoted by some organisations in Zambia, cover crops are viewed by some extension workers and farmers as 'useless sophistication' with limited chances of widespread adoption by smallholder farmers especially in the case of non-edible cover crops.

In some areas, cover cropping is not a feasible option for maintaining soil cover in CA. The long and harsh dry season during which arable fields are used for communal grazing of animals precludes the use of cover crops in much of smallholder agriculture in southern Africa. Smallholder farmers are, instead, recommended to retain any available crop residue as surface mulch in CA (CFU, 2007; ZCATF). In CA, crop residues from the harvested crop are not burned but uniformly spread on the soil surface. The crop residue mulch protects the soil from rain impact and the wind. The extent of soil cover provided depends on the decomposition of the crop residue as influenced by the C: N ratio with residue with low C:N ratio such as that obtained from legume crops providing limited soil cover (USDA NRCS, 2011). Ideally, crop residue mulch should cover the soil at least up until full crop canopy is attained. In the short term, crop residue mulching is reported to reduce soil erosion, improve soil moisture content through increased water infiltration, reduced evaporation and water run-off (Thierfelder & Wall, 2009; Mupangwa *et al*., 2009) and may lead to better crop-water balance (Wall, 2007). The improvement in soil moisture content is important in semi-arid areas where water availability is an important constraint to crop production. The benefits associated with mulching in the medium-term include increased organic matter (Chivenge *et al*., 2007) which can lead to improvements in soil water holding capacity, structure and nutrient availability (FAO, 2010). Minimum tillage in combination with mulching is also reported to increase biological activity (Nhamo, 2007) which leads to increased biodiversity and soil regeneration. Mulches also moderate soil temperatures in areas with temperature extremes (Kassam *et al*., 2009) and may be useful in suppressing weed growth (Christofolleti *et al*., 2007).

However, crop residue mulching is also associated with a number of issues that limit its integration into different types of farming systems. In Europe, retention of crop residue was associated with poor crop seedling emergence probably due to low temperature under the mulch in early spring (Derpsch, 2008). Low yields were often obtained where crop residue was retained. Farmers also experienced difficulties in planting into a thick layer of crop residue mulch. This required specialized no-till equipment which was expensive to purchase. Rusinamhodzi *et al*. (2011) report that crop residue mulching is associated with decreased maize yields on poorly drained soil in the high rainfall regions of Zimbabwe. In smallholder areas in semi-arid Africa, the problem is of limited availability of crop residue mulch (Erenstein, 2002). Plant biomass production is low under smallholder agriculture and whatever crop residue is available is grazed *in situ* by free ranging livestock or transported to kraal pens to be used as fodder during the long winter period. Consequently, the adoption of crop residue is low under these farming systems.

2.3.1.3 Crop rotation

Cropping sequences that include crops with different resource use and/ or growth patterns are fundamental to sustainable cropping systems. Among the benefits of a well-designed rotation are maintenance of good soil physical conditions and organic matter, improved distribution of plant nutrients in the soil, increased soil fertility, control of some diseases and pests which may lead to a reduction in costs of pesticides, increased biodiversity and improvements in yield (FAO, 2010; Ncube, 2007; Fischer *et al*., 2002). Consequently, crop rotation is an important management tool in CA and is reported to contribute to the long-term sustainability of CA systems (Ekboir, 2002; Bolliger *et al*., 2006).

A well–planned rotation that meets multiple objectives is recommended in CA. The objectives of a rotation usually include food and fodder production, residue production, pest and disease control and nutrient recycling. Rotation sequences that include crops with different lifecycles, planting and harvesting dates, rooting depth and growth habit diversify the cropping system and may result in the greatest benefits. In South America, recommended rotations under CA include cash and cover crops grown throughout the year (Fig. 2.2). The benefits associated with these rotations are decreased pests and increased profits (Derpsch, 2008). Rotating crops such as maize whose crop residues have a high C:N ratio with legume cover crops with low C:N ratio residues facilitates the decomposition of the cereal residue (USDA NCRS, 2011). The slower decomposition of crop residues with high C:N ratio assure that the soil is covered for a longer period than would be the case when only legume residues are retained. In southern Africa, recommended rotations in CA include maize, the major staple crop, cash crops such as cotton (*Gossypium hirsutum* L.) and an N-fixing legume crop (Baudron *et al*., 2007; ZCATF, 2009). In semi-arid areas, drought tolerant crops such as sorghum (*Sorghum bicolor* L.), pearl millet (*Pennisetum glaucum* L. R. Br.) and cowpeas are recommended under CA. However, legume cropping is confined to small areas under smallholder agriculture due to poorly developed markets (Ncube, 2007). As a result, smallholder CA farmers are recommended to crop legumes on 30% of the area under CA (CFU, 2007). However, only a minority of smallholders practice rotation on fields reported to be under. Baudron *et al*. (2012b) attributes the low adoption of crop rotation under smallholder agriculture to labour requirements, dietary needs and marketability of crops. Most smallholder farmers in Zimbabwe prefer to grow the staple maize crop year after year even on reported CA fields (Mazvimavi *et al*., 2011).

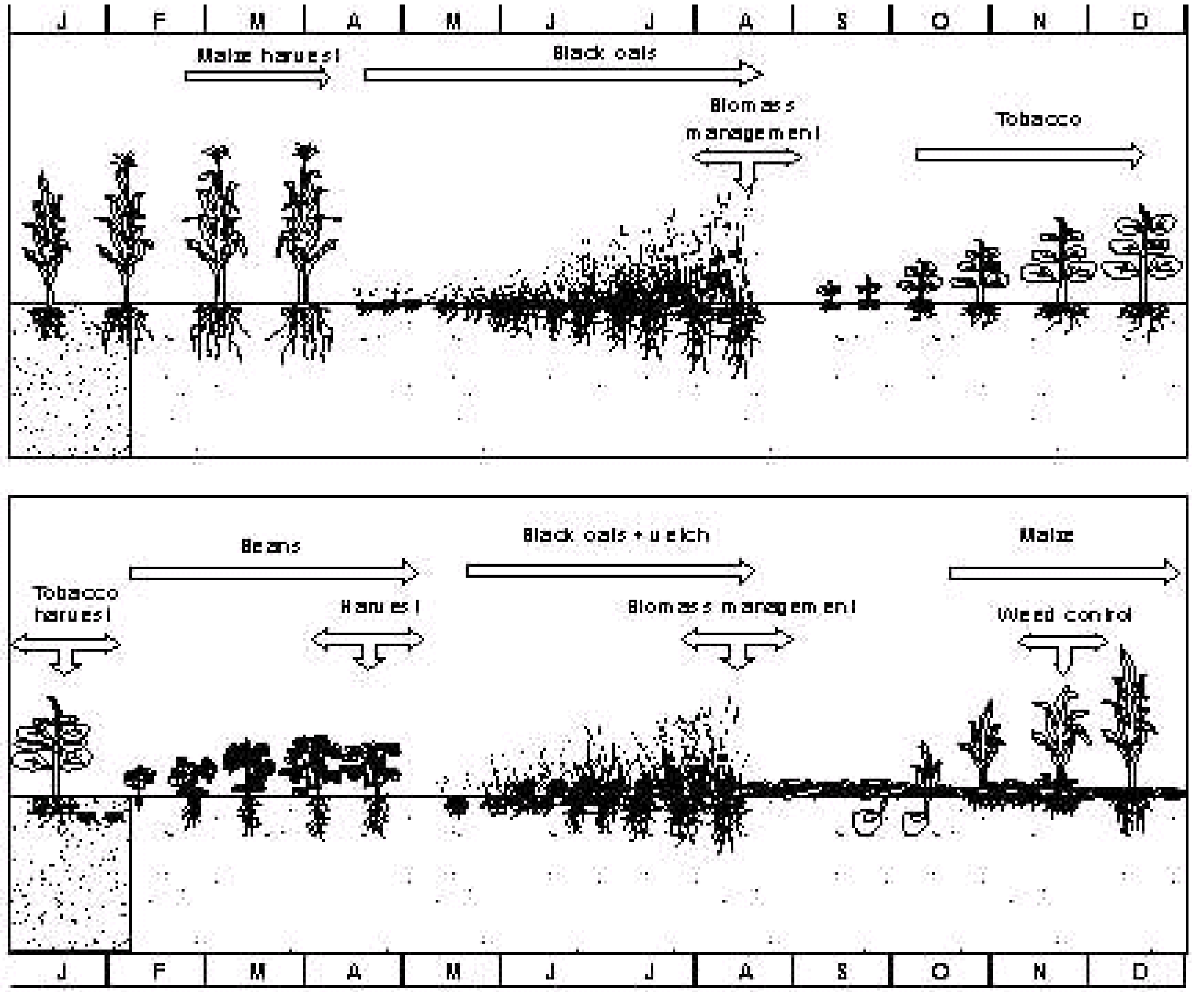


Fig. 2.2 A diversified crop rotation to maintain soil fertility and break pest lifecycle (FAO, 2012)

2.3.2 Benefits associated with CA

Conservation agriculture is widely perceived as a way of farming with great potential for all agro-ecological systems and farm sizes (FAO, 2006). The adoption of CA in virtually all crops, agro-ecological regions and farm sizes is cited as evidence for the universal applicability of CA. CA promoters refer to phases of CA adoption (Fig. 2.3) to explain the benefits derived from CA during the different phases of CA adoption. In the first phase of CA adoption, the main benefits derived from CA are a reduction in labour, time and draught power required for tillage (FAO, 2012). However, within these first two years of CA adoption the reduction in costs for tillage are offset by an increase in the cost of agro-chemicals especially herbicides for weed control. Crop production and profits may be equal to or lower than obtained from the farmer's conventional tillage practice (Fig. 2.3) Improvements in soil conditions are expected to begin from the third year of CA adoption when initial increases in soil fertility result in enhanced crop yields. The profitability of CA continues to increase with the maximum economic, agronomic and environmental benefits expected when the system is well established six to seven years after CA adoption. Indeed CA has been reported to increase and stabilise crop yields (Wall, 2007; Hobbs *et al*., 2008) and increase net farm income (FAO, 2012b). Furthermore improvements in water and soil quality have also been attributed to CA (Lal, 2009).

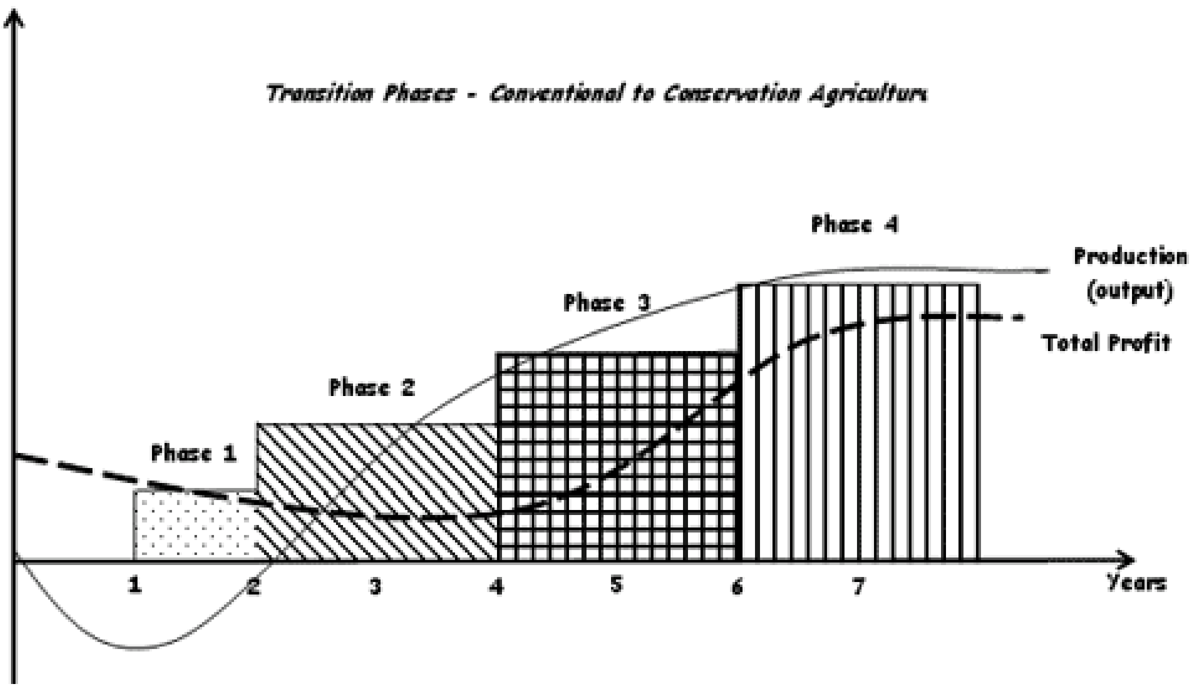


Fig. 2.3 The theoretical transition phases from conventional practice to CA (FAO, 2012b)

Under manual CA systems in sub-Saharan Africa, marked improvements in crop yield have been reported under smallholder farmers CA practices (Ito *et al*., 2007; Grabowski, 2011; Nkala *et al*., 2011, Marongwe *et al*., 2011). Smallholder farmers without access to draught animal power have adopted a hoe-based CA system where handheld hoes are used to prepare planting basins on un-ploughed land during the dry season. The planting basin tillage system is practiced in conjunction with retention of crop residue mulching, cereal/legume rotations and improved management that includes the precise application of fertiliser into planting basins (CFU, 2007, Twomlow *et al*., 2008; ZCATF, 2009). This hoe-based CA system is referred to as conservation farming (CF) in Zimbabwe and Zambia. A study carried out on fields of CF farmers in semi-arid Zambia showed that CF produced on average an additional 1 900 kg ha^{-1} of maize grain compared to the conventional mouldboard plough tillage (GART, 2008). The most benefit accrued from early planting (Fig. 2.4) as CF permitted farmers to plant with the first effective rains. Timely weeding was the second most important management factor in smallholder CF responsible for increased yield as according to Twomlow *et al*. (2006) excessive weed growth is widely recognised as one of the main constraints in smallholder crop. The other benefits were derived f in sub-Saharan Africa. The remaining benefits from CF were obtained from improved fertility due to precision application of fertiliser, soil fertility increases from crop residue mulching and inclusion of N-fixing legumes in rotation and lastly from improvements in water harvesting.

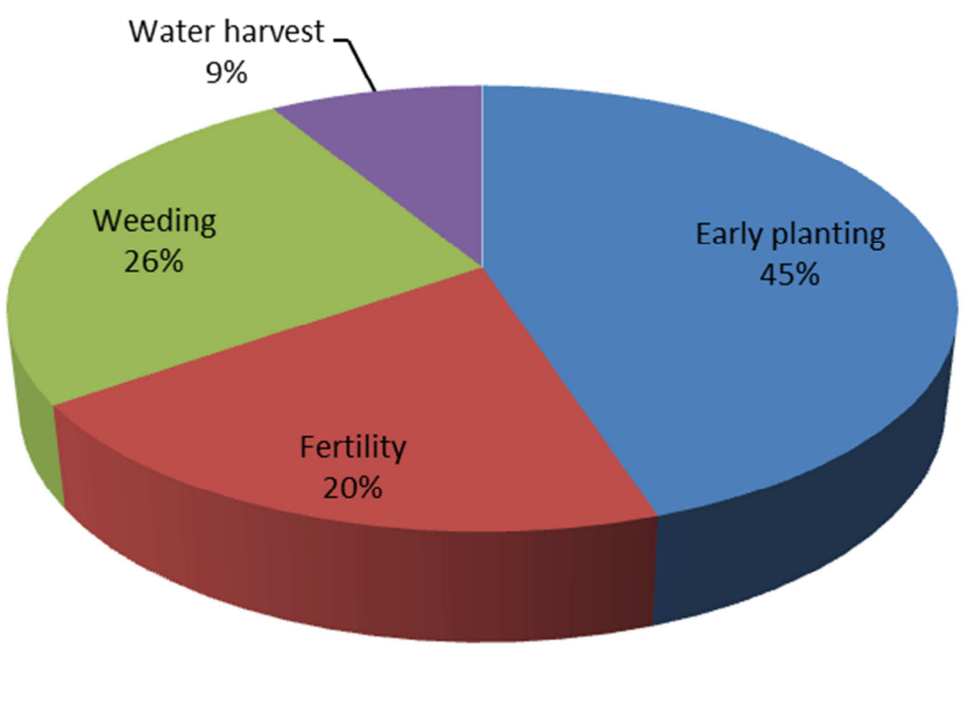


Fig. 2.4 Proportion contributed to increased maize grain yields on smallholder farmers' CF fields in southern Zambia (Adopted from GART, 2008)

2.3.3 Challenges to CA adoption

Although CA is practiced on all the continents (Table 2.1) where cropping is done, only 9% of the world's cropped area is under CA (Friedrich *et al*., 2012). The low adoption of CA worldwide challenges the assertion that CA is a universal technology. In the USA, despite more than 30 years of research and promotion, only 16% of cropped area is under CA with the majority of the area in North-West USA. A similar trend is reported in Brazil with the highest adoption is observed in southern Brazil especially on large and mechanised farms (Bolliger *et a*l., 2006; Derpsch, 2008). The continents with the lowest CA adoption are Europe and Africa (Table 2.1). These low adoption rates of a technology reported to have significant agronomic and economic benefits point to issues with CA.

Table 2.1 The proportion of the total area under CA in the different continents (Adopted from Friedrich *et al*., 2012)

Continent	% contribution to total area under CA
South America	45
North America	32
Australia	14
Asia	7
Europe	1
Africa	1

There is increasing evidence to show that CA is unsuitable in some farming systems and some soil types. Yield losses have been reported when CA is practiced on poorly drained soils due to increased waterlogging (Rusinamhodzi *et al*., 2011). In the rice-wheat systems in the Indo-Gangetic Plains only wheat (*Triticum aestivum* L.) is grown under no-till whereas in the rice (*Oryza sativa* L.) phase of the rotation conventional tillage is required (Hobbs *et al*., 2008). Conservation agriculture has been reported to be associated with soil compaction on coarse textured soils in Zambia (Baudron *et al*., 2012a) and on sandy and loam soils in Australia (Rainbow, 2008). Ribeiro *et al*. (2005) report that smallholder CA farmers in Brazil resort to occasional tillage to combat soil compaction. However, the problems of soil compaction may be a result of less than the recommended CA practices being implemented by farmers.

According to Friedrich *et al*. (2012) less than 50% of the area reported to be under CA in South America is under all three CA principles. Due to better prices for soyabeans (*Glycine max* (L.) Merr.), many CA farmers are opting to grow soyabean as a monoculture in CA and are even excluding cover crops between soyabean crops. Ribeiro *et al*. (2005) also reported that market preferences limited diversity in crop rotations by smallholder farmers in Brazil. Crop rotation is not the only CA principle not being practiced on fields reported to be under CA. According to Friedrich *et al*. (2011) less than 20% of the area under CA in the USA is under permanent no-till. In some farming systems, practicing diverse crop rotations is limited by market issues, farmer food preferences and the capital and labour required to produce new crops such as cover crops. The result is that the quality of what is reported as CA is often less than the recommended CA from which maximum benefits are obtained.

Crop residue mulches are not being retained on CA fields for a number of reasons. In Europe the requirement to retain crop residues led to dis-adoption of conservation tillage practices due lower yields on mulched fields and the need to be specialized seeding equipment for use on these fields (Derpsch, 2008). In contrast, the problem in much of southern Africa is to do with limited crop residues for mulching. Giller *et al*. (2009) among other researchers argues that adoption of CA will remain low in smallholder agriculture in sub-Saharan Africa as the technology is not compatible with most smallholder farming systems. The retention of crop residue as a permanent soil cover is not possible due to their multiple uses on smallholder farms (Nyathi *et al*., 2011) and the current land tenure systems in which arable fields turn into communal grazing areas during the dry season. In addition, the retention of crop residues is perceived by smallholder farmers in southern Africa to increase termite populations that may subsequently attack crop (Baudron *et al*., 2007). Increased incidence of diseases such as root rot has been reported with retention of crop residues (Rainbow, 2008). Retention of crop residues with high C: N ratios such as maize and wheat residues results in temporary N immobilization (USDA NRCS, 2011) that may necessitate the application of increased rates of N fertiliser in CA (Rusinamhodzi *et al*., 2010). The benefits of weed suppression often ascribed to crop residue mulching require thick layers of mulch (Christofolleti *et al*., 2007) which are unavailable under smallholder farming in semi-arid Africa.

According to Andersson & Giller (2012) 'weeds are the Achilles heel of CA'. Weed management is believed by many to be the main constraint to the widespread adoption of CA (Bolliger *et al*., 2006). There have been reports of increases in herbicide use and occasional tillage in smallholder CA in Brazil (Ribeiro *et al*., 2006) and doubling of labour requirements for hoe weeding in smallholder CA in southern Africa (Haggblade & Tembo, 2003; Baudron *et al*., 2007). However, CA promoters argue that these weed problems are linked with sub-optimal CA practices because under CA weed pressure decreases and management improves after the initial two years (FAO, 2012a; Thierfelder & Wall, undated).

2.4 Weed dynamics under CA

Weed infestations are claimed to decrease with time under CA resulting in a weed community that is more manageable when recommended CA practices are followed. However, the majority of farmers have only adopted those CA principles that fit into their farming systems. It is therefore important to review literature on the effects of individual CA principles before weed dynamics under CA are studied.

2.4.1 Tillage effect on weeds

2.4.1.1 Weed seed bank response

The soil weed seed bank is the reserve of viable weed seeds found on the surface and within the soil (Dekker, 1999). The seeds in the seed bank were previously shed by standing vegetation or dispersed into the area from other regions. The importance of the weed seed bank is that it potentially determines the composition of weed flora in arable fields (Forcella, 1992; Akobundu & Ekeleme, 2002). For weed species that reproduce from seed, the weed seed bank is viewed as the driver of annual weed infestations in the field. However, the size of weed seed banks in agricultural land varies, ranging from less than 100 (Carter & Ivany, 2006) to more than 90 000 seeds m^{-2} (Bárberi & Lo Cascio, 2001). The size and weed diversity of the seed bank under arable fields is believed to be a reflection of past and current farming practices (Buhler *et al*., 1997; Albrecht, 2005).

Tillage is one management practice that is known to have a major effect on the weed seed bank. This is because soil inversion is the primary cause of vertical seed movement in agricultural lands (Benvenuti, 2007). Weed seed movement within the soil profile depends on the amount of soil disturbance associated with a tillage technique (Sester *et al*., 2007). A number of studies have shown that conventional mouldboard ploughing results in a more even distribution of weed seeds within the plough layers whereas in MT systems, fresh weeds seeds are maintained in the upper soil layers (Mashingaidze *et al*., 1995; Bárberi & Lo Cascio, 2001; Cardina *et al*., 2002; Chauhan *et al*., 2006b; Vasileiadis *et al*, 2007). Ploughing results in re-distribution of seeds through the soil profile resulting in burial of seeds from the surface layer and exhumation of previously buried seed (Chauhan & Johnson, 2010). In contrast, in systems with minimum soil inversion such as MT systems seeds are not buried and with time are concentrated in the surface layer. However, soil type is reported to also influence the vertical movement of weed seeds within the soil profile. Carter & Ivany (2001) observed concentration of weed seeds in the 10 -20 cm layer rather than in the upper 10 cm in MT systems on a fine sandy loam. This was attributed to the greater vertical movement of seeds in sandy soils because of their low colloidal activity and aggregate entrapment. Benvenuti (2007) reported that cracks in clay soils prone to shrink-swell processes can allow for movement of small seeds from the surface to lower soil layers. As a result, the greater concentration of weed seeds in the surface soil layer may not always be observed under MT systems.

Seed placement within the soil profile has a critical effect on seed germination and survival (Mohler, 1993). Some studies have reported a decline in the seed bank size within seven years under no-till compared to conventional plough tillage (Tørresen *et al*., 2003; Sester *et al*., 2007). The shallow seed placement in systems with no soil inversion may result in a rapid decline in the seed bank due to high seed emergence. This is because seed germination and emergence is higher from the surface soil layer than from greater soil depths (Sester *et al*., 2007). The reduction in light and thermal fluctuations, higher CO_2 and lower O_2 levels at greater soil depths probably result in decreased seed germination and emergence, and even induction of secondary dormancy in some weed species (Benvenuti *et al*., 2001; Chauhan & Johnson, 2010). In addition, seed viability in the surface soil layer is reduced through seed desiccation and the effect of pathogens and predators. Minimum tillage systems have been observed to have increased levels of fauna than conventional plough tillage by Nhamo (2007). Without soil inversion, there is limited addition of fresh weed seeds from the surface layer to lower soil depths. The number of weed seeds below the surface layer eventually declines with time due to mortality caused by diseases, predators and aging of seeds (Clements *et al.*, 1996; Tørresen *et al*., 2003).

However, an increase in the size of the seed bank under no-till has been observed in other research (Dorado *et al*., 1999; Carter & Ivany, 2006). The increase in weed seed bank has been attributed to protection of weed seed by crop residue and less movement of seed through soil profile resulting in less dormancy breaking mechanism in soils with fewer disturbances (Vencill *et al*., 1994). In contrast, Bárberi & Lo Cascio (2001) observed no differences in seed bank size between no-till and mouldboard plough. Therefore, the effect of tillage on the soil weed seed bank presents mixed results with disparity reported on the effects of crop residue mulch on weed seeds found in the soil surface. In terms of weed composition, weed diversity has been reported to increase (Dorado *et al*., 1999), decrease (Carter & Ivany, 2006), and not differ (Bárberi & Lo Cascio, 2001) in no-till relative to conventional plough tillage. The small-seeded *Portula oleracea* L. was found in greater densities in no-till than in conventional plough tillage (Dorado *et al*., 1999).

In summary, the effect of tillage on seed bank size and weed diversity was not consistent. This is probably due to differences in management between studies as according to Unger *et al*., (1999) changes in the composition of the weed seed bank are due to poor weed control that allow weed escapes to reach maturity and replenish the weed seed bank. In most studies, minimum tillage systems were associated with maintenance of weed seeds in the upper surface soil layer in contrast to ploughing which resulted in even distribution of weed seeds through the soil profile.

2.4.1.2 Weed seed germination and emergence

The driving force for weed infestations in arable fields is the weed seed bank (Akobundu & Ekeleme, 2002). However, the placement of seed within the soil profile determines the number of viable seed that germinate and successfully emerge. This is because the regeneration of plants from seeds requires that seeds capable of germination be in an environment conducive for weed seedling recruitment. The variation in seed placement in the different tillage systems is likely to result in differences in the level of weed emergence. Furthermore, weed species differ in germination and emergence requirements as well as means of propagation. The differences in seed placement may lead to changes in weed composition in emergent weeds where conventional plough tillage is replaced by MT systems.

Under conventional plough tillage fresh weed seeds are buried at depths from which successful emergence is low for most weed species (Forcella *et al*., 2000). This is because for a viable seed, light, temperature and moisture are the main drivers of the germination process (Grundy, 2003) and these become less favourable for germination with increase in soil depth. Ploughing also destroys existing weeds and, thus, creates a clean seedbed at planting and up to four weeks after planting (Mabasa *et al*., 1998). However, ploughing results in the uniform distribution of weed seeds through the plough layer. A consequence of this is that the ploughing operation brings to the surface soil layer previously buried weed seed. Conventional tillage may, therefore, stimulate weed germination through exposure of buried seed to light, aeration of soil, increase in soil temperature fluctuations, release of soil-bound volatile inhibitors, increase in seed-moisture contact and removal of plant canopy (Franke *et al*., 2007; Chauhan & Johnson, 2010). Ploughing can also break dormancy in weed species that require seed coat scarification. Conventional plough tillage has been associated with summer dicot weed species (Derksen *et al*., 1993) and species such as *Xanthium strumarium* L. and *Digitaria sanguinalis* L. Scop. (Vencill *et al*., 1994) that require soil burial before germination and emergence can occur. Tillage reduces the mechanical strength of soil and this enables more seedlings to emerge (Mohler & Galford, 1997). As a result, although ploughing creates a clean seedbed at planting other weed management strategies are still required to manage weeds under conventional plough tillage.

Minimum tillage systems are commonly perceived by both farmers and researchers to have higher weed infestations than conventional plough. The maintenance of a greater proportion of weeds seeds in the surface layer in MT systems is expected to result in increased weed emergence as seeds are placed in an environment conducive for germination and emergence. Increased weed infestations have been observed within the first four years under *badza* (hoe) holing (Vogel, 1994) and ripping (Mabasa *et al*., 1998; Makanganise *et al*., 2001) in Zimbabwe and under planting basins in Zambia (Muliokela *et al*., 2001). However, longer-term studies on weed population in MT systems are lacking for southern Africa. Similar results of increased weed growth in MT compared to conventional plough tillage were reported in a review of tillage done by Chauhan *et al*. (2006a) which included some long-term tillage studies.

The maintenance of weeds seeds near the soil surface may result in changes in emergent weed species composition. The optimum depth for emergence is less than 20 mm for most weed species (Mohler, 1993, Ekeleme *et al*., 2005) with emergence declining rapidly with depth as most seeds lack sufficient pre-emergence reserves required for shoot-radicle elongation. On a relative basis, weed species with large seeds are able to emerge from greater soil depths than the small-seeded (Benvenuti *et al*., 2001). These differences in seed size may lead to shifts in weeds under different tillage systems. Tillage systems with less soil disturbance such as no-till have been reported to be associated with increased densities of small-seed weed species such as *P. oleracea* (Tuesca *et al.,* 2001; Chauhan *et al*., 2006b; Chauhan & Johnson, 2009) and *Conyza bonariensis (*Wu *et al*., 2007*)* that are favoured by shallow soil placement. This is because small small-seeded weed species tend to require light for germination (Chauhan *et al*., 2006a). The lack of weed seed burial has also been observed to promote densities of wind-dispersed species especially where crop residues are retained. Increased density of wind-dispersed weed species including *Senecio vulgaris* L. and *Conyza canadensis* (L.) Cronquist. were reported under reduced tillage systems by Derksen *et al*. (1993). Weed germination has also been reported to change under MT systems. Bullied *et al.* (2003) observed earlier weed emergence under MT than conventional tillage, probably as a result of the shallow seed placement in MT systems. Germination under MT has also been reported to be sporadic and to occur over longer periods than in conventional plough tillage (SWOARC, 1990).

However, the concentration of seeds on the surface layer may result in low weed seedling recruitment in MT systems. This is because the surface layer is viewed as a zone where seeds have a limited chance of establishment due to increased seed desiccation, predation and seed decay. As a result, weed emergence on the soil surface is less than that obtained for seeds buried at 50 –100 mm deep (Mohler & Galford, 1997, Shrestha *et al*., 2006). Chauhan *et al*. (2006b) report that the emergence of the weed species *Lolium rigidum* Gaudin was lower under no-till compared to minimum tillage due to rapid desiccation and increased predation of seeds on or near the soil surface The perceived increase in weed infestation in MT systems may, therefore, be higher than what actually occurs under actual field conditions.

Conventional mouldboard tillage is associated with plants that thrive on disturbed land (Zanin *et a*l., 1999), such as annual weeds which germinate, grow rapidly and produce seeds between seedbed tillage and harvest (Moyer *et al*., 1994). In contrast, the life cycle of perennial weeds is disrupted by multiple tillage operations that reduce the energy reserves in roots or other storage organs of these plants. Tillage also uproots and buries the reproductive structures of perennial weeds at depths unfavourable for emergence (Shrestha *et al*., 2006). Infestations of perennial weeds may, thus, be expected to increase in MT systems. Increased growth of perennial weeds has been reported under MT systems (Derksen *et al*., 1993; Vogel, 1994; Makanganise *et al*., 2001; Tuesca *et al*., 2001; Tørreson *et al*., 2003; Thomas *et al*., 2004) while no shifts to predominantly perennial weed species have been reported in other studies ((Shrestha *et al*., 2006). Perennial weed species were mainly associated with minimum tillage systems where weeds were controlled using no-chemical weed control methods suggesting that the weed shifts were also influenced by the efficacy of the weed control methods used in study to control the perennial weeds. This observation is supported by the findings of Vencill *et al*. (1994) that demonstrated that increasing the number of herbicides used diminished any differences in weed species composition between tillage systems. On the other hand, shallow plough tillage is associated with high weed infestation of perennial weeds as without deep tillage most perennial weeds survive to re-infest fields (Moyer *et al*., 1994). Under smallholder farmers practices in Zimbabwe, Mabasa *et al.* (1995) observed increased density of *Cynadon dactylon* (L.) Pers. after ploughing and harrowing and concluded that under shallow tilling the weed increased because the tillage operations were in effect cutting and spreading the stolons and rhizomes of *C.*

dactylon throughout the field. Tsimba *et al*. (1999) report that ploughing depth under smallholder agriculture rarely exceeds 15 cm due to quality of plough used and the poor condition of oxen at the beginning of the rainy season in Zimbabwe.

Therefore, research suggests that the replacement of conventional plough tillage with MT systems may result in changes in weed infestation, weed composition and weed periodicity that may necessitate changes in current weed management practices by farmers. Weed management and practices such as crop residue mulching also influenced these changes in weed species composition with tillage.

2.4.2 Crop residue mulching effects on weeds

Among the benefits reported to be associated with retention of crop residue on the soil surface in CA is weed suppression which can lead to improvement in weed management in CA (FAO, 2010; ZCATF, 2009). This is because crop residue mulching can influence weed seed germination and seedling emergence by altering the environment surrounding weed seeds (Erenstein, 2002; Chauhan & Johnson, 2010). Crop residue mulches have been reported to reduce weed density (Bilalis *et al*., 2003; Christoffoleti *et al*., 2007; Chauhan & Johnson, 2008) and weed biomass (Gill *et al*., 1992; Bilalis *et al*., 2003). Retention of mulch increases organisms and insects in reduced tillage systems (Ekboir, 2002; Nhamo, 2007) which may lead to increased seed predation (Christoffoleti *et al*., 2007). However, weed suppression under mulch is mostly a result of the physical and / or chemical effects of the residues on weed emergence and growth.

2.4.2.1 Physical effect of mulches

The retention of crop residue mulch changes the soil micro-environment in which weed seeds are found (Erenstein, 2002). A layer of mulch on the soil surface results in a reduction in light transmittance (Teasdale & Mohler, 1993) and this decreases the germination of most small-seeded weed species that require light for germination. Furthermore, reduced light levels reduce growth of any seedling that may have emerged underneath the crop residue mulch leading to low weed biomass accumulation. Mulch retention also lowers soil temperature and temperature amplitude and this affects weed germination of those species that use thermal amplitude as a germination cue. Bilalis *et al*. (2003) observed low weed density under a wheat residue mulch that provided a soil cover of 60% and attributed the decline in weed germination to the reduced soil temperature oscillations recorded under this mulch. A thick layer of mulch can also impede growth of a weed seedling resulting in delayed weed emergence (Teasdale & Mohler, 1993). The delayed emergence may also occur as a result of the low soil temperature and light levels under the mulch. Late emerging weeds are less competitive than weeds that emerge with the crop. Crop residue mulches also conserve soil moisture (Mupangwa, 2009). However, the improved soil moisture conditions under mulch can lead to increased weed growth during dry weather conditions (Teasdale & Mohler, 1993; Buhler *et al*., 1996).

2.4.2.2 Chemical effects of mulches

Weed suppression can also occur through chemical properties of mulch. Some crop residues exude phytotoxic allelochemicals into the growth environment of weeds and greatly reduce their germination and growth (Wu *et al*., 2000). Sorghum (*Sorghum bicolor* L.) seedlings reduced germination of some weed species while the crop's growing roots released sorgoleone an allelochemical that reduced growth of several weeds (Roth *et al*., 2000). Phenolic acids exuded by decomposing sorghum residues and roots also have allelopathic effects. Decomposing rice and wheat residues are also allelopathic and have the potential to suppress weed growth (Minorsky, 2002).

2.4.3 Weed response to diversified crop rotations

Improved weed management strategies may be possible with practices such as crop rotation that diversify selection pressure (Liebman *et al*., 2004). Alternating crops over a series of growing seasons breaks cycles, increases weed diversity and prevents development of one type of weed community that may become un-manageable (Locke *et al*., 2002). In crop rotations the greater variability in the type and timing of soil, crop and weed management practices can result in more opportunities for weed mortality events than in monoculture. In no-till, a maize monocrop had a larger seed bank than that under a maize-oats-hay rotation (Cardina *et al*., 2002) suggesting greater opportunities for seed return in the monocrop than the rotation.

Rotations have also been reported to reduce the density of above-ground weed flora (Manley *et al*., 2002). A number of mechanisms have been reported for the reduction in weed growth under crop rotation compared to under a sole crop. Different crops require different weed management strategies or timing of a particular control option which results in the variation in selection pressure on weeds. This limits the association of a weed species to a particular crop species. Weed species that were found in a wheat crop were generally absent in soyabean (Tuesca *et al*., 2001) with a similar observation made by Smith & Gross (2007) for wheat and maize/soyabean systems. The differences in weed species are probably due to the use of herbicides with a different spectrum of weed control. In addition, allelopathic crops like wheat can significantly reduce populations of susceptible weed species during their phase of the rotation. The types of crops included in a rotation are important due to differences between crops in competitiveness against weeds. Clements *et al.* (1996) report that increased weed density was observed in soyabean than in maize due to the smaller canopy of soyabean which made it less competitive for light than maize resulting in increased weed emergence under the soyabean canopy. Dorado et al. (1999) observed higher weed density in a barley/vetch rotation than barley monocrop due to the less competitive vetch crop that allowed weeds to establish during the crop's growth.

The crop sequence and number of crops in rotation have been shown to influence weed growth in crop rotations. A high number of grass weeds were observed on fallow plots after the sorghum phase of a rotation (Unger *et al*., 1999). This was attributed to the difficulty experienced in controlling weed species with a similar lifecycle to sorghum. These weed species escaped control, reached maturity and produced seed that later emerged in the fallow period. According to Anderson (2006) a more diverse rotation including two cool and two warm season crops rotation more effectively reduced weed density than a three-crop or two-crop rotation. As a result, a rotation with dry pea/winter wheat/maize/ pearl millet had a weed management cost of \$38 ha^{-1} compared to \$75 ha^{-1} for the winter wheat/pearl millet rotation. Douecet *et al*. (1999)

found that differences in weed management between crops in rotation accounted for 38% of variation in weed density whereas the crop rotation only accounted for about 6% of the weed density variation.

Crops with different growth patterns and management practices are more likely to result in disruption of weed life cycles than similar crops. This is because a narrow crop rotation can create conditions that benefit weed species that have a niche similar to crops in rotation (Dorado *et al*., 1999). Legume crops have the ability to suppress weeds through competition and allelopathic effects (Liebman & Davis, 2000) and should be rotated with cereal crops. Inclusion of small grains such as barley in rotations can significantly reduce weed populations (Liebman & Dyck, 1993) due to allelopathy. Cereals such as sorghum have been observed to suppress weed growth for up to one year (Roth *et al*., 2000). The effects of crop rotation on weed population dynamics are, however, complex and variable depending on an interaction of the competitiveness of crop, associated management, tillage practices and climate (Brainard *et al*., 2008). It is clear from this discussion that different types of crop sequences will have variable effects on weed growth highlighting the need to design crop rotations that diversify selection pressure within the field and result in increased weed deaths.

2.5. Weed management in CA

Conservation agriculture is reported to lead to sustainable long-term weed management that has the potential to benefit smallholder farmers by facilitating tasks such as weeding (Ekboir, 2002). This is because under non-inversion tillage, seed bank depletion is expected to occur (Wall, 2007) as buried weed seed remains at depths from which there is limited emergence and with time the seed eventually dies (Dekker, 1999). The seed maintained in the surface layer is lost due to exposure to seed predators and harsh environmental conditions. Although the concentration of weed seeds in the surface layer may result in increased weed infestations in MT systems, good management practices are expected to lead to reduction in weed populations with time in CA

(FAO, 2010). These practices include diverse crop rotations and the provision of permanent soil cover through crop residue mulching and the growing of cover crops.

The adoption of minimum-tillage based systems was facilitated by the availability of herbicides to replace the role of ploughing in controlling weeds (Bolliger *et al*., 2006). Giller *et al*. (2009) argue that the reliance of conventional tillage systems on ploughing has been replaced by a heavy reliance on herbicides in CA systems. Where permanent soil cover and diverse crop rotations that include cover crops are practiced improvements in weed management have been reported under CA. According to Kliewer *et al.* (1998) cited in Derpsh (2008) cost herbicides was reduced in sunnhemp and sunflower when grown in rotation with short duration green manure cover crops compared to the monoculture in Paraguay. However, for the majority of CA farmers weed management in CA still poses a major challenge especially under smallholder farming (Ribeiro *et al*., 2005; Bolliger *et al.,* 2006) probably because of the partial adoption of CA practices..

In CA, there are some differences in the type and timing of herbicides used compared to conventional plough tillage. Without tillage to control winter weeds, a burndown herbicide such as glyphosate or paraquat or 2.4 D (2.4-dichlorophenoxy) acetic acid) is applied before planting in CA (Shrestha *et al*., 2006 Derpsch, 2008). These herbicides are also used to desiccate cover crops before the main crop is planted. The plant residues from the dead weeds and cover crops are used as mulch contributing to increased soil cover. Growing cover crops during fallow period is recommended under CA for effective weed management in North and South America as it reduces weed seed return during this period (Derpsch, 2008). The herbicides used after the crop is planted are similar to those used under conventional plough tillage. However, the crop residue may adsorb soil-applied herbicides and higher than conventional rates may have to be used in CA to compensate for this (Locke *et al*., 2002). Other weed control strategies used in CA include hand hoe weeding when weed pressure is low and the use of knife rollers (FAO, 2012a)

In southern Africa, the recommended weed management in CA under smallholder agriculture comprises frequent weeding using the handheld hoe (Baudron *et al*., 2007; ZCATF, 2009). Farmers are recommended to hoe weed CA fields up to six times during the cropping season to ensure minimal weed seed return (Baudron *et a*l., 2006; ZCATF, 2009) compared to the two weedings normally carried out under conventional plough tillage. Research done at the Golden Valley Agricultural Research Trust in Zambia suggests that labour required for hoe weeding in CA is reduced by 50% after six years if timely weeding is done (Baudron *et al*., 2007). Hoe weeding is the main method of weed control used by smallholder farmers in sub-Saharan Africa (Gianessi, 2009). The use of mechanical weed control practices such as cultivators after crop has emerged is prohibited in CA due to the level of soil disturbance involved (ZCATF, 2009). Herbicides are not used by the majority of smallholder farmers due to limited availability and prohibitively high costs. However, there has been research done in southern Africa that assessed the use of glyphosate applied using a type of weed wipe manufactured in Zambia called the Zamwipe™. Reports from Zambia showed that use of Zamwipe™ can significantly reduce labour requirements in CF (Baudron *et al*., 2007). However, Mashingaidze *et al*. (2009a) reported that the Zamwipe™ was difficult to use in the presence of crop residues as the unsecured wiping pad constantly fell off. This probably led to the highly variable weed kill observed in this study.

The use of crop rotation may not be effective in suppressing weed growth due to limitations placed on number and type of crops in rotation sequence under smallholder farm conditions. In semi-arid areas of southern Africa cropping is confined only to the wet summer season under dryland smallholder agriculture. In addition, farmers prefer to monocrop maize on the most productive fields and as a result most smallholder farmers are practicing maize monoculture on the reported CA fields (Mazvimavi *et al*., 2011). Permanent soil cover through crop residue mulching or cover crops is not possible under the smallholder farming systems in the region. Derpsch (2008) identifies the growing of cover crops during what was previously the fallow period under conventional tillage as the key to improved weed management in CA. This is because the soil is permanently covered throughout the year minimising the growth and subsequent seed set by weeds during the fallow period. In contrast, in southern Africa the soil is bare during the dry season as any crop residue present in fields is grazed on by livestock. This period may allow for the growth of annual winter weeds and perennial weeds if hoe weeding is not done to keep the fields weed-free. As a result farmers are encouraged to carry out a weeding at or after harvesting to reduce any weed growth a process called winter weeding. Farmers are recommended to retain at least 30% soil cover at planting in CA. However, the majority of smallholder farmers are unable to retain any crop residues as they are used as an important feed source for livestock during the dry season (Nyathi *et al.,* 2011).

Putting all these factors together, weed dynamics and management under CA in smallholder agriculture are likely to differ from what is reported in CA literature based mainly on practices in the Americas.

2.6 Weed management in smallholder agriculture in Zimbabwe

According to Twomlow & Dhliwayo (1999) the most important constraint limiting maize production in smallholder sub-Saharan Africa is excessive weed growth. Weeding is the most labour intensive operation on smallholder farms (Mashingaidze, 2004) with farmers investing between 35 to 70 % of total agricultural labour on weeding (Waddington & Karigwindi, 1996). As a result women and children who bear most of the brunt for weeding are subjected to a low quality of life.

There are limited options for weed control on smallholder farms especially for the resource-poor farmers. Hand tools and to a limited extent animal drawn equipment are used for weed control in smallholder agriculture in Zimbabwe. The most widely used method to control weeds in smallholder agriculture is hand hoe weeding. However, this method is slow, labour intensive and inefficient (Chivinge, 1990) requiring between 100 – 210 person hours ha^{-1} (Ellis-Jones, 1993; Vogel, 1994; Tshuma *et al*., 2011). Twomlow *et al*. (1997) found hoe weeding to be effective in controlling weeds when done early. However, it is reported to be less effective in heavy soils, under conditions of excessive moisture, perennial and annual weeds that reproduce vegetatively (Chivinge, 1990). The majority of smallholder farmers is dependent on family labour for weeding and rarely achieves timely weeding when using hoe weeding (Makanaganise *et al*., 2001). This is because early in the season there is competition for family labour for planting, herding livestock and weeding. A common consequence of these early season labour bottlenecks is delayed weeding with at times the first weeding after planting done 7 weeks after planting. Forty-two percent of smallholder farmers in sub-humid Zimbabwe first weeded their early planted maize more than five weeks after planting which resulted in a grain yield loss of 28% (Shumba *et al*., 1989). On the other hand, uncontrolled weed growth reduced maize growth by between 34 – 96 % in communal areas of Zimbabwe (Mabasa & Nyahunzvi, 1994). Maize is weeded once or twice per season by most smallholders under conventional plough tillage. Resource-poor farmers plant crop late and weed only once resulting in low crop yields (Riches *et al*., 1998). However, despite its limitations hoe weeding is the main weed control method promoted for use in smallholder CA.

Mechanical weed control is comparatively faster and less labour intensive than hoe weeding (Table 2.2) but the limited access of the majority of smallholder farmers to draught animal power and equipment means this method is used by only the well-resourced farmers. Conventional mouldboard plough carried out in winter and spring plays an important role in producing a weed-free seedbed for up to four weeks after planting (Mabasa *et al*., 1998). Secondary tillage operations to control weeds can be done using the spike tooth harrow, tyne cultivator (Chivinge 1990) or with mouldboard plough (Twomlow *et al*., 1997). For efficient weed control, crop cultivation should be done with well-trained animals to avoid crop damage and when weeds are still young. However, mechanical weed control is not recommended as it is viewed as increasing tillage intensity.

Table 2.2 Labour requirements in three weeding systems commonly used by smallholder farmers in semi-arid Zimbabwe (Adopted from Ellis-Jones *et al*., 1993)

Weed control method	Person hours ha^{-1}		
	Manual	Mechanical	Total
Hand hoe weeing	133	0	133
Cultivator	52	16	68
Mouldboard plough	27	28	55

The use of cultural practices such as crop rotation for weed control has limited applicability under smallholder conditions where monocultures are grown by most farmers (Chivinge, 1990). In maize the use of certified seed by the majority of farmers minimises weed seed introduction through contaminated seed. However, retained seed is used for crops like groundnuts and legumes with the possibility of introduction of weeds through the use of contaminated seed. Crop establishment on smallholder fields is poor under conventional tillage. However,, improvement in maize establishment have been reported under CA and this may facilitate weed management (GART, 2008). The use of fertilisers in semi-arid areas is quite low (Rusike *et al*., 2003) and this reduces crop competitiveness against weeds. However, the use of lower than the recommended rates and precision application in CA (Twomlow et al., 2009) can result in increased crop vigour and competitiveness against weeds early in the cropping season. Herbicides are not an economically feasible option for most smallholders due to unavailability and prohibitively high cost (Gianessi, 2009).

2.7 Conclusion

Although CA has the potential to address the challenge of low crop productivity sustainably, adoption of the technology remains low especially in Africa. There is a trend by the majority of farmers to adopt only the CA principles that fit into their current farming systems. However, CA promoters posit that benefits of CA including improvement in weed management can be realised as from the third year of adoption when recommended practices are followed. Further, they attribute the problems in weed management reported under to sub-optimal practices on most farms especially under smallholder farms. A review of literature shows that although CA practices can reduce weed growth, other management practices especially weeding also influence weed dynamics under CA. There is currently no information on weed population dynamics under recommended and actual smallholder CA practices in southern Africa. Increased weed pressure and adverse weed species shifts under CA practices would present a management constraint to resource-poor smallholder farmers whose only option of weed control is hoe weeding.

CHAPTER 3

CROP YIELD AND WEED GROWTH UNDER CONSERVATION AGRICULTURE IN SEMI-ARID ZIMBABWE

ABSTRACT

Constraints to effective weed management may be the main reason for the small area under minimum tillage (MT) in smallholder farming in southern Africa. The effect of maize residue mulching and intensity of hand hoe weeding on the growth of weeds, cowpea (*Vigna unguiculata cv.* IT 86D-719) and sorghum (*Sorghum bicolor cv.* Macia) was investigated in the fifth and sixth years of a conservation agriculture (CA) field experiment at Matopos Research Station (28^0 30.92`E, $20^0$ 23.32`S). The experiment was a split-plot randomized complete block design with three replications. Tillage was the main plot factor (conventional tillage (CONV) - mouldboard plough compared against MT systems - ripper tine and planting basins) and maize residue mulch rate (0, 4 and 8 t ha^{-1}) the sub-plot factor. Hoe weeding was done either four times (high weeding intensity) or twice (low weeding intensity) during the cropping season. Planting and weeding were done at the same time in all treatments. There was markedly greater early season weed growth in MT systems relative to CONV tillage in both crop species. In sorghum, MT (planting basins: 40.3 kg ha^{-1}; ripper tine: 34.8 kg ha^{-1}) systems had higher cumulative weed biomass measured after planting than CONV tillage (29.9 kg ha^{-1}) system. Maize mulching was generally associated with increased mid- to late- season weed growth in the two crops probably due to improved soil moisture conservation during periods of low precipitation. Weed suppression by the maize mulch was observed only in sorghum and limited to early in the cropping season with no effect observed for the remainder of the sorghum rotation phase. The high weeding intensity treatment had lower weed growth in both crops and better sorghum yield than low weeding intensity. The MT systems had poor crop establishment which translated into low yields. Cowpea grain yield obtained from MT systems was less than 300 kg ha^{-1} compared to 413 kg ha^{-1} in CONV tillage. The poor sorghum establishment in MT systems translated into low grain yield as sorghum grain yield was lowest in planting basins (2 602 kg ha^{-1}) and highest in CONV tillage with 4 159 kg ha^{-1}. Results suggest that CA systems require early and frequent hoe weeding even after four years to reduce weed infestations and improve crop growth. This higher

demand on a smallholder household's limited labour supply throughout the cropping season will be a key determinant of the spread and adoption of CA in southern Africa.

Keywords: Conservation agriculture, maize residue mulch, hoe weeding, cowpea, sorghum, weeds

3.1 INTRODUCTION

Conservation agriculture (CA) is being promoted to smallholder farmers in sub-Saharan Africa to increase productivity, reduce farmers' vulnerability to drought, and address low draught power ownership levels and to combat increasing levels of land degradation (FAO, 2010). The majority of smallholder farmers in the region are only practicing minimum tillage without crop residue mulching and crop rotation (Haggblade & Tembo, 2003; Mazvimavi & Twomlow, 2009). Yield increases of between 30 and 120 % have been reported under the MT systems of planting basin and ripper tine. However, the fields are reported to require more weeding effort than conventional plough tillage. In southern Africa there have been reports of a doubling in labour required for hand hoe weeding of maize and cotton grown under planting basins (Haggblade & Tembo, 2003) as well as increases in weeding frequency compared to conventional mouldboard plough tillage (Baudron *et al.*, 2007; Mazvimavi & Twomlow, 2009).

Promoters of CA attribute the weed problems reported on smallholder farmers' fields to partial adoption of CA. They argue that in CA weeds are only a problem in the first two years and, thereafter, weed infestations and weeding effort decline with time under CA (FAO, 2012a). However, the is no empirical evidence from southern Africa to support these claims but are based on sparse reports from South America from large mechanised farms where CA consists of permanent soil cover, diverse crop rotations including cover crops and efficient weed control using herbicides. Furthermore, reports of the serious challenges faced by smallholder farmers in Brazil with respect to weed management under CA have largely been. Under smallholder conditions, weed pressure has remained high under CA requiring increased herbicide use compared to conventional tillage even after more than 10 years of CA practices in Brazil

(Bolliger *et al*., 2006, Gowing & Palmer, 2008). The smallholder farmers occasionally resort to tillage in order to control weeds in CA (Ribeiro *et al*., 2005).

Specific research on weed population dynamics under CA as it is being recommended for smallholder farmers in southern Africa is lacking. Previous studies in the region evaluated the effect of minimum tillage (Vogel, 1994; Mabasa *et al*., 1998) or conservation tillage (Gill *et al*. 1992; Vogel, 1994, Muliokela *et al*. 2001) but not the simultaneous application of all the three principles on field weed infestation.

This study investigated whether weed infestation and requirement for hoe weeding were lower under CA than in conventional mouldboard plough tillage in the fifth and sixth year of CA and had the following specific objectives:

1. To determine the effect of tillage on weed density, cowpea and sorghum growth in the second phase of a maize-cowpea-sorghum three-year cropping system;
2. To quantify the effect of maize mulch rates on weed, cowpea and sorghum growth under the different tillage systems;
3. To determine the effect of intensity of hand hoe weeding on weed and crop growth in the fifth and sixth years of CA.

3.2 MATERIALS AND METHODS

3.2.1 Location

The study was conducted in the fifth (2008/09) and sixth (2009/10) years of a CA field experiment established in 2004 at West Acre Creek of Matopos Research Station Farm, Zimbabwe (28^0 30.92`E, $20^0$ 23.32`S; 1 344 m above sea level). The station is characterized by semi-arid climatic conditions and is considered to be representative of climatic conditions found in southwest Zimbabwe and much of Botswana, southern Mozambique and southern Zambia (Twomlow *et al*., 2006). The rainfall season is unimodal with distinct wet (November – March) and dry (April – October) seasons. The wet season is characterized by highly variable rainfall (250 – 1400 mm) with a mean long-term annual rainfall of 580 mm. The soil at the site is derived from micaceous schists and is classified as a Chromic-Leptic Cambisol (FAO, 1998) with 45% clay, 19% silt and 36% sand in the 0 – 0.44 m layer (Moyo, 2001). The soil is prone to waterlogging during exceptionally wet seasons. In 2008, the upper 0.15 m soil layer had a pH (water) of 6, a soil organic carbon content of 1.2% and bulk density of 1.4 g cm^{-3} (Mupangwa, 2009).

3.2.2 Treatments and experimental layout

In 2004, an experiment was designed to compare the effect of minimum tillage and maize residue mulching on soil water and crop yields of a three-year maize-cowpea-sorghum rotation (Mupangwa, 2009). The experiment was set up as a split-plot with plots arranged in a randomized complete block design with three replications. Tillage system was the main plot (63 x 6 m) factor and maize residue mulching the sub-plot (8 x 6 m) factor. In 2008 and 2009, hand hoe weeding intensity was added as a treatment factor at two levels (high and low weeding intensity). The weeding treatments were superimposed on sub-plots that received maize mulch rates of 0, 4 and 8 t ha^{-1} with each mulch rate replicated twice per main plot. The use of high maize residue mulch rates used in this study was based on findings of previous research from both tropical and temperate regions that demonstrated that effective weed suppression occurred under mulch rates that provided at least 60% soil cover (Gill *et al*., 1992; Bilalis *et al*., 2003; Christofolleti *et al*., 2007). Previous reports at the same site had shown that retention of maize residue at 2 t ha-1 had a comparable weed density to that under where no maize mulch rate was retained (Mupangwa, 2009; Mashingaidze *et al*., 2009a) An assessment of soil cover provided by maize residue at the study site indicated that 60% soil cover was achieved at a maize mulch rate of 4 t ha^{-1}. However, since maize residue yields from the 2007/08 season averaged 1.5 t ha^{-1}, additional maize residue was imported from neighbouring fields to achieve the treatment rates. In the sorghum phase of the rotation during 2009/10 season, cowpea residue was not retained as with its low C:N ratio it decomposes rapidly resulting in limited soil cover at planting. Instead, the available maize residue from fields at Matopos Research Station was used to provide mulch cover in sorghum.

Weeding at the high intensity treatment was carried out a week before planting, a week after planting (WAP), at 5 WAP and before harvesting (weeding W1 to W4 in Fig. 3.1). The high weeding intensity treatment followed the CA recommendation of frequent weeding aimed at minimizing weed seed return to the soil seed bank. This weeding regime's objective was to provide a clean seedbed for the crop, remove the first weed flush to emerge with the crop, reduce weed competition during the critical first 40 days of crops' growth and remove last weed cohorts emerging at end of the rains. The low weeding intensity treatment comprised hoe weeding a week before planting and at 5 WAP (weeding W1 and W3 in Fig.3.1). This treatment simulated the smallholder farmer practice of planting into a clean seedbed after early summer mouldboard ploughing and then hoe weeding 40 or more days after planting (Twomlow *et al*., 2006).

3.2.3 Crop management

3.2.3.1 Land preparation

Weeds were removed from all plots using hand hoes in June 2008. Maize residue was uniformly applied to sub-plots as surface mulch in August 2008. Planting basin (PB) and ripper tine (RT) tillage were carried out in September 2008 as per guidelines of the Zimbabwean CA Taskforce (Twomlow *et al*., 2008; ZCATF, 2009). Planting basins with dimensions of 0.15 m (length) x 0.15 m (width) x 0.15 m (depth) were dug using hand hoes at an inter-row spacing of 0.9 m and intra-row spacing of 0.6 m. Rip lines were opened at 0.9 m inter-row spacing using a commercially available ZimPlow® ripper tine attached to the beam of a donkey-drawn mouldboard plough. A ripping depth of between 0.15 m and 0.18 m was achieved with a single pass of the implement. In November 2008, to prevent incorporation of maize residue during ploughing, residues were removed from mouldboard plough (CONV tillage) plots before ploughing. At the first effective rains (50 mm) ploughing was done using a donkey-drawn ZimPlow® VS200 mouldboard plough and a depth of 0.15 m was achieved. Maize residues were returned to CONV tillage plots after which planting furrows were opened using hand hoes at an inter-row spacing of 0.6 m recommended for cowpeas in Zimbabwe. No basal fertilizer was applied.

The same land preparation methods were carried out in the 2009/10 cropping season. However, two additional dry-season hoe weedings were done, in August 2009 before mulching and in September 2009 prior to PB and RT tillage, in order to keep plots weed-free. The high weed growth observed during the period between June and September 2009 was probably due to residual soil moisture from the wet 2008/09 season that may have promoted increased weed germination and growth. The basin and rip line positions were maintained across the two seasons, as they had been in the previous four seasons (Mupangwa, 2009). In the 2009/10 season, cattle kraal manure (17.5% organic carbon, 0.13% N, 0.11% P) was applied as a basal soil fertility amendment at a rate of 3 t ha^{-1}. Manure was spot applied into planting basins and banded along the rip line in September 2009. As in the 2008/09 season, ploughing was done at first effective rains in November 2009 and planting furrows were opened at the recommended spacing for sorghum of 0.75 m and manure was banded along the furrows.

3.2.3.2 Planting and management

Since the majority of smallholder farmers in Zimbabwe commonly retain seed of minor crops such as cowpea, retained cowpea seed of an early maturing, semi-determinate cowpea variety, IT 86D-719 (source: IITA, Nigeria) was planted in all tillage systems on 26 December 2008. In both PB and RT, the recommendation of the Zimbabwean CA Taskforce (Twomlow *et al*., 2008; ZCATF, 2009) was followed in planting cowpea. Five cowpea seeds were planted per planting basin and thinned to four seedlings at 4 WAP to give a cowpea density of 74 074 plants ha^{-1}. In RT tillage, two cowpea seeds were planted per planting station and stations were spaced 0.15 m apart. At 4 WAP, the cowpea seedlings were thinned to one seedling per planting station to achieve the same cowpea density in RT as in PB. In CONV tillage, one cowpea seed was planted at an intra-row spacing of 0.25 m to achieve the recommended cowpea density of 66 667 plants ha^{-1}. The cowpea crop was not fertilized since most smallholder farmers neither apply manure nor inorganic fertilizer to legume crops (Ncube, 2007). Thiodan 35EC (80 ml in 20L water) was sprayed on cowpea at 4 WAP and during flowering to control aphids (*Aphis craccivora* L.). Thinning, spraying and weeding were carried at the same time in all tillage systems. The cowpea crop was harvested in April 2009.

An early maturing sorghum variety Macia was planted on 2 December 2009. In PB, the same planting and thinning method used in cowpeas was used to give a sorghum density of 74 074 plants ha^{-1}. In both RT and CONV tillage, sorghum seed was dribbled along planting furrows and thinned at 4 WAP to an intra-row spacing of 0.15 m to give a density of 74 074 plants ha^{-1} in RT and 88 889 plants ha^{-1} in CONV tillage. Ammonium nitrate (34.5% N) was applied to sorghum at a rate of 20 kg N ha^{-1} as topdressing at 5 WAP. Planting, weeding and fertilizer application were carried at the same time in all treatments. Sorghum was harvested in April 2010.

3.2.4 Data collection

3.2.4.1 Weed density and biomass

Weed density and biomass per sub-plot were determined from 0.6 x 0.9 m quadrats that were randomly placed at two positions in each sub-plot. The quadrats were placed centred on the inter-row so as to include four planting basins in PB and two rip furrows in RT. Weed density data was collected before weeding at 1 week before planting, 1 and 4 WAP; and at 9 and 13 WAP. Weed biomass in the 2008/09 season was collected starting at 4 WAP, and at all weed sampling times in 2009/10 season. Weeds sampled in each sub-plot were cut at ground level and oven-dried at 60 ^{0}C to constant weight and the dry weight determined. The timing of the weed sampling aimed to measure weeds just before planting, first flush of weeds that emerged with the crop, within the critical period of weed control and at crop canopy closure.

3.2.4.2 Crop yield

Cowpea was harvested at one picking when pods were observed to be fully mature and dry. Sorghum was harvested when heads were observed to be uniformly mature and dry. The number of plants, grain yield and stover (above-ground biomass minus grain) dry matter were determined from a net plot of four central rows each 6 m long in both cowpea and sorghum. In addition, cowpea pod number per plant and sorghum heads per net plot were determined from a sample of 10 plants from within the net plot. Grain yield was standardized to 12.5% moisture content.

3.2.5 Statistical analysis

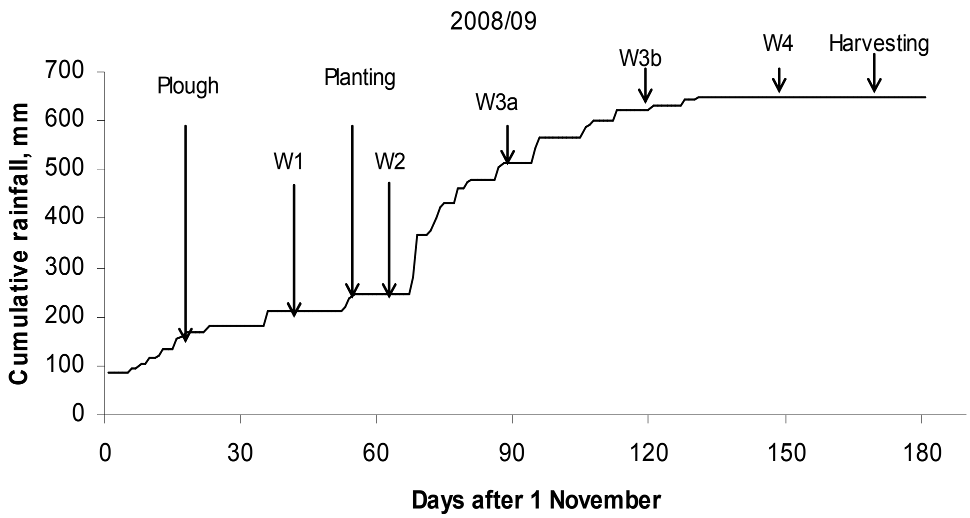
Prior to analysis, plots of residuals vs predicted values generated using GenStat Release 9.1 for the different transformations indicated that the square root (x +0.5) transformation improved variance homogeneity (Gomez & Gomez, 1984) of weed density and biomass in both the 2008/09 and 2009/10 cropping seasons. All weed and crop data were subjected to analysis of variance using GenStat Release 9.1 (Lawes Agricultural Trust, 2006). The means of the treatments were separated by least significant difference (LSD) at 5% level of significance.

3.3 RESULTS AND DISCUSSION

3.3.1 Seasonal rainfall

In both seasons, the start of the rainy season and distribution of rain within the season influenced the timing of crop management practices (Fig. 3.1). The low precipitation received after ploughing in the 2008/09 cropping season resulted in cowpea being planted in the last week of December 2008, more than a month after ploughing. The month of January 2009 received 42% of the total 2008/09 seasonal rainfall and the incessant rains led to re-weeding of all sub-plots (weeding W3a and W3b in Fig. 3.1) as hoe weeding was observed to be ineffective under the excessively wet soil conditions. The continuous rainfall also made it difficult to spray Thiodan 35EC for aphid control at two week intervals as is recommended. Cowpea establishment was poor in this season probably due to high seedling mortality as cowpea is prone to fungal diseases under wet conditions (Dugje *et al*., 2009).

The 2009/10 season was characterized by good early rainfall distribution and consequently sorghum was planted in early December 2009, a week after ploughing. The rains peaked in December (29% of total seasonal rainfall) but declined from January to March 2010. However, the rains increased in April 2010 resulting in 20% of the season's rains falling after the sorghum crop had reached physiological maturity. Both seasons received more than the long-term 69 year mean annual rainfall of 580 mm for Matopos Research Station.



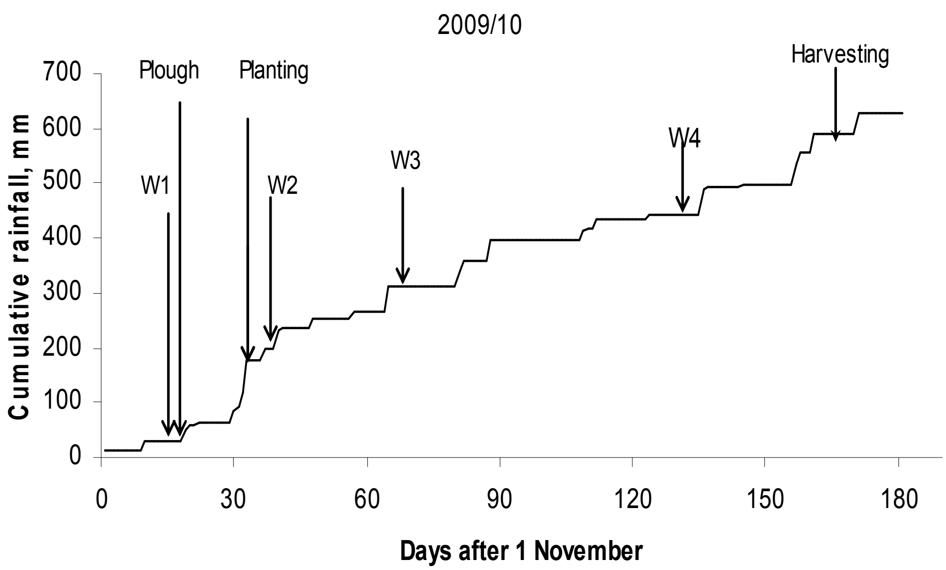


Fig. 3.1 Cumulative daily rainfall received and the timing of crop management practices at Matopos, Zimbabwe in the 2008/09 and 2009/10 cropping seasons. W1, W2, W3 and W4: high intensity hoe weeding operations; W1 and W3: low intensity hoe weeding operations

3.3.2 Weed density and biomass

There was no significant ($P > 0.05$) tillage x maize mulch rate x weeding intensity interaction on weed density and biomass in both crops. The significant two-way interactions were the tillage x weeding intensity interaction was significant ($P < 0.05$) for weed biomass at 4 WAP in cowpea (Fig. 3.2) and tillage x maize mulch rate interaction on weed biomass at 4 WAP in sorghum (Fig. 3.3). The significant main treatment and interactions effects are discussed below in detail under the respective subtitles.

3.3.2.1 Effects of tillage

Tillage had a significant ($P < 0.05$) effect on weed density one week before cowpea was planted where ripper tine had 3-fold and PB 2-fold the weed density (3.4 $m^{-2)}$ of the CONV tillage system. Weed emergence under MT systems was higher than under CONV tillage because without soil inversion weed seeds remained in the soil surface layer where suitable environmental conditions may have stimulated weed germination. The surface soil layer is characterized by high light penetration, high levels of O_2 gas, thermal fluctuations and moisture oscillations which often trigger seed germination (Benvenuti *et al*., 2001). In contrast, under CONV tillage most weed seeds were buried at soil depths where conditions induced seed dormancy leading to low weed emergence.

Similar results were in the season that preceded the cowpea phase being reported on in this study by Mashingaidze *et al.* (2009b) which demonstrated that even in the fourth year of CA a greater weed density resulted in MT than in CONV tillage systems. This may necessitate earlier weeding in RT and PB tillage systems than would be the case in CONV tillage, at a time when labor demand is still high. The low weed infestation observed in CONV tillage plots at 28 days after ploughing in this study (Plate 3.1) is in agreement with the findings of Mabasa *et al, (*1998) from on-farm studies in Zimbabwe that showed that early summer ploughing reduced the need for subsequent weeding for up to four weeks after crop emergence.

Plate 3.1 Low weed infestation in a) CONV tillage compared to b) RT a week after cowpea was planted at Matopos Research Station during the 2008/09 season. *Abbreviations:* CONV - Mouldboard plough; RT – Ripper tine

In cowpeas, MT systems were found to have significantly ($P < 0.05$) greater weed biomass than CONV tillage at 4 WAP (Table 3.1). However, this effect was confounded within the significant ($P < 0.05$) tillage x weeding intensity interaction which showed that MT systems had 37% more weed biomass than CONV tillage only in the low weeding intensity treatment (Fig. 3.2). The absence of a significant difference between MT and CONV tillage systems when a second within cropping season weeding was carried out a week after cowpea was planted demonstrated the need for more frequent hoe weeding in MT systems to achieve weed levels comparable to those in CONV tillage. The same trend of higher weed growth in the less intensive tillage systems was also observed in sorghum. A week before sorghum was planted; PB had the highest weed biomass ($P < 0.05$) of the three tillage systems (Table 3.1). The weed biomass in PB was 58%

more than in CONV tillage with weed biomass in RT being intermediate but not significantly different to that in CONV tillage. In the week after sorghum was planted, MT systems had double ($P < 0.05$) the weed biomass of CONV tillage. As a result, total weed biomass of MT systems was 16% higher ($P < 0.01$) than that of CONV tillage (Table 3.1). Since weed density measured after planting did not significantly vary with tillage in both seasons, the differences observed in weed biomass must have been mainly due to variation in weed growth between tillage systems.

Weeds such as *Commelina benghalensis* L., *Alternanthera repen* (L.) Link., *Boerhavia diffusa* L., *Leucas martinicensis* (Jacq.)R.Br. and some grass species were observed to grow rapidly with the first effective rains in MT systems in both seasons. The weed *A. repens* has a deep tap root that allows plant to regenerate and tolerate drought. *Commelina benghalensis* has stems with high moisture content and once plant is well-rooted it can survive without moisture (Wilson, 1981). In addition, *C. benghalensis* has rhizomes which re-grow rapidly at onset of rains (Holm *et al*., 1971).The undisturbed root systems and rhizomes under MT systems may have given these weeds a head start at the onset of the rainy season and resulted in greater weed biomass accumulation under MT systems than CONV tillage. Perennial weeds have been reported to establish rapidly in non-inversion tillage fields in studies done by Makanganise *et al*. (2001) in Zimbabwe; Kombiok and Alhassan (2007) in Ghana. In addition, the weeds *C. benghalensis* and *A. repens* as well as *Portulaca oleracea* L., were observed to quickly regenerate after hoe weeding under wet conditions. This suggests that shallow hoe weeding as done in this study was not fully effective in controlling these weeds. It may, in fact, have increased weed infestations when the cut stems gave rise to new weed plants. However, this issue can be resolved by removing weeds from field after hoeing as is done by some smallholder farmers so as to prevent uprooted weeds from re-establishing under wet conditions.

Both PB and RT tillage systems had greater weed growth than CONV tillage early in the cropping season. This period falls within the first third of most crops life cycle that is required to be kept weed free to avert yield loss (Mashingaidze, 2004). According to Akobundu (1987) sorghum required 35 and cowpea 40 weed free-days after planting to prevent weeds from causing significant yield reduction. The increased weed growth under MT in both the 5th and 6th

years of the CA experiment contradicts literature (Wall, 2007; FAO, 2010) that states that weed growth will increase in the first years but decline and become easier to control with time in CA. The high early season weed growth suggests a potential for increased weed competition that would probably necessitate early weed control strategies to be implemented if significant crop yield losses are to be averted.

Table 3.1 Tillage main effect on weed biomass in cowpea and sorghum grown at Matopos Research Station in 2008/09 and 2009/10 seasons

	Tillage	Weed biomass(kg ha^{-1})					
Crop	system	-1[§] WAP	1 WAP	4 WAP	9 WAP	13 WAP	Total[∞]
Cowpea	CONV			29.4	17.5	21.6	41.9
	RT			42.8	14.2	19.0	49.6
	PB			40.5	14.6	18.4	48.1
	LSD $_{(0.05)}$			8.26	ns	ns	ns
Sorghum	CONV	8.9	1.8	20.0	13.6	5.0	29.9
	RT	10.2	5.8	22.3	14.5	6.0	34.8
	PB	14.4	7.3	26.0	14.7	7.1	40.3
	LSD $_{(0.05)}$	3.49	2.62	ns	ns	ns	4.13

[§]One week before planting; [∞]Cumulative weed biomass after planting (WAP). Square root (x + 0.5) transformed data presented. *Abbreviations*: CONV - Mouldboard plough; RT - Ripper tine; PB - Planting basin; LSD - least significant difference; ns - not significantly different.

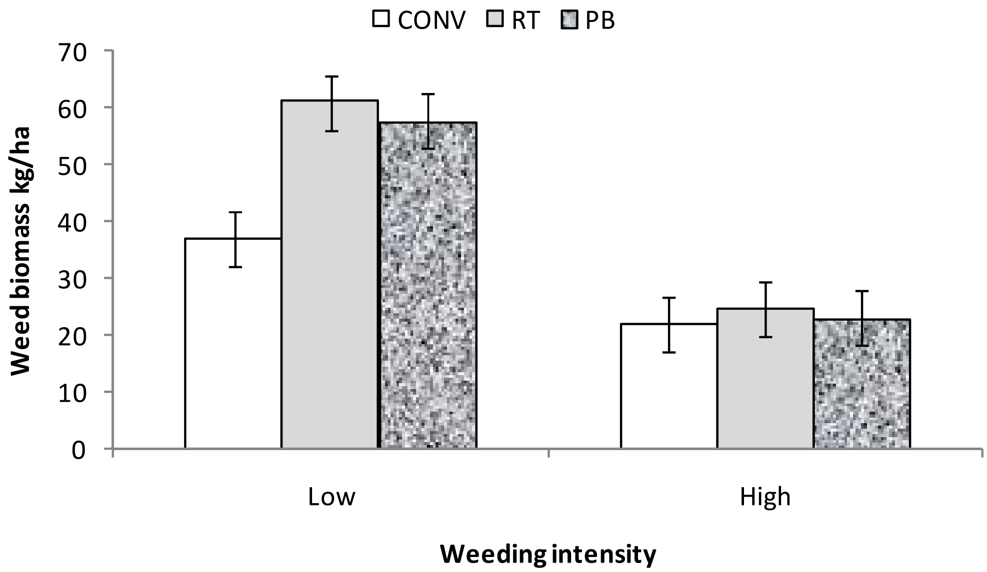


Fig. 3.2 Tillage x weeding intensity interaction on weed biomass at 4 WAP in cowpea grown in 2008/09 at Matopos, Zimbabwe. Narrow bars represent ±SED. Square root (x + 0.5) transformed data presented. *Abbreviations*: CONV - Mouldboard plough; RT – Ripper tine; PB – Planting basins; SED - standard error of difference of the means

3.3.2.2 Effects of maize mulch rate

Maize residue mulching significantly ($P < 0.01$) increased total weed density in cowpea by at least 7% compared to the un-mulched treatment (Table 3.2). Although the trend of increased weed density with mulching was observed at all sampling times in cowpeas, the effect was only significant as from the middle of the 2008/09 cropping season. Weed density increased by at least 16% ($P < 0.05$) at 9 WAP and 20% ($P < 0.01$) at 13 WAP in mulched plots. In sorghum, the maize mulch rate of 4 t ha^{-1} had the highest weed density at 4 WAP and when summed across all sampling times (Table 3.2). Maize mulch application was also associated with high weed biomass in sorghum at both 9 and 13 WAP (Table 3.2). Weed biomass increased by at least 22% ($P < 0.01$) at 9 WAP and 13% ($P < 0.05$) at 13 WAP under mulching. Consequently, it would appear from these observations that the retention of maize residue rather than suppressing weeds as is widely reported (Bilalis *et al.,* 2003; FAO, 2010) increased the emergence of weed seedlings and their subsequent survival rate compared to un-mulched plots.

Soils under maize mulch were reported to have had higher soil water content than un-mulched soils by Mupangwa *et al*. (2007) in the first phase of the maize-cowpea-sorghum rotation of this study at Matopos Research Station. It may, therefore, be that the high weed growth under mulch was due to improved water conservation than in un-mulched soils. Corresponding results were obtained by Buhler *et al*. (1996) in the USA who reported that in a below average rainfall season the retention of 5 t ha^{-1} of maize residue resulted in increased weed density of some annual weed species due to improved soil moisture conditions. According to Mohler and Teasdale (1993) 'safe sites' maybe created under the residue where more uniform soil moisture and moderate temperatures are maintained during hot dry periods and these can increase weed germination and growth.

While an increase in weed density and biomass at the end of the crop's life cycle may not be important in terms of crop/weed competition, these late weeds if allowed to shed seeds add to the weed seed bank and become a source of future weed infestations. In fact weeds growing over the winter period in Zimbabwe have been shown to deplete residual soil moisture (Bruneau & Twomlow, 1999). In order to prevent replenishment of the soil weed seed bank and conserve residual soil moisture for the next season, smallholder farmers should be encouraged to control the late season weeds. However, competition for labour is likely to occur between weeding and harvesting as farmers will be beginning to harvest the early planted crops. This is then followed by harvesting of all other crops before livestock are allowed to graze freely in fields. In fact Mazvimavi *et al*. (2011) report that in Zimbabwe only about 56% of smallholder CF farmers weeded their fields soon after harvesting in May/ June (winter weeding) during the 2008/09 cropping season. The rest of the farmers weeded fields during planting basin preparation which is usually carried out by smallholder farmers from August to as late as November.

Maize residue mulching did, however, suppress weed growth but this was only observed in sorghum and confined to early cropping season. Retention of maize mulch at the highest rate of 8 t ha^{-1} decreased ($P < 0.05$) decreased weed biomass at 1 WAP by 19% (Table 3.2). No significant suppression in weed growth was observed at the intermediate maize mulch rate of 4 t ha^{-1}. There was a significant ($P < 0.01$) tillage x maize mulch rate interaction on weed biomass at 4 WAP that showed that mulching at both rates reduced weed biomass only under PB tillage systems (Fig. 3.3). In this study, maize residue mulching was observed to provide a soil cover of 60% at 4 t ha^{-1} and 100% at 8 t ha^{-1} and the shading effect of the mulch probably led to a reduction in soil temperature oscillations and the amount of light reaching the soil surface. Since temperature and light are important cues for seed dormancy and germination for most annual weed species, shading of the soil surface by the mulch early in the season before the sorghum canopy had fully formed resulted in suppression of weed emergence and growth.

Bilalis *et al*. (2003) observed that both weed density and biomass decreased with increased wheat residue mulch on an organic farm in Greece. In Zambia, Gill *et al.* (1992) found that 5 t ha^{-1} of grass (*Cynodon* species) residues significantly reduced weed biomass in the first 42 days of maize growth in a MT system. Mashingaidze *et al*. (1995) in work done in Zimbabwe using wheat residues as mulch also observed greater suppression in weed emergence in MT systems than in conventional tillage. The concentration of weed seeds in the soil surface in MT systems may make them more susceptible to the effects of mulch on weed germination than weed seeds in CONV that are buried at greater soil depths.

While the observed weed suppression may be useful in reducing labour demands early in the cropping season, only a minority of smallholder farmers are able to retain maize residue at the levels (4 t ha^{-1} or more) used in this study in their fields. The amount of crop residue available for use as mulch is limited by low biomass production under rainfed conditions in semi-arid areas of southern Africa (Wall, 2007). In addition, the multiple uses of crop residues that include residue use as feed for livestock in the mixed crop/livestock farming systems common under smallholder agriculture in southern Africa and the use of crop residues for composting further reduce crop residue availability for mulching. Due to these constraints, the rates of crop residue available for mulching in marginal areas are so low that they are unlikely to eliminate the need for early weeding in MT systems as suggested by Gill *et al*. (1992).

The observation that maize residue mulching consistently resulted in increased weed density and biomass from the middle of the season had not been reported before in southern Africa. The finding is important in that one of the major reasons given to farmers for adopting crop residue mulching is weed suppression. However, this study showed that maize mulching can result in increased weed pressure that can reduce crop yield if not controlled. There is a need to carry out a similar study on a sandy soil to verify whether the same weed responses as observed under the clay loam in this study occur. If similar results were to be observed on a lighter textured soils it could be concluded that in terms of weed suppression, smallholder farmers in semi-arid areas may be better off using residues to feed livestock and composting as maize residue mulching is associated with increased late season weed growth that may require late season weeding to prevent seed return as recommended under CA.

Table 3.2 Maize mulch rate main effect on weed density (m^{-2}) and biomass ($kg\ ha^{-1}$) growth in cowpea and sorghum grown at Matopos Research Station in 2008/09 and 2009/10 seasons

Crop	Mulch $t\ ha^{-1}$	Weed growth					
		-1[∞]WAP	1 WAP	4 WAP	9 WAP	13 WAP	Total[§]
Weed density m^{-2}							
Cowpea	0	9.1	5.8	7.6	5.8	5.9b	13.0
	4	9.8	7.2	8.4	6.9	7.1a	14.6
	8	8.9	5.6	8.2	6.7	7.1a	13.9
	LSD $_{(0.05)}$	ns	ns	ns	0.85	0.60	1.87
Sorghum	0	12.3	5.6	24.9	11.5	16.4	34.2
	4	11.4	4.2	21.8	14.2	21.3	35.3
	8	9.7	5.0	21.6	17.1	18.6	35.7
	LSD $_{(0.05)}$	ns	ns	ns	2.63	1.16	ns
Weed biomass $kg\ ha^{-1}$							
Cowpea	0			36.8	15.5	18.2	44.8
	4			41.6	15.2	20.7	50.4
	8			34.4	15.5	20.0	44.4
	LSD $_{(0.05)}$			ns	ns	ns	ns
Sorghum	0	3.4	8.0	10.8	5.5	5.2	15.7
	4	3.7	7.6	12.6	5.8	5.5	17.0
	8	3.2	6.5	10.7	6.3	5.0	15.0
	LSD $_{(0.05)}$	ns	1.07	1.30	ns	ns	1.44

[∞]One week before planting; [§]Cumulative weed biomass weeks after planting (WAP). Square root ($x + 0.5$) transformed data presented. *Abbreviations*: LSD - least significant difference; ns - not significantly different.

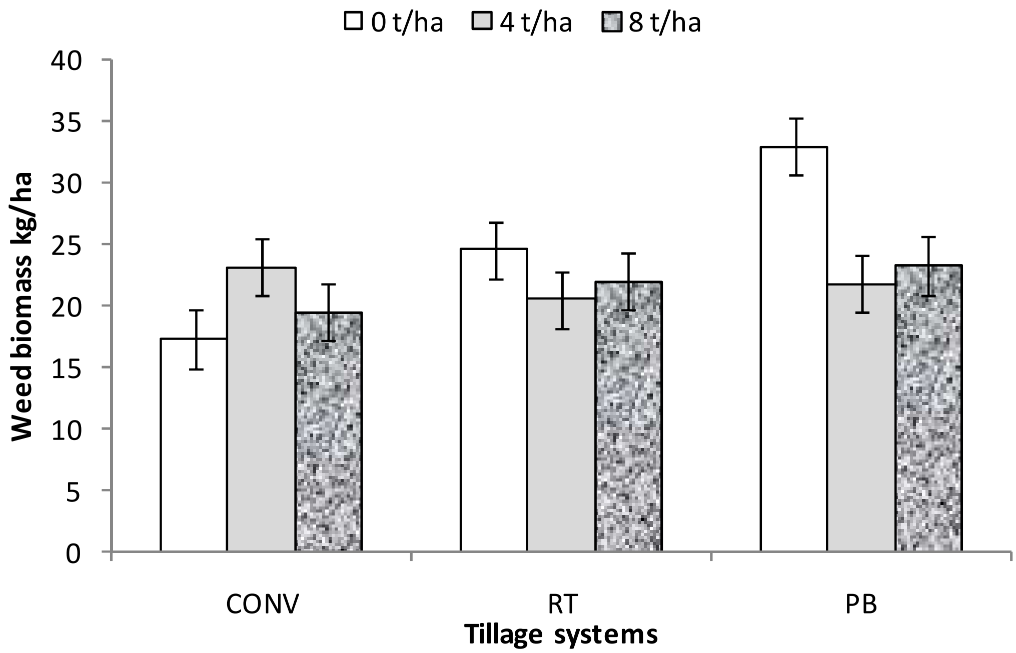


Fig. 3.3 Tillage x maize mulch rate interaction on weed biomass at 4 WAP in sorghum at Matopos, Zimbabwe in the 2009/10 season. Narrow bars represent ± SED. Square root (x + 0.5) transformed data presented. *Abbreviations*: CONV - Mouldboard plough; RT - Ripper tine; PB - Planting basins; SED - standard error of difference of the means

3.3.2.3 Effect of intensity of hoe weeding

In cowpea, the low weeding intensity treatment increased ($P < 0.05$) weed density by 13% at 13 WAP and this translated into significantly ($P < 0.001$) higher weed biomass measured at 13 WAP (Table 3.3). At 4 WAP, higher weed biomass was observed in the low weeding intensity treatment than in high weeding intensity only in PB and RT tillage systems (Fig. 3.2). There was no difference in weed biomass at 4 WAP between the MT and CONV tillage systems at the high weeding intensity treatment. Similar results were obtained by Tørreson *et al.* (2003) in a field study in Norway where the use of herbicides diminished differences between tillage systems compared to where no herbicides were applied. The high weeding intensity treatment significantly ($P < 0.001$) reduced total weed biomass (between 4 and 13 WAP) by 48% compared to the low weeding intensity treatment in cowpeas. In sorghum, weeding four times within the cropping season significantly reduced weed biomass and density at 4, 9 and 13 WAP (Table 3.3). In addition, the plots that had received the high weeding intensity treatment when cowpea was grown in 2008/09 season had a weed density at 1 WAP that was 19% ($P < 0.01$) less than that of the low weeding intensity treatment (Table 3.3). When summed over all weed sampling times after sorghum was planted, the high weeding treatment reduced weed density by 36% and weed biomass by 53% compared to the low weeding intensity treatment.

Thus, frequent hand hoe weeding, as demonstrated in a number of studies throughout Africa (Mashingaidze, 2004; Chikoye *et al*., 2007; Gianessi, 2009), can significantly reduce both weed emergence and growth across the cropping season. It was also effective in reducing early season weed growth in sorghum grown under MT (Plate 3.2) to the level found in CONV tillage. However, the four hoe weedings in addition to the dry season weeding(s) carried out in this study may not be a feasible option for the majority of resource-poor smallholder farmers. Although promoters of CA argue that weed management inputs decline after the first three years (FAO, 2012; Thiefelder & Wall, undated)) the findings from this study after four years of CA appear not to support this. Bolliger *et al*. (2006) report that the majority of smallholder zero-till (CA) farmers in southern Brazil find it difficult to control weeds without herbicides more than 20 years after replacing ploughing with zero-till. This dependence by zero-till smallholder farmers in Brazil on herbicides for effective weed control is reported to have increased herbicide use by 17% compared to conventional tillage.

Consequently, this high weeding demand for MT systems will probably limit the area under these tillage systems in smallholder crop production systems. Labour required for hoe weeding under CONV tillage in semi-arid Zimbabwe has been reported at 133 and 173 person hours ha^{-1} by Ellis-Jones et al. (1993) and Vogel (1994), respectively. In contrast, MT systems are associated with increased labour requirements for hoe weeding with mulch ripping requiring 173 person hours ha^{-1} and hand hoeing tillage 204 person hours ha^{-1} (Vogel, 1994). Although mulch ripping was observed to suppress weeds, more time was required during weeding as maize stalks present on the soil surface obstructed hoe weeding The requirement for frequent weeding throughout the cropping season is likely to exacerbate the labour constraints faced by the majority of smallholder farmers in southern Africa. The high prevalence of HIV/AIDS in Zimbabwe has reduced labour availability in communal areas (Mashingaidze, 2004). Labour intensive technologies such as CA are likely to adversely affect the quality of life of women and children as they bear most most of the weeding burden in smallholder agriculture. It is, therefore, likely that the area under PB and RT systems will be limited by the difficulty experienced by smallholder farmers in carrying out timely and frequent year-long weed management over large areas using the labour-intensive hand hoe weeding method.

Research in CA should focus on low-cost cultural practices such intercropping cover crops such as cowpea with main crops, selection of competitive crops and cultivars, improved fertility management and optimum crop densities so as to minimize weed growth. In order to facilitate adoption on large areas the use of burn-down herbicides such as glyphosate and paraquat should be considered for weed control before crop emergence. Spot application of herbicides to patches with troublesome weeds can also be an option. The use of soil applied pre-emergence herbicides and post-emergence during cropping season may, however, prove to be too knowledge intensive for smallholder farmers. This is because use of some herbicides requires that information on soil pH, organic matter and clay content be known to determine appropriate application rates. This information is largely unknown to most smallholder farmers. Glyphosate is often the herbicide recommended for use in CA. However, use of glyphosate continuously will eventually result in emergence of weed species resistant to the herbicide. Weed species resistant to glyphosate have been reported in the USA and other parts of the world (Prather *et al*., 2000). In order to minimize the development of herbicide resistance, farmers should rotate herbicides with different modes of actions. This, however, assumes that smallholder farmer is knowledgeable on modes of action of herbicides and the different herbicides are available on the market which is unlikely to be the case in smallholder agriculture in Zimbabwe. Therefore, research should be aimed at developing an Integrated Weed Management program that diversifies selection pressure in fields.

Table 3.3 Effect of hoe weeding intensity main effect on weed density (m^{-2}) and biomass (kg ha^{-1}) in cowpea and sorghum grown at Matopos Research Station in 2008/09 and 2009/10 seasons

Crop	Weeding intensity	Weed growth					
		-1[∞] WAP	1 WAP	4 WAP	9 WAP	13 WAP	Total[§]
Weed density m^{-2}							
Cowpea	Low			8.1	6.5	7.1	14.2
	High			8.1	6.5	6.3	13.5
	$LSD_{(0.05)}$			ns	ns	0.79	ns
Sorghum	Low		8.2	14.5	6.9	6.5	19.4
	High		6.7	8.2	4.7	3.9	12.4
	$LSD_{(0.05)}$		0.94	1.14	0.75	1.00	1.23
Weed biomass kg ha^{-1}							
Cowpea	Low			51.9	15.9	25.1	61.6
	High			23.2	14.9	14.2	32.6
	$LSD_{(0.05)}$			6.49	ns	3.59	5.48
Sorghum	Low	10.6	5.2	31.6	16.8	9.0	47.7
	High	11.6	4.6	14.0	11.8	3.0	22.3
	$LSD_{(0.05)}$	ns	ns	4.16	0.70	6.89	5.03

[∞] One week before planting; [§] Cumulative weed growth weeks after planting (WAP). Square root (x + 0.5) transformed data presented. *Abbreviations*: LSD - least significant difference; ns - not significantly different.

Plate 3.2 Higher weed growth observed four weeks after sorghum was planted in PB sub-plot (a) weeded only before planting compared to another PB sub-plot (b) weeded at one week before planting and 1 week after planting at Matopos Research Station during the 2009/10 season. *Abbreviations:* PB - Planting basins

3.3.3 Crop performance

3.3.3.1 Cowpea

Cowpea population attained in sub-plots for all treaments in the 2008/09 season was less than 50% of the recommended population of 66 667 plants ha^{-1}. The use of retained seed, late planting and the incessant rainfall received in January 2009 (Fig. 3.1) likely contributed to poor crop establishment. Conventional tillage had the highest number of pods per plant which translated into significantly ($P < 0.05$) higher grain yield (81%) than in MT systems (Table 3.4). Cowpea grain yield in 2008/09 season was low and close to the Zimbabwe national average yield for smallholder farmers of 300 kg ha^{-1} (Nhamo *et al*., 2003). However, high grain yield of over 1

200 kg ha^{-1} of the cowpea cultivar IT86 D-179 have been reported by Mupangwa (2009) in the first phase of the maize-cowpea-sorghum rotation of this CA experiment and by Fatokun (2002) in Nigeria. In both studies, there was good cowpea establishment and growth due to conducive environmental and management conditions. Olufajo and Singh (2002) identified low plant population as one of the major factors limiting yield in cowpea production. In addition, although no formal aphid assessment was done, there was probably poor aphid control in this study as the incessant rains during January 2009 (Fig. 3.1) limited the number of spray applications to only two during the period with severe aphid infestation. Schulz *et al*. (2001) reported that cowpea that is not adequately protected from insect damage produces less grain and more leaf and vine dry matter. This is borne out by the high cowpea stover (> 1 300 kg ha^{-1}) in all the tillage systems (Table 3.4) and this translated to low harvest indexes of between 8 and 17%.

Maize residue mulching had no effect on cowpea yield (Table 3.4) in this relatively wet season. Although the high weeding intensity treatment increased cowpea grain yield by 23%, the yield difference between the two weeding intensities was not statistically significant. Akobundu (1982) found at least two weedings in the first 5 weeks of cowpea growth to be sufficient to avert yield decline from weed infestation under humid conditions. Hoe weeding in the low weeding intensity treatment was carried out within this critical period. It may, therefore, be difficult to convince smallholder farmers to carry out more weedings later in the season for no additional yield benefit for a crop that, although it is an important food source, receives a lower level of management compared to major staples crops such as maize and cash crops like cotton (*Gossypium hirsutum* L.) in smallholder agriculture.

Table 3.4 Response of cowpea yield to tillage, maize mulch rate and hand hoe weeding intensity at Matopos, Zimbabwe in 2008/09 season

Tillage	Maize mulch rate (tha^{-1})	Pods $plant^{-1}$		Grain yield ($kgha^{-1}$)		Stover ($kg\ ha^{-1}$)	
		Weeding intensity					
		High	Low	High	Low	High	Low
CONV	0	29	19	546	392	2654	1429
	4	26	22	580	287	3457	1975
	8	23	21	372	299	3179	1975
	Mean	26	21	499	326	3097	1793
RT	0	22	23	313	351	1173	1440
	4	25	15	251	252	1605	1029
	8	21	22	232	231	1337	1379
	Mean	23	20	265	278	1372	1283
PB	0	15	16	246	255	1317	1235
	4	14	13	252	204	1399	1193
	8	14	15	224	188	1440	1770
	Mean	14	15	241	216	1385	1399
$LSD_{0.05}$ (Tillage)		4.2		120.2		5061.3	
$LSD_{0.05}$ (Mulch)		3.6		78.5		3535.2	
$LSD_{0.05}$ (Tillage x Mulch)		2.4		79.3		2845.7	
$LSD_{0.05}$ (Weeding)		6.2		136.0		6123.1	
$LSD_{0.05}$ (Tillage X Weeding)		4.1		137.0		4928.9	
$LSD_{0.05}$ (Mulch x Weeding)		4.4		119.7		4748.6	
$LSD_{0.05}$ (Tillage x Mulch x Weeding)		7.7		207.		8219.6	

Abbreviation: CONV - Mouldboard plough; RT - Ripper tine; PB - Planting basins; LSD - least significant difference

3.3.3.2 Sorghum

In sorghum, CONV tillage had the highest plant density at harvesting, with the density in PB being 81% lower than in CONV tillage (Table 3.5). The wide spacing of 0.9 x 0.6 m that is recommended in PB tillage systems by the Zimbabwe CA Taskforce (Twomlow *et al*. 2008a; ZCATF, 2009) may have been one of the factors responsible for the low sorghum density in PB. The low sorghum stand in PB tillage systems probably contributed to the low grain yield as sorghum grain yield at Matopos in 2009/10 season was positively correlated ($P < 0.01$; r^2 =

0.411) with sorghum density. The sorghum grain yield obtained under CONV tillage was 1 557 kg more than for PB with the same trend in sorghum stover yield.

Maize residue mulching significantly ($P < 0.05$) reduced sorghum grain yield by 15% (Table 3.5). The high weed biomass under mulched plots at both 9 and 13 WAP (Table 3.2) probably reduced sorghum yield through increased competition during the boot stage. On average, the sorghum crop in this study was observed to have reached 50% booting at 9 WAP. Since potential seed number per panicle is determined during the boot stage (Vanderlip, 1993) increased weed competition may have reduced seed number per panicle and ultimately grain yield. This is because seed number per panicle is highly related to sorghum grain yield (Heinrich *et al.*, (1983). Weed biomass at 13 WAP was observed to be negatively correlated ($P < 0.01$; $r^2 = 0.36$) to sorghum grain yield with the same trend observed at 9 WAP. The grain yield obtained under the low weeding intensity treatment was significantly ($P < 0.05$) lower (19%) than that obtained at the high weeding intensity treatment (Table 3.5) indicating the benefits of high weeding intensity on sorghum yield. However, the industrial and commercial use of sorghum and all small grains is very limited in Zimbabwe (Sukume *et al*., 2005). In semi-arid areas in Zimbabwe, sorghum production was reported to be unprofitable due to a combination of low yields (< 500kg ha^{-1}) and the low producer price (Hikwa *et al*., 2009). In this study improved fertility and weeding increased sorghum yield to over 2.5 t ha^{-1} in all tillage systems. However, the associated cost of the extra inputs, labour for weeding and bird scaring are likely to make sorghum production less profitable compared to maize which has a more ready market. These issues and the fact that sorghum plays a minor role in food security in Zimbabwe (Rukuni *et al*., 2006) maybe the reason sorghum ranks after maize and pearl millet in terms of production in Zimbabwe.

Table 3.5. Response of sorghum yield to tillage, maize mulch and weeding intensity treatments at Matopos, Zimbabwe in 2009/10 season

Tillage	Mulch rate (tha^{-1})	Ears ha^{-1}		Grain yield ($kgha^{-1}$)		Stover ($kg\ ha^{-1}$)	
		Weeding intensity					
		High	Low	High	Low	High	Low
CONV	0	81667	71852	5378	3896	5050	3944
	4	74259	72222	3503	4474	5370	4367
	8	63889	64074	4122	3581	5092	4983
	Mean	73272	69383	4334	3984	5171	4431
RT	0	46451	56636	5031	3500	3676	2022
	4	59877	66204	3859	2886	3771	3328
	8	52315	59259	3697	3580	3705	2578
	Mean	52881	60699	4196	3322	3717	2643
PB	0	31790	41975	2885	2535	2206	1536
	4	32407	38117	3193	1775	2961	1385
	8	32099	42284	2853	2372	2633	2320
	Mean	32099	40792	2977	2227	2600	1747
$LSD_{0.05}$ (Tillage)		18848.7		752.4		925.4	
$LSD_{0.05}$ (Mulch)		8255.4		485.9		464.9	
$LSD_{0.05}$ (Tillage x Mulch)		53050.1		526.7		339.5	
$LSD_{0.05}$ (Weeding)		14298.8		841.7		805.2	
$LSD_{0.05}$ (Tillage X Weeding)		9266.6		912.3		588.1	
$LSD_{0.05}$ (Mulch x Weeding)		10090.2		775.4		596.3	
$LSD_{0.05}$ (Tillage x Mulch x Weeding)		17476.7		1343.1		1032.9	

Abbreviation: CONV - Mouldboard plough; RT - Ripper tine; PB - Planting basins; LSD - least significant difference

3.4 CONCLUSION

In contrast to claims that weed pressure is only high within the first three of CA adoption, this study demonstrated CA systems that are being currently recommended to smallholder farmers had higher early season weed infestation than CONV tillage five and six years after CA adoption. This greater early season weed pressure under CA would require early and more frequent weeding to avert significant crop yield loss that is likely to exacerbate existing labour bottlenecks in smallholder crop production systems. Contrary to the widely held belief of suppression of weed growth on mulching, maize residue mulching increased mid-to-late season weed growth in both seasons of the study suggesting that this practice can aggravate problems with weed control faced by smallholder farmers that have replaced CONV tillage with CA in semi-arid areas. Based on the high weed growth and low grain yield in both crop species on mulching, there was limited justification for retaining maize residue as mulch in the medium term in CA. Overall weed growth was decreased and crop grain yield improved with increasing hand hoe weeding intensity irrespective of the tillage systems demonstrating that early and frequent hoe weeding is effective in controlling weeds. However, the majority of smallholder farmers lack sufficient labour to carry out the four hoe weedings as done in this study. Low cowpea and sorghum grain yields were realized in MT systems probably due to poorer crop establishment compared to CONV tillage. The use of retained cowpea seed in this study and excessive rains soon after planting probably contributed to poor cowpea establishment and low grain yield observed especially under CA. In order for CA to be practiced on large areas by smallholder farmers, there is need for research on the economic feasibility of using herbicides and cultural practices such as intercropping with fast growing legume for early season weed control. Research on optimal spacing and density of small grains and legumes is required so as to improve on crop yield and also aid in weed management in CA. There is need for long term studies of weed population dynamics under CA to be done under both heavy and light textured soils.

CHAPTER 4

RESPONSE OF WEED FLORA TO CONSERVATION AGRICULTURE SYSTEMS AND WEEDING INTENSITY IN SEMI-ARID ZIMBABWE

ABSTRACT

The perception that minimum tillage systems are associated with increased weed pressure and more difficult to manage weed species may be limiting adoption of CA among smallholder farmers in southern Africa most of whom have limited access to herbicides. A field study was conducted in the fifth (cowpea crop *Vigna unguiculata cv.* IT 86D-719) and sixth (sorghum crop *Sorghum bicolor cv.* Macia) seasons of a long-term conservation agriculture trial at Matopos Research Station (28^0 30.92`E, $20^0$ 23.32`S) to determine the effect of tillage, maize mulch rates and intensity of hoe weeding on weed species density and community diversity. The experiment was a split-plot randomized complete block design with three replications. Tillage was the main plot factor; conventional tillage versus the minimum tillage (MT) systems of ripper tine and planting basins. Maize mulch rate (0, 4 and 8 t ha^{-1}) was the sub-plot factor to which was super-imposed the intensity of hoe weeding treatment (low and high) as from the fifth season. Tillage system had no significant ($P < 0.05$) effect on community diversity although MT systems were associated with small seeded weed species such as *Portulaca oleracea* that may have benefited from shallow seed placement. Retaining moderate quantities of maize mulch may exacerbate smallholder weeding burden as the maize mulch rate of 4 t ha^{-1} had the highest weed density in both crops and a community dominated by the problematic *Setaria* spp. and *Elusine indica* in the sorghum phase of the rotation. However, the highest maize mulch rate (8 t ha^{-1}) reduced density of *P. oleracea* and *Corchorus tridens* at the low weeding intensity in sorghum. Weed density was lower and community diversity higher in the high than the low weeding intensity treatment in sorghum. Although frequent hoe weeding can be used to control weeds in MT systems, labour shortages may ultimately limit the area under MT in smallholder agriculture.

Key words: Tillage, maize mulch, hoe weeding intensity, weed diversity, cowpea, sorghum

4.1 INTRODUCTION

The major biophysical constraints to rainfed crop production in the semi-arid areas of southern Africa are unreliable rainfall and infertile soils (Twomlow *et al*., 2006) with smallholder productivity further limited by poor crop management practices (Sanchez, 2002). Conservation agriculture (CA) based on the principles of minimum tillage, permanent organic soil cover and crop rotation is being currently promoted to smallholder farmers in southern Africa to increase productivity levels (FAO, 2010). Although the majority of smallholder farmers face constraints in implementing full CA (Giller *et al*., 2009), there is increasing evidence that higher and more stable crop yields are being obtained in fields under minimum tillage compared to conventional ploughing (Wall, 2007).

Farooq *et al*. (2011) contend that integrated weed management is the fourth component / principle of successful CA. This is because weed control is identified as the biggest and often most difficult challenge in management faced by farmers that adopt minimum tillage (Gowing & Palmer, 2008). A review done by Chauhan *et al*. (2006a) reviewed tillage research mostly done in temperate regions and found that minimum tillage systems had higher weed density compared to conventional tillage. There is, also, mounting evidence of increased weed density under minimum tillage systems from research done in sub-Saharan Africa (Mabasa *et al*., 1998; Baudron *et al*., 2007). Furthermore, studies of minimum tillage systems indicated higher densities of perennial weed species in Zimbabwe (Vogel, 1994; Makanganise *et al*., 2001) compared to conventional tillage. These shifts to new and possibly more difficult to control weed species under minimum tillage systems is probably limiting the widespread uptake of CA by resource-poor farmers in Africa who lack access to herbicides.

However, according to literature on CA, adverse changes in weed species composition are limited under recommended CA practices (FAO, 2010). The weed composition changes that occur under CA instead result in a more diverse weed community that is easy to manage. This is attributed to the simultaneous practice of MT, crop residue mulching and crop rotation that diverse the selection pressure on weeds and thereby minimise the emergence of a dominant weed species that may prove to be difficult to control. There is no research regarding the impact of tillage systems and maize residue mulching on weed communities in medium-term CA where weeds are managed using hoe weeding.

The specific objectives were:

1. To determine the effect of tillage and maize mulch rate on weed species composition and weed community diversity;
2. To investigate the effect of hoe weeding intensity on the composition of weed species in the community under CA.

4.2 MATERIALS AND METHODS

4.2.1 Experimental design and crop management

The experimental design and agronomic management were as presented in Chapter 3.

4.2.2 Data collection

Weeds were sampled at 1, 4, 9 and 13 WAP from a 0.5 m^2 quadrat thrown twice at random positions into each sub-plot as described in Chapter 3. Weeds were identified to species level following Makanganise and Mabasa, (1999) and counted. Stem counts replaced plant counts for perennial monocots. A number of grasses (*Setaria incrassata* (Hochst.) Hack; *Setaria pumila* (Poir.) Roem. & Schult; *Setaria verticillata* (L.) Beauv., and *Aristidia aspera)* was classified as *Setaria* spp. due to difficulties in identifying them at the seedling stage.

4.2.3 Statistical analysis

Square root (x + 0.5) transformed cumulative weed density measured between 1 and 13 WAP for each species was subjected to ANOVA (GenStat 9.1). The analysis of the weed density and diversity data was performed separately for each season (crop). The treatment and interaction least significant differences (LSD) of the means from split-plot ANOVA were used to separate treatment means at 5% level of significance.

Weed diversity was measured using weed species richness (number of species) and the Shannon-Weiner diversity and evenness indices. Shannon-Weiner' diversity index $H^{'}$ was calculated for each sub-plot after Magurran (1988) as follows:

$$H^{'} = (N \ln N - Sum\ (n \ln n)) / N \qquad \textit{Equation 1}$$

where $H^{'}$ measures species diversity through proportional abundance of species, with a higher value signifying greater diversity, N is the total population density m^{-2} and n is the population of each weed species found in this area;

and evenness index E

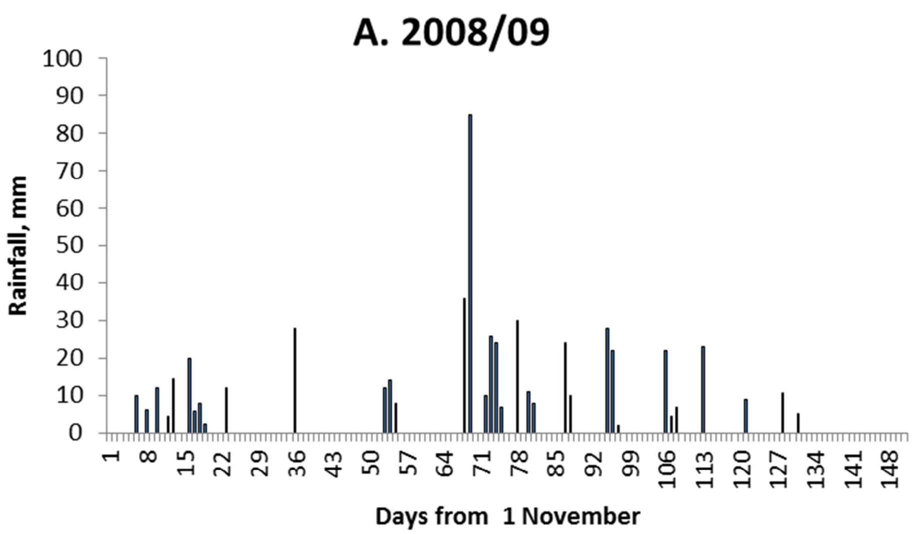
$$E = H^{'} / \ln N \qquad \textit{Equation 2}$$

where E is the relationship between the observed number of species and total number of species, with a greater value indicating greater uniformity between species abundances.

4.3 RESULTS AND DISCUSSION

4.3.1 Seasonal rainfall

Rainfall distribution varied between the 2008/09 and 2009/10 season with an more even rainfall distribution experienced in the second season (Fig. 4.1). At Matopos, the period between October and March has a 70-year mean rainfall of 533 mm with on average 242 mm received between October and December and 291 mm falling within the last half of the season (Mupangwa, 2009). No rainfall was recorded in October of both seasons. The rainfall distribution during the 2008/09 cropping season differed widely from the average season at Matops in that about 72% of the seasons rainfall fell between January and March with most of the rainfall concentrated between day 67 and 73 (Fig. 4.1A). In contrast, the first half of the 2008/09 season was quite dry receiving 35% less rainfall than the average season. Rainfall in the 2009/10 season was more evenly distributed between the two halves of the season although the rainfall received in the second half of the season was 20% less than the average rainfall received between January and March at this site (Fig. 4.B). As a result, the 2009/10 season was a below average rainfall season and the 2008/09 a slightly above average seasons. These differences in precipitation are likely to affect weed emergence between the two seasons.



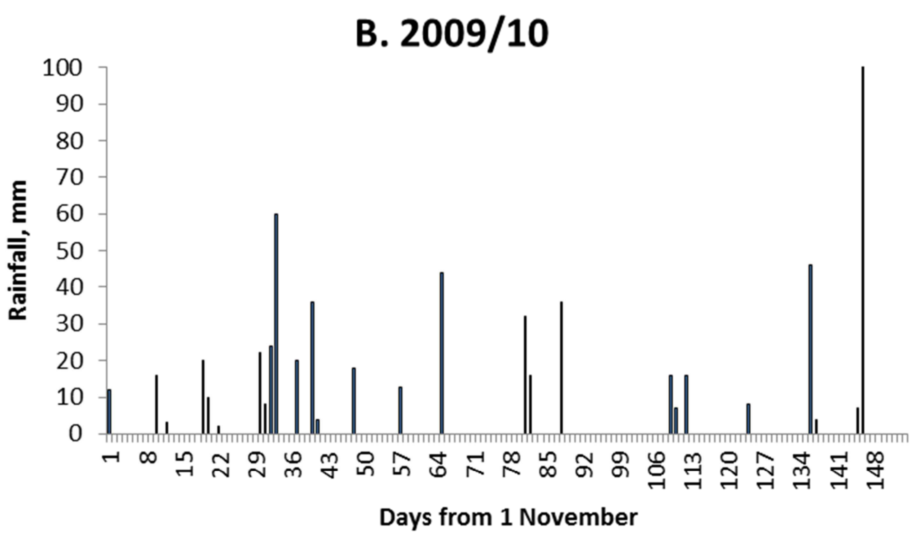


Fig. 4.1 Daily rainfall received between November and March at Matopos Research Station during the A. 2008/09 (561.1 mm) and B. 2009/10 (499.5 mm) cropping seasons

4.3.2 General effects on weed species and density

The weed species identified and the significant treatment effects of tillage, maize mulch rate and weeding intensity on individual weed species density and community diversity in cowpea and sorghum crops are summarized in Tables 4.1 to 4.5. There was no significant ($P < 0.05$) tillage x maize mulch rate x weeding intensity interaction on weed composition in both crops. The tillage x maize mulch rate interaction was significant ($P < 0.05$) for the density of *Leucas martinicensis*, *Setaria* spp. and *Urochloa panicoides* in cowpeas during the 2008/09 season and *Boerhavia diffusa* and *Schkuria pinnata* in sorghum during the 2009/10 season (Fig. 4.2). There was a significant ($P < 0.05$) tillage x weeding intensity interaction on the density of *Argemone mexicana*, *Cleome monophylla* and *Malva verticillata* in cowpeas during 2008/09 season and *A. mexicana*, *Bidens pilosa* and *U. panicoides* in sorghum during the 2009/10 season (Fig. 4.3). The maize mulch rate x weeding intensity interaction was significant ($P < 0.05$) for the density of *Ipomea plebia*, *S. pinnata* and *Setaria* spp. (Fig. 4.4) and annual monocots (Fig. 4.5) in sorghum grown during the 2009/10 season. These interactions are discussed below in detail under the respective subtitles.

4.3.3 Specific weed densities

Twenty-six weed species were identified in the cowpea phase in the first 13 weeks after planting (Table 4.1). Of these, twenty-four were also found among the twenty-five weed species identified in the sorghum phase the following season. Of the 27 weed species identified during the two years of the study, all the monocot weed species were present in both seasons. However, the perennial dicot *Sida alba* was absent in the 2008/09 season and the annual dicots *Gnaphalium pensylvanicum* and *Malva verticillata* were absent in the 2009/10 season. The density of most weed species varied with season probably reflecting the differences between the two seasons in terms of precipitation (Fig. 4.1) and the conditions required by the different weed species for growth under the different stages of the rotation.

Annual weed species made up over 95% by density of the weed community with annual monocots being the most abundant weed group in both crops (Table 4.1). The dominant weed species in the two crops were *Setaria* spp., *L. martinicensis* and *C. benghalensis*. However, in sorghum these species only comprised 67% of the weed community compared to 71% in cowpeas. The weed *E. prostrata* that was a minor weed in cowpea (0.1% of community) increased in density in sorghum (6.5% of community) to become the fourth most abundant weed in the community. In addition, weed density (m^{-2}) under sorghum was 41% higher than under cowpea.

The majority of annual weed seeds requires light for germination and may have benefited from increased light penetration under the more open sorghum canopy. Sorghum is reported to grow slowly early in the cropping season with maximum growth occurring before or after anthesis (Traor`e *et al*., 2003), which occurred nine weeks after planting for the sorghum crop in this experiment. In contrast, the semi-erect cowpea variety used in this study was observed to grow fast and cover the ground earlier than sorghum. The fast canopy development in cowpea probably resulted soil shading and suppression of weed germination. Based on these observations, the use of competitive crops or cultivars is one of the strategies that can be used by resource-poor farmers to suppress growth of annual weed species early in the cropping season.

Table 4.1 Mean density of weed species (no. m^{-2}) found in the first 13 weeks in cowpea and sorghum crops grown at Matopos Research Station during the 2008/09 and 2009/10 seasons, respectively

Life cycle	Latin binomial	Mean density m^{-2}	
		Cowpea	Sorghum
Annual dicots		87.3	123.7
	Acalypha crenata Hochst. Ex. A. Rich.	2.4	1.8
	Acanthospermum hispidum DC.	0.1	0.0
	Alternanthera repens (Linnaens) Link	10.9	15.9
	Amaranthus hybrius L.	0.7	0.8
	Argemone mexicana L.	2.0	0.2
	Bidens pilosa L.	1.2	7.3
	Cleome monophylla L.	0.4	0.1
	*Conyza albida (*Retz.) E.H. Walker	2.9	0.4
	Corchorus tridens L.	10.0	11.1
	Datura stramonium L.	0.1	0.4
	Euphorbia prostrate Ait.	0.2	17.8
	Gnaphalium pensylvanicum Willd	6.3	-
	Ipomea plebia L.	-	0.2
	Leucas martinicensis (Jacq.)R.Br.	42.4	53.9
	Malva verticillata L.	0.1	-
	Portulaca oleracea L.	3.1	8.2
	Schkuria pinnata (lam.) Thell.	2.1	1.6
	Sonchus oleraceus L.	1.1	3.4
	Tagetes minuta L.	1.2	3.4
Annual monocots		101.7	139.9
	Commelina benghalensis L.	13.9	18.5
	Eleusine indica (L.) Gaertn.	4.3	3.5
	Setaria spp.	87.7	110.5
	Urochloa panicoides Beauv.	0.8	7.4
Perennial dicot		3.6	3.7
	Boerhavia diffusa L.	3.6	2.6
	Sida alba L.	-	1.1
Perennial monocot		2.2	7.0
	Cynodon dactylon (L.) Pers.	1.8	1.3
	Cyperus esculentus L.	0.4	0.1
	Total	194.8	274.3

A '-' shows species was absent from system.

4.3.3.1 Tillage effect

Tillage had no significant (P > 0.05) effect on the total weed density in both cowpea and sorghum crops (Table 4.2). Conventional tillage was associated with significantly (P < 0.05) greater densities of *A. crenata* and *C. tridens* than the MT systems in cowpea. Although not statistically significant, a similar trend was observed for the two weed species in sorghum. The density of *S. alba* was significantly (P < 0.05) higher in CONV tillage than in MT systems in sorghum (Table 4.2). The weed *C. tridens* is characterized by a high degree of dormancy with germination increasing with seed coat scarification (Dzerefos *et al*., 1994). Weed species such as *C. tridens* that require burial in order to germinate may, therefore, be favoured in CONV tillage and decline in MT systems where there is no soil inversion. Such species survive soil burial by undergoing dormancy which is broken when the seeds encounter suitable conditions when they are brought to the soil surface through subsequent ploughing events.

A significantly (P < 0.05) higher density of *P. oleracea* was found under MT systems than CONV tillage in cowpea (Table 4.2). A similar significant (P < 0.05) trend was observed for *S. pinnata* in sorghum where weed density was 38% higher under MT systems than CONV tillage. The weed species *P. oleracea* is small seeded (Makanganise & Mabasa, 1999) and is likely to be more sensitive to light than large seeded weeds (Chauhan *et al*., 2006a) such as *C. tridens.* Small seeded weed species may, therefore, benefit from the low seed burial and exposure of seed to light under MT systems. Chauhan and Johnson (2009) also observed that *P. oleracea* emergence was greater under zero till than under conventional tillage. The ability of *P. oleracea* to survive for some time after being uprooted then setting root and producing new plants under moist conditions makes it difficult to eradicate by cultivation. This species, therefore, has the potential to become a serious weed in MT systems especially for resource-poor farmers without access to pre-emergence herbicides.

Table 4.2 Effect of tillage main effect on cumulative density of weed species[∞] found in cowpea (2008/09 season) and sorghum (2009/10 season) in the first 13 weeks after planting (WAP) at Matopos Research Station

Weed species	Weed density (m^{-2})							
	Cowpea				Sorghum			
	Tillage system				Tillage system			
	CONV	RT	PB	$LSD_{0.05}$	CONV	RT	PB	$LSD_{0.05}$
A. crenata	2.1	1.0	1.2	0.74	1.8	1.1	1.0	ns
C. tridens	4.0	2.4	2.3	0.83	3.8	3.0	2.9	ns
P. oleracea	1.4	2.0	1.9	0.41	2.8	2.6	2.6	ns
S. pinnata	1.0	1.4	1.4	ns	0.8	1.3	1.4	0.43
S. alba	-	-	-		1.5	1.0	0.8	0.39
Total density	14.5	13.7	13.3	ns	14.8	17.0	15.9	ns

[∞] Weed species that had a significant response to treatment in at least one crop. Square root (x + 0.5) transformed data presented with value of 0.7 = 0 untransformed data. Abbreviations: CONV - Conventional mouldboard plough, RT - ripper tine; PB - Planting basin; LSD - Least significant difference; ns - not significantly different.

4.3.3.2 Maize mulch effect

Mulching was generally associated with an increase (P < 0.05) in weed density compared to the un-mulched treatment in both the cowpea and sorghum crops. Retaining maize residue as surface mulch significantly (P < 0.05) increased the density of *C. albida, E. indica, G. pensylvanicum*, *L. martinicensis* and *S. pinnata* under cowpea and *L. martinicensis*, *S. pinnata* and *Setaria* spp. under sorghum (Table 4.3) in this study. The changes in soil temperature, moisture, light availability and soil nitrate levels on crop residue mulching (Christofolleti *et al*., 2007) probably created conditions favourable for the germination of some weed species. If the maize mulch resulted in moisture conservation as was previously reported by Mupangwa (2009) at the same site, this may have increased the germination and growth of species such *C. albida* and *G. pensylvanicum* that are commonly found in damp places. In addition, the maize residue may have trapped seeds of wind-dispersed weed species such as *C. albida* and *L. martinicensis* which later germinated and increased the density of these weed species under the mulch treatment.

For some weed species, the increase in density on mulch retention was specific to a tillage system. Of interest was the significant ($P < 0.05$) increase in weed density observed on mulching in MT systems for *L. martinicensis, Setaria* spp. and *U. panicoides* in the cowpea phase of the rotation and for *S. pinnata* and *B. diffusa* in the sorghum phase (Fig. 4.2). The association of *S. pinnata* with MT systems (Table 4.2) and mulching suggests that this weed is likely to be found in greater densities under CA than CONV tillage. However, the weed is easily controlled by mechanical methods including hoe weeding and is, thus, unlikely to emerge as a problem weed in CA.

The intermediate maize mulch rate of 4 t ha^{-1} had the highest density ($P < 0.05$) of *L. martinicensis,* and increased annual dicot weed density by 18% and total weed density by 11% ($P < 0.01$) compared to the un-mulched treatment in the cowpea crop. A similar significant ($P < 0.05$) trend was observed in the sorghum crop for *P. oleracea*, *Setaria* spp. and *L. martinicensis* with increases in annual monocots (15%) and total weed density (8%) at 4 t ha^{-1} maize mulch rate relative to where no mulch was retained (Table 4.3). In most cases, a lower weed density was observed under the maize mulch rate of 8 t ha^{-1} than the 4 t ha^{-1} maize mulch rate. This may have been due to a reduction in seed germination due to increased shading of the soil under the thicker layer of mulch at 8 t ha^{-1}.

The presence of maize residue at rates of 4 and 8 t ha^{-1} on the soil surface was also associated with weed suppression in some species. Reduced weed density on mulching was observed only in sorghum where significant ($P < 0.05$) suppression was observed across all tillage systems in the densities of *C. tridens*, *P. oleracea* and *E. prostrata* (Table 4.3) and under ripper tine for *B. diffusa* (Fig 4.3). Chauhan and Johnson (2009) also observed that P. *oleracea* seedling emergence declined exponentially with increased rates of rice residue. Crop residue mulch has been reported to reduce light transmittance and daily soil temperature amplitude which can lead to weed seed germination reduction or inhibition (Christofolleti *et al*., 2007).This may be the reason for the lower weed density of some species under the maize mulch in the sorghum crop. In addition, for small seeded weed species like *P. oleracea* the maize mulch may have acted as a physical barrier to weed seedling emergence and growth. For *C. tridens* and *P. oleracea* a significant reduction in density was observed only at a maize mulch rate of 8 t ha^{-1}. However, smallholder farmers in semi-arid areas are unlikely to retain even the lower maize reside rate (4 t ha^{-1}) due to the current low cereal residue yields and their important use as livestock feed in mixed crop-livestock systems.

In this study, the effect of the maize mulch on weed density varied with species, crop grown (Table 4.3) and for some species with tillage system (Fig. 4.2) which makes it impossible to make generic conclusions. According to Farooq *et al*. (2011), generalised statements about CA are often inappropriate because the effect of CA components is in most cases site specific with interactions between CA components common. Weed suppression on maize residue mulching was observed for some weed species, but not all, and only under the sorghum phase of the rotation. For species such as *P. oleracea* that had high densities under MT systems (Table 4.2), mulching as is being promoted under CA can be a weed control strategy.

However, retaining 4 t ha^{-1} or more of maize residue for suppression of four out of twenty five weed species with no overall decrease in weed density is unlikely to be a practice that is adopted by smallholder farmers. Maize mulching was, however, observed to increase the density of problematic weeds species such as *E. indica* in the cowpea phase of the rotation (Table 4.3) which is reported to be the most aggressive weed in Zimbabwe (Makanganise & Mabasa, 1999). The marked increase in total weed density in general and of specific problem weeds especially at the maize mulch rate of 4 t ha^{-1} is likely to exacerbate smallholder farmers' weed management problems.

Table 4.3 Effect of maize mulch rate main effect on cumulative density of weed species[∞] found in cowpea (2008/09 season) and sorghum (2009/10 season) in the first 13 WAP at Matopos Research Station

Weed species	Weed density (m^{-2})							
	Cowpea				Sorghum			
	Mulch rate t ha^{-1}				Mulch rate t ha^{-1}			
	0	4	8	LSD $_{(0.05)}$	0	4	8	LSD $_{(0.05)}$
G. pensylvanicum	1.8	2.7	2.7	0.50	-	-	-	
C. albida	1.2	1.7	2.1	0.57	0.9	0.8	0.9	ns
C. tridens	3.5	3.0	2.8	ns	3.9	3.2	2.7	0.70
B. diffusa	2.2	1.6	1.7	ns	1.7	1.3	1.7	0.38
E. indica	1.4	2.3	2.3	0.70	1.6	1.7	1.9	ns
E. prostrata	0.8	0.8	0.7	ns	4.8	3.6	2.9	1.00
L. martinicensis	4.2	5.7	4.8	ns	4.8	8.0	6.5	1.96
P. oleracea	1.9	1.7	1.6	ns	2.9	3.0	2.2	0.63
S. pinnata	0.9	1.1	1.8	0.63	0.7	1.0	1.8	0.32
Setaria spp.	8.6	9.1	9.0	ns	9.3	11.1	8.8	1.29
Annual dicot	8.3	10.1	9.0	1.23	10.5	11.5	10.2	ns
Annual monocot	9.4	10.2	10.1	ns	10.5	12.3	10.5	1.51
Perennial dicot	2.2	1.6	1.7	ns	2.0	1.6	1.9	ns
Perennial monocot	1.4	1.0	1.0	ns	2.1	0.9	1.8	ns
Total	13.0b	14.6a	13.9a	0.89	15.7b	17.0a	15.0b	1.44

[∞] Weed species that had a significant response to treatment in at least one crop. Square root (x + 0.5) transformed data presented with value of 0.7 = 0 untransformed data. *Abbreviations*: LSD - least significant difference; ns - not significantly different.

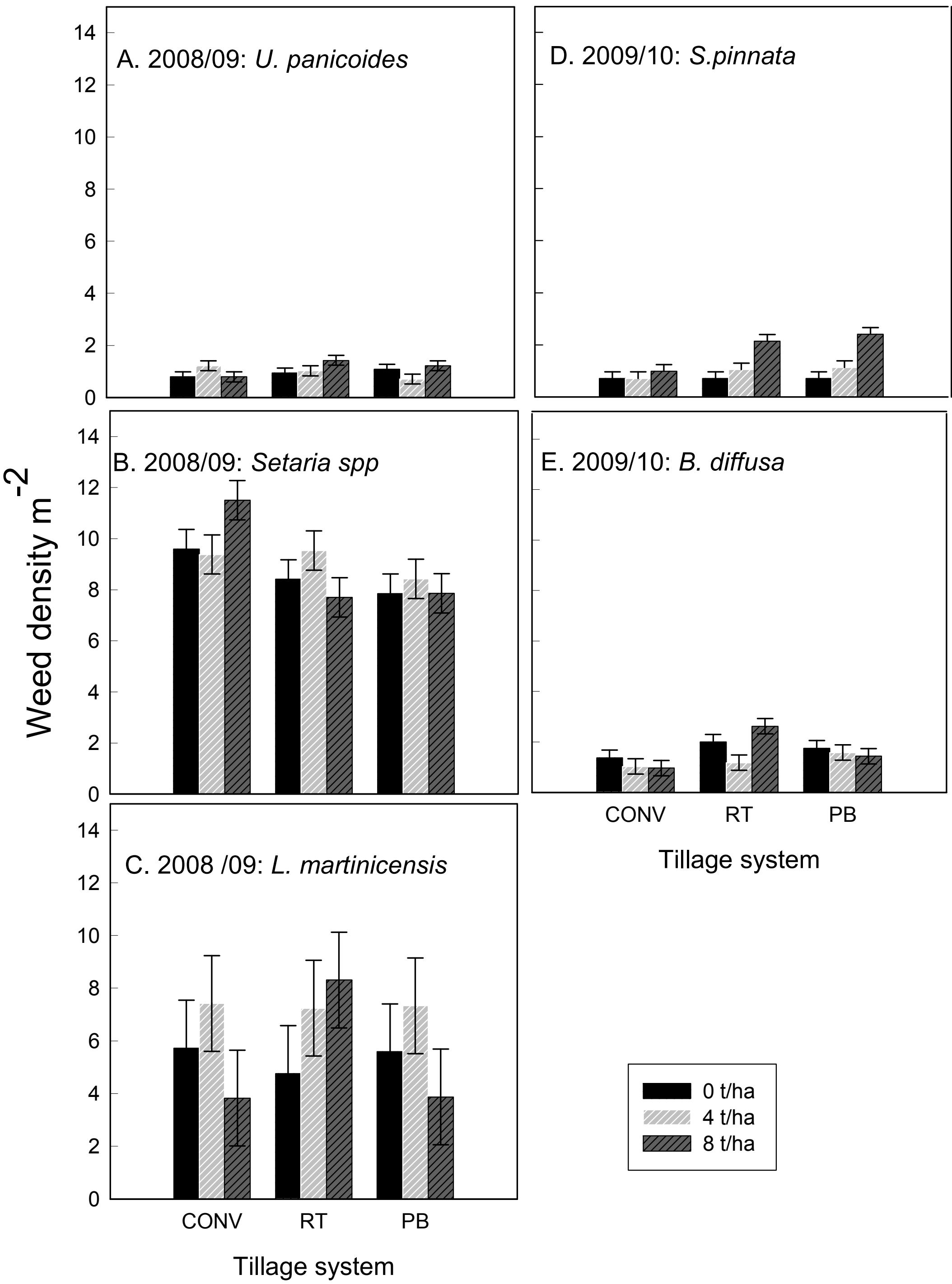


Fig 4.2 Tillage x maize mulch rate interaction on cumulative density in first 13 weeks of **A.** *U. panicoides*, **B.** *Setaria* spp. and **C.** *L. martinicensis* in cowpea (2008/09) and **D.** *S. pinnata* and **E.** *B. diffusa* in sorghum (2009/10) grown at Matopos Research Station. Narrow bars represent ± SED. Square root (x + 0.5) transformed data presented. *Abbreviations*: CONV - Conventional mouldboard plough, RT - ripper tine, PB - Planting basin; SED - Standard error of difference of the means

4.3.3.3 Intensity of hoe weeding effect

The high weeding intensity treatment significantly (P < 0.001) reduced total weed density, the density of annual dicots by 31% and annual monocots by 43% in the sorghum crop (Table 4.4). The higher density of annual weeds observed in the low weeding intensity treatment in sorghum may be a result of the greater seed returns to the soil seed bank under cowpea. During the cowpea phase of the rotation, the shorter weeding period in the low weeding intensity probably allowed most of the late season annual weeds to produce seed and add to the soil reservoir. Doubling the number of hoe weeding operations within the cropping season significantly (P < 0.05) decreased the density of *S. oleraceus* in the cowpea crop and of *A. repens, A. mexicana*, *B. pilosa*, *C. benghalensis*, *E. indica*, *L. martinicensis, S. pinnata*, *Setaria* spp. and *U. panicoides* in the sorghum phase of the rotation (Table 4.4). However for some species in both crops, the effect of weeding intensity was confounded within the significant (P < 0.05) tillage x weeding intensity interaction (Fig. 4.3). The density of *C. monophylla* in the cowpea crop and *A. mexicana* in both crops was reduced in the high weeding treatment than in low weeding intensity only under CONV tillage (Fig 4.3 B, C and F). On the other hand, the high weeding intensity treatment in the RT system reduced the density of *M. verticillata* in cowpea crop and of *U. panicoides* and *B. pilosa* in the sorghum crop compared to the low weeding intensity treatment (Fig. 4.3 A, D and E).

In addition, the effect of the intensity of hoe weeding was confounded within the significant (P < 0.05) maize mulch rate x weeding intensity for *I. plebia*, *S. pinnata* and *Setaria* spp. in the sorghum crop (Fig. 4.4). The density *I. plebia* was reduced on mulching only in the low weeding intensity treatment (Fig. 4.4A). The significant (P < 0.01) interaction for *S. pinnata* showed that the high weed density at 8 t ha^{-1} (Table 3) was found only under the low weeding intensity treatment (Fig. 4.4B). On the other hand, the high *Setaria* spp. density on maize mulching in sorghum (Table 4.3) was found under the high weeding intensity treatment (Fig. 4.4C). In contrast, under the low weeding intensity treatment, there was significant suppression of *Setaria* spp. at the maize mulch rate of 8 t ha^{-1}. A similar trend was observed for the annual monocots in the sorghum crop (Fig. 4.5) which was not surprising as *Setaria* spp. was the dominant weed in this group comprising 90% by density. The results from the annual monocots and *I. plebia* suggest that mulching may be a useful strategy for reducing the density of these weed species under low weed management conditions.

In agreement with the findings of Gianessi (2009), timely and frequent weeding reduced weed infestations in all tillage practices in this study. The stronger responses of weed species density to weeding intensity and maize mulching than to tillage system suggests that these had a stronger effect on weed seed germination and emergence than tillage. Booth & Swanton (2002) also noted that weed management methods such as herbicide application are a stronger constraint to community assembly than tillage intensity. Based on the findings of this study frequent and timely hoe weeding was effective in reducing weed density and should, therefore, be encouraged in MT systems of resource-poor smallholder farmers until alternative weed management regimes such as herbicides become possible. However, it is worth noting that the requirement for a high weeding frequency in CA as observed in this study has been cited by smallholder farmers in southern Africa as the main constraint to expansion of the area under CA-based tillage systems (Baudron *et al*., 2007).

Table 4.4 Effect of intensity of hand-hoe weeding main effect on density of weed species[∞] found in the first 13 WAP in cowpea (2008/09 season) and sorghum (2009/10 season) crops at Matopos

Weed species	Weed density (m^{-2})							
	Cowpea				Sorghum			
	Weeding intensity				Weeding intensity			
	Low	High	LSD (0.05	% change	Low	High	LSD (0.05)	% change
A. repens	2.6	2.6	ns		4.2	2.8	0.99	33
A. mexicana	1.2	1.2	ns		0.9	0.7	0.09	22
B. pilosa	1.1	1.1	ns		2.6	1.7	0.57	35
C. benghalensis	3.2	2.6	ns		4.9	2.8	0.79	43
E. indica	1.5	1.2	ns		2.1	1.4	0.60	33
L. martinicensis	5.0	4.8	ns		8.3	4.6	1.29	45
S. oleracea	1.2	0.9	0.22	25	1.0	0.9	ns	
S. pinnata	1.2	1.2	ns		1.4	1.0	0.30	29
Setaria spp.	8.7	8.3	ns		12.a	7.0	1.17	45
U. panicoides	0.9	0.8	ns		2.9	2.0	0.63	31
Annual dicot	9.4	8.9	ns		12.8	8.7	0.99	32
Annual monocot	10.2	9.6	ns		14.1	8.1	1.21	43
Perennial dicot	1.8	1.8	ns		1.5	1.6	ns	
Perennial monocot	1.0	1.2	ns		1.8	1.4	ns	
Total	14.2	13.5	ns		19.4a	12.4b	1.23	36

[∞] Weed species that had a significant response to treatment in at least one crop. Square root (x + 0.5) transformed data presented with value of 0.7 = 0 untransformed data. *Abbreviations*: CONV - Conventional mouldboard plough, RT - ripper tine, PB - Planting basin; LSD - Least significant difference; ns - not significantly different.

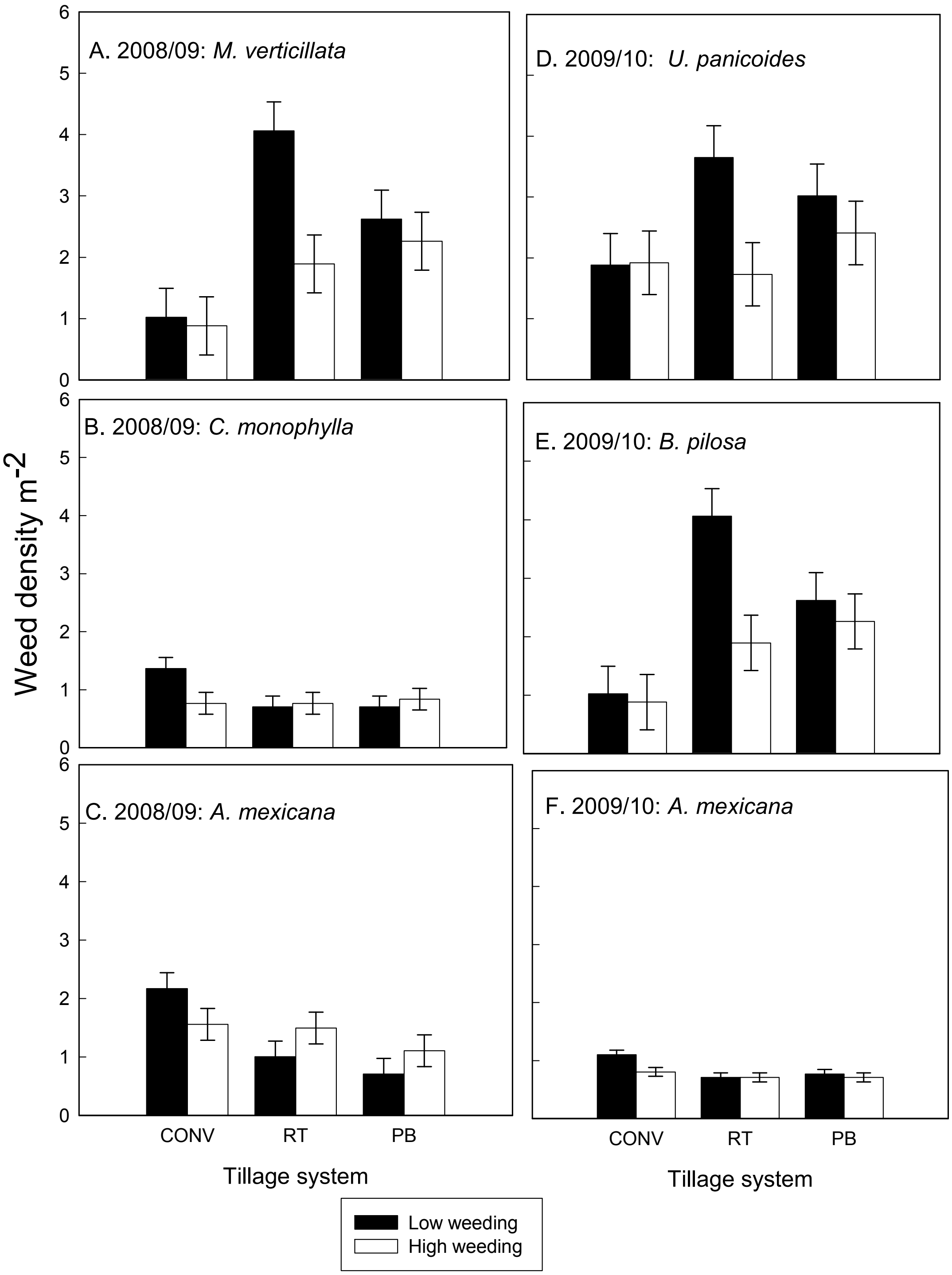


Fig 4.3 Tillage x weeding intensity interaction on cumulative density in first 13 weeks after planting of **A.** *M. verticillata*, **B.** C. *monophylla* and **C.** *A. Mexicana* in cowpea (2008/09) grown and **D.** *U. panacoides*, **E.** *B. pilosa* and **F.** *A. mexicana* in sorghum (2009/10) grown at Matopos Research Station. Narrow bars represent ± SED. Square root (x + 0.5) transformed data presented. *Abbreviations*: CONV - Conventional mouldboard plough, RT - ripper tine, PB - Planting basin; SED - Standard error of difference of the means

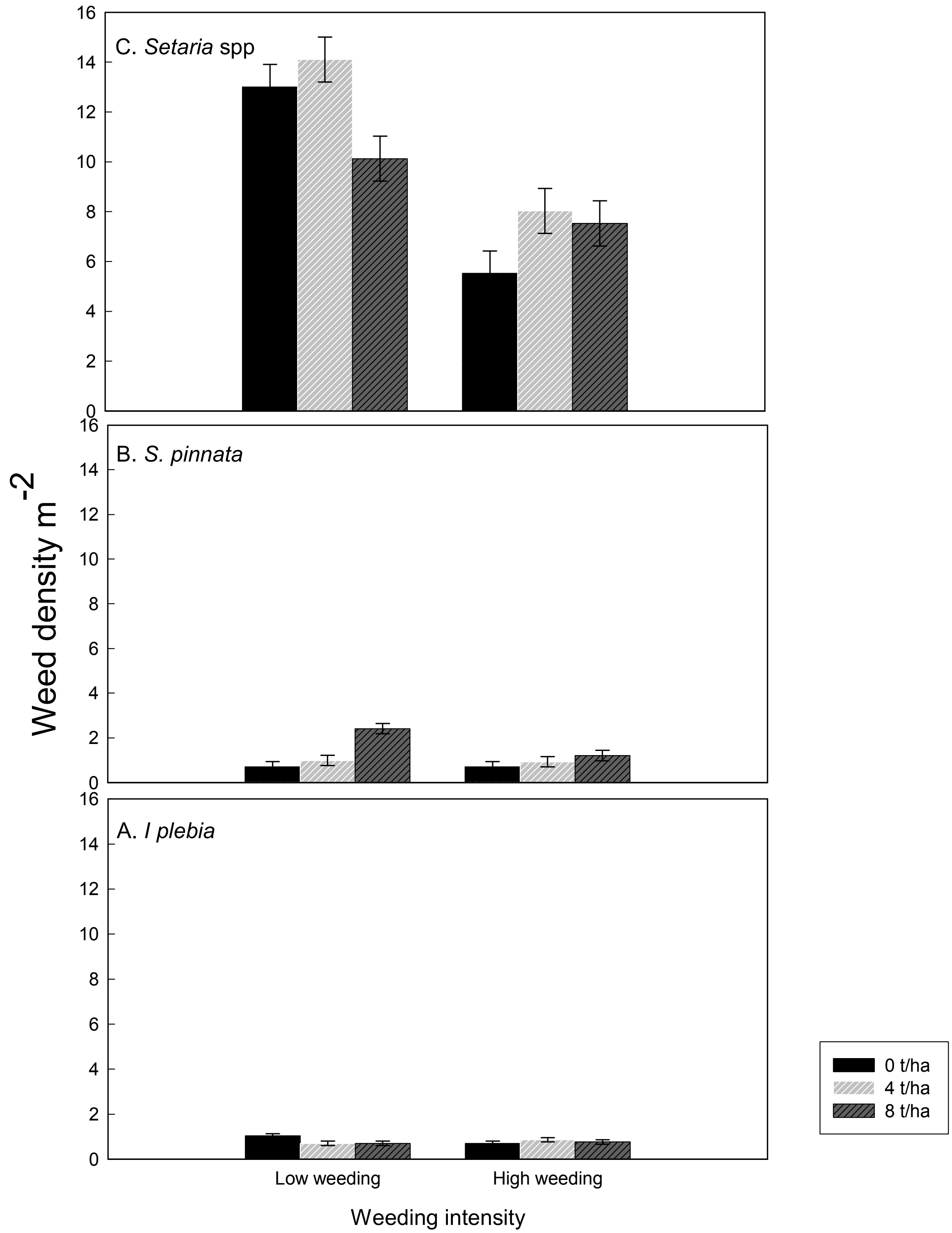


Fig 4.4 Maize mulch rate x weeding intensity interaction on cumulative density in first 13 weeks after planting of **A.** *I. plebia,* **B.** *S. pinnata* and **C.** *Setaria* spp. in sorghum grown at Matopos Research Station. Narrow bars represent ± SED. Square root (x + 0.5) transformed data presented. *Abbreviations:* SED -Standard error of difference of the means

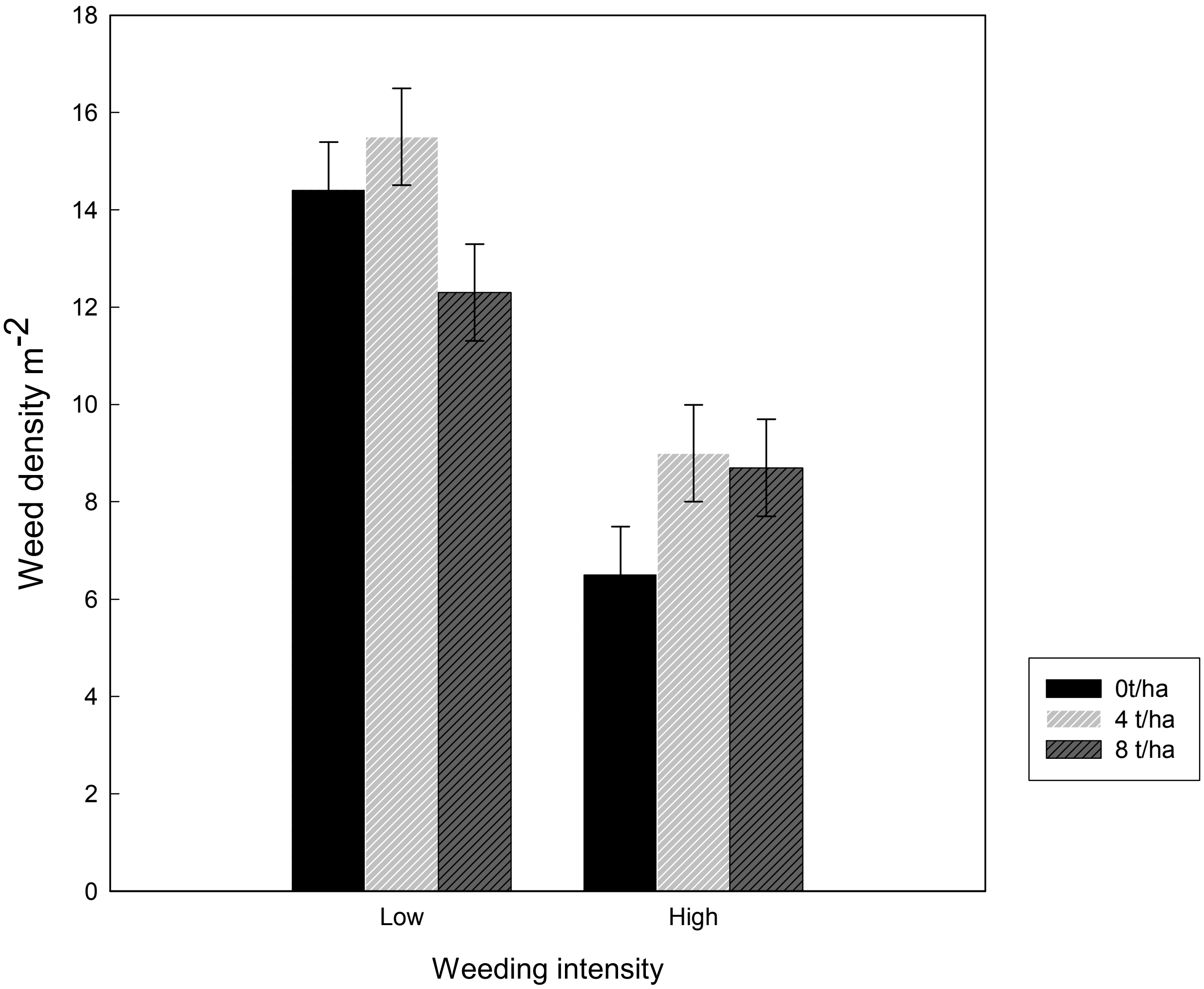


Fig. 4.5 Maize mulch rate x weeding intensity interaction on cumulative density in the first 13 weeks after planting of annual monocot species found in sorghum grown during the 2009/10 season at Matopos Research Station. Narrow bars represent ± SED. Square root (x + 0.5) transformed data presented. *Abbreviations:* SED - Standard error of difference of the means

4.3.4 Weed community diversity

Tillage had no significant effect on species richness, Shannon's diversity (H) and evenness (E) indices in both the cowpea and sorghum phases of the rotation (Table 4.5) which results are consistent with the findings of Legere *et al*. (2005). This lack of an increase in weed diversity with reduction in soil disturbance can be attributed to the confounding effect of other agronomic and environmental factors. Weed diversity indices in this study were low ($H^{'} < 2.0$) and similar to indices recorded in maize fields in eastern Zimbabwe by Manduna-Madamombe *et al*. (2008).

The evenness index values suggest little evidence of dominant weed species in any of the tillage systems.

Although there were changes in the density of some weed species on maize mulching (Table 4.3), the number of weed species in the communities did not vary in both crops (Table 4.5). However, in sorghum the intermediate maize mulch rate of 4 t ha^{-1} had the least diverse ($P < 0.05$) weed community and the lowest weed species evenness (Table 4.5). The weed community under the 4 t ha^{-1} maize mulch rate had a higher proportion of *Setaria* spp. and *L. martinicensis* which were the two most dominant species in the weed communities under the mulch treatments. These weed species probably took advantage of the improved soil surface conditions for germination under the intermediate mulch rate as reflected by the associated high weed density under this mulch rate (Table 4.3). The *Setaria* spp. group is one of the worst weed groups in the world and competes for resources efficiently resulting in the exclusion of other weed species (Dekker, 2003).

The low weeding intensity treatment was associated with a significantly ($P < 0.05$) higher number of weed species than observed at the high weeding intensity across all the tillage systems in sorghum (Table 4.5). This suggests that more weed species were able to emerge and grow successfully in the low weeding intensity treatment than in the high weeding intensity treatment. This is consistent with the findings of Legere *et al*. (2005) who noted that weed diversity indices are more consistently affected by weed management. However, in this study the individual weed species in the weed community under the low weeding intensity treatment were less ($P < 0.01$) evenly distributed resulting in a less diverse weed community (Table 4.5). The density of abundant weed species such as *Setaria* spp., *L. martinicensis* and *A. repens* were higher in the low weeding intensity treatment compared to high weeding intensity resulting in these species being more dominant in the low intensity community. The low weeding intensity treatment is a reflection of the current smallholder farmers' weeding practices. The less diverse community under the low weeding intensity treatment may result in weed management problems. According to Miyazawa *et al*. (2004), high weed community diversity may facilitate weed control in sustainable agriculture by enhancing competition among weed species and preventing the dominance of a single weed species especially if this is a problem weed in arable fields.

Table 4.5 Richness (number of species per plot), diversity (Shannon's H' index) and evenness (Shannon's E index) for weed species present under different main treatments in cowpea (2008/09 season) and sorghum (2009/10 season) crops grown at Matopos Research Station

Treatment	Cowpea weed diversity indices			Sorghum weed diversity indices		
	Richness	Diversity	Evenness	Richness	Diversity	Evenness
Tillage						
CONV	11.4	1.48	0.61	13.2	1.73	0.68
RT	12.1	1.63	0.66	13.2	1.78	0.68
PB	11.6	1.63	0.67	12.4	1.73	0.71
LSD $_{(0.05)}$	ns	ns	ns	ns	ns	ns
Mulch t ha^{-1}						
0	11.1	1.55	0.65	12.9	1.81	0.71
4	12.2	1.56	0.63	12.2	1.61	0.65
8	11.9	1.62	0.66	13.1	1.83	0.70
LSD $_{(0.05)}$	ns	ns	ns	ns	0.167	ns
Weeding intensity						
Low	12	1.6	0.65	13.6	1.7	0.65
High	11.5	1.56	0.64	12.2	1.8	0.72
LSD $_{(0.05)}$	ns	ns	ns	1.16	ns	0.0367

Abbreviations: CONV - Conventional mouldboard plough, RT - ripper tine, PB - Planting basin; LSD - Least significant difference; ns - not significantly different.

4.4 CONCLUSION

This study provided new information that confirmed that CA can minimize the development of a weed community dominated by weed species associated with MT systems. The findings demonstrated that although *P. oleracea,* this species is unlikely to be a problem in CA when high maize residue rates of 8 t ha^{-1}. However, when maize residue retention is less than 8 t ha^{-1} *P.oleracea* may be a problem under CA. The weed *P. oleracea* can be difficult to control without herbicides as it also propagates by vegetative reproduction. This weed species was effectively controlled in this study through frequent hoe weeding. The weed species *S. pinnata* is likely to increase under CA as it was associated with MT systems and maize residue mulching. However, the weed was easily controlled when hoe weeding was done frequently. Maize mulching and use of a diversified crop rotation probably contributed to the lack of differences in weed community diversity between MT systems and CONV tillage. However, the intermediate maize residue rate of 4 t ha^{-1} had the least diverse weed community in sorghum probably as a result of the increased density under mulch of dominant weed species such as *Setaria* spp., *L. martinicensis* and *I. indica*. However, *e*arly and frequent hoe weeding effectively reduced weed density of these species by over 40%. This study demonstrated that the effect of mulching was dependent on tillage system, season and weed species such that generic conclusions on mulch effect on weeds were difficult to make. There was no evidence of a shift to more difficult to control weeds under CA in this study probably due to the effect of the different crops in the rotation and the differential effect of maize mulch on weed species emergence in the different seasons. There is a need to carry out a study of weed population dynamics in under smallholder farmer conditions and management CA. The effect of crop rotation on weed composition needs to be investigated using experiment where the different cropping systems including the monoculture are present in each season.

CHAPTER 5

WEED COMPOSITION IN MAIZE (*ZEA MAYS* L.) FIELDS UNDER SMALLHOLDER CONSERVATION FARMING

ABSTRACT

Smallholder farmers in southern Africa have reported on increased labour requirements for hoe weeding due to high weed infestations in conservation farming (CF) fields. However, CF proponents claim that weed pressure and labour requirements for weeding decrease within the first three years under the recommended CF practices. An observational study was carried out during the 2008/09 cropping season on 21 maize fields in Wards 12 and 14 of Masvingo District to determine weed composition in fields that had been under CF for different years. Fields were grouped into CF3- (under CF for 2 or 3 years) and CF3+ (under CF for 4 or 5 years) with conventional mouldboard plough tillage (CONV tillage) used as the control group. Participatory Rural Appraisal (PRA) techniques were used to obtain farmer perception of the most limiting constraints in CF. Neither crop residue mulching to provide a soil cover of at least 30% soil cover at planting nor cereal/legume rotations had been practiced in the past four seasons by the 17 farmers reported to be practicing CF. The farmers had only adopted the minimum tillage system of planting basins (PB) and the associated improvements in management. Hereafter, the CF fields will be referred to as PB fields. Tillage had no significant effect on weed density and species composition. However, the first post-planting hoe weeding was done at least 15 days earlier ($P < 0.05$) in PB than in CONV tillage suggesting higher early season weed growth in PB relative to CONV tillage. Three post-planting weedings were carried out in PB compared to only two under CONV tillage. Farmer ranking of the main constraints in PB were low rainfall > input unavailability > labour > pests. It seemed that farmers were committing PB to small acreages equivalent to the inputs supplied by NGOs. Under these low areas, weeds could be managed by available family labour. At least double the maize grain yield was obtained from PB compared to CONV tillage (mean: 1 052 kg ha^{-1}) probably as a result of improvements in soil fertility and weed management. However, grain yield decreased with increase in weed density at 3 WAP highlighting the importance of early season weed control in maize. As labour requirements for weeding did not decline with time in PB, there is need to investigate the use of herbicides to

reduce early season weeding burden on smallholder farms. Management practices such as the use of poorly composted manure may have contributed to the high weed infestations and introduced some new weed species in some PB fields.

Key words: Conservation farming, tillage system, on-farm, weed emergence, weed density

5.1 INTRODUCTION

In Zimbabwe, there has been wide-scale promotion of conservation farming (CF) to smallholder farmers that began in 2004 with about 5 000 households and by 2009 the number had increased almost to 100 000 (Marongwe *et al*., 2011). Conservation farming was promoted to farmers without draught animal power and enabled the farmers to plant early without the need for ploughing (Mazvimavi & Twomlow 2009). Improvements in planting date, fertility management and water harvesting have resulted in a doubling of the yields in CF compared to conventional plough tillage u (Twomlow *et al.*, 2008). However, Mazvimavi et al. (2011) observed that the area under CF has remained low despite the marked yield increases under this practice. Marongwe *et al*. (2011) attributed the low CF adoption to increased labour especially for weeding.

The extent of adoption of the three principles of conservation farming (CF) and level of field management of CF fields by smallholder farmers is reported to differ between farmers (Mazvimavi *et al*., 2011). The majority of CF farmers are reported to be practicing only the minimum tillage system of planting basins. However, some farmers with more experience in CF have also begun incorporating crop residue mulching and crop rotation. Surveys done by ICRISAT showed that the CF component adopted differed with area and with farmer. Adoption of only planting basins is expected to lead to increased weed pressure and the development to control weed species. However, where CF is practiced with good management it is claimed that weed pressure will reduce after the first three years leading to reduced weeding effort over time. However, the level of soil cover and crop rotation sequence determine the level of weed infestations. Ribeiro *et al*. (2005) report that smallholder farmers in Brazil, despite rotating crops and retaining some soil cover, still struggle to control weeds under CA after more than 10 years. Information documenting weed population dynamics under CF as adopted by smallholder farmers in Zimbabwe is currently unavailable.

The objectives of this on-farm observational study are to:

1. Characterize the main form of CF adoption by smallholder farmers
2. determine weed infestation and composition in fields that had been under CF for different periods of time.
3. identify farmer perceptions on production constraints in CF.

5.2 MATERIALS AND METHODS

5.2.1 Site description

An observational field study was used to assess weed composition in CF fields and Participatory Rural Appraisal (PRA) techniques to identify farmer perceptions of constraints to CF in Ward 12 (30^0 53' E, 20^0 30' S; altitude of 1094 – 1101 m) and Ward 14 (31^0 09' E, 20^0 20' S,; altitude 1041 - 1087 m) of Masvingo District of Zimbabwe during the 2008/09 cropping season. Masvingo District is one area in semi-arid Zimbabwe where high CF adoption has been recorded among smallholder farmers, with the practicing farmers including those that were trained and provided with inputs for CF by CARE International as well as spontaneous adopters (Pedzisa *et al*., 2010). Farmers in Wards 12 and 14 of Masvingo District have practiced CF for varying lengths of time and, thus, provided a chance to test the hypothesis that high weed infestations in CF were only confined to the initial two years. Observational studies were considered appropriate for this study as they are useful for determining changes in parameters of interest under actual farmer practices (Bullied *et al*., 2003; Lawson *et al*., 2006).

Masvingo District has an average annual rainfall of 582 mm with a range of 102 – 1 037 mm (Mugabe *et al*., 2004). However, about 7% of the district receives more moderate rainfall (650 – 800 mm per annum) and this includes the area around Lake Mutirikwi (FAO, 2009). Wards 12 and 14 are found within this relatively wetter area that is classified as Natural Region III by

Vincent & Thomas (1960). The rest of the district falls under Natural Region IV. The main rainy season is from mid-November to mid-March with mid-season dry spells commonly experienced between December and January. The mean summer and winter temperatures are 23^0C and 10^0C, respectively. Soils are of the fersiallitic type (Nyamapfene, 1991). Soil analysis was done in November 2008 on 23 fields that were monitored for weed growth during the 2008/09 season. The results indicated that the sandy loam soils in Wards 12 and 14 were relatively acidic with low nutrient status (mean pH (water) 5.1 ±0.70, organic carbon 1±0.33%, total N 0.1± 0.037% and total P 0.04±0.016%).

The major crops grown in Wards 12 and 14 are maize (*Zea mays* L.), groundnuts (*Arachis hypogea* L.), bambarra groundnut (*Vigna subterranean* (L.) Verdc), finger millet (*Eleusine coracana* Gaertn.) and sweet potato (*Ipomea batatas* L.) Other crops include cowpea (*Vigna unguiculata* (L.) Walp), sunflower (*Helianthus annum* L.), sugar beans (*Phaseolus vulgaris* L.), sorghum (*Sorgum bicolor* (L.) Moench), pearl millet (*Pennisetum glaucum* (L.) R.Br.), water melon (*Citrullus lanatus* var. *lanatus* Thunb), cow melon (*Citrullus lanatus* var. *citroides* Thunb) and sweet sorghum (*Sorghum vulgare* Pers.). Crops such as cowpea, pumpkin, melons and sweet sorghum are grown as minor crops in maize and groundnut fields. Most farming systems are mixed crop/livestock systems with varying amounts of livestock such as beef cattle, goats and pigs kept.

5.2.2 Focus group discussion

Prior to the field study, focus group discussions were conducted in November 2008 in each ward. To select farmers who participated in FGD, a list of all farmers in the ward compiled by the AGRITEX officer was used to group farmers according to adoption or non-adoption of CF since its inception in 2004. This gave two groups, the CF and non-CF farmers. For the non-CF group, 20 farmers were randomly selected and invited to attend an FGD at the local ward meeting place on an appointed date. The CF group was further stratified into early and late adopters of CF and ten farmers were randomly selected from each group and invited to attend a separate FGD. The two FGD meetings were conducted on the same day but at different times per ward. The aim of the focus group discussion was to get a view of farmers' perceptions of constraints to crop production in CONV tillage and CF. Each focus group discussion lasted about 2 hours. In Ward 14, two separate focus group discussions were conducted and were attended by 16 non-CF and 15 CF farmers. However, in Ward 12 over 100 farmers were found assembled at the meeting point. The large turnout of mostly non-CF farmers may have been based on the farmers' hope that the meeting was convened for selection of new CF farmers by CARE International who would then be provided with inputs for use on CF fields. Due to the large number of participants and wet conditions on the day, only a single discussion was held in Ward 12. During each focus group discussion, notes were recorded on flip charts by the facilitator (researcher) and in a notebook by the co-facilitator (extension officer).

5.2.3 Field study

Farmers whose fields were monitored during the 2008/09 season were drawn from the sample of farmers that attended the focus group discussion in each ward. During the FGD, interested farmers were invited to participate in the study. From the group of interested non-CF farmers, farmers were selected based on the presence of field that had been under the same method of conventional tillage for a minimum of 5 years, farmer had not adopted CF on any of their fields in the previous seasons and field accessibility. In both wards, the majority of non-CF farmers used mouldboard ploughing tillage with some farmers without draught animal power using traditional hand hoe tillage. Six non-CF farmers (three per ward) were selected and the fields that were monitored ranged in size from 0.1 to 0.6 ha. Most of the fields monitored were outer fields that in the past four years (2005-2008) had had a two-year maize-groundnut rotation The majority of farmers used the ox-drawn Zimplow® VS200 mouldboard plough to prepare fields in early summer with planting done using third furrow planting. The decision to use farmers who had not previously adopted CF before was based on the observation that farmers that adopted a technology usually changed some of their traditional practices to those used in the new technology (Romney *et al*., 2005; Pedzisa *et al.*, 2010). This group is hereafter referred to as CONV tillage.

Since equilibrium after change in cultural practices including tillage usually occurs after the third year of practice (SWOARC, 1990; Ekboir, 2002) and high weed pressure under CF is believed to decline after three years (FAO, 2012), CF farmers were placed in two groups based on the number of years the field had been under CF. Those with 2 or 3 years' experience with CF comprised the first group and farmers with greater than 3 years of CF experience the other group. For CF, the years a field had been under CF, field accessibility, farmer willingness to participate and CF fields that had not been used as demonstration or experimental plots by CARE, ICRISAT or the extension officer were important considerations in selecting fields to be monitored. The fields that had been under CF for three years or less was viewed as being in the transition phase from CONV tillage practices to CF and is hereafter referred to as CF3-. The size of CF3- fields was 0.1 ha in Ward 12 and 0.05 ha in Ward 14 with the majority (78%) of fields were located close to the homestead. Fields where CF was practiced for more than three years were viewed as fields where CF was well established is hereafter referred to as CF3+. The size of fields was 0.1 ha in Ward 12 and 0.05 ha in Ward 14 as for the CF3- group. There was equal distribution of homestead and outer fields in the PB3+ group. A total of 23 farmers were selected with one of the farmers having both CF and CONV tillage fields to give a total of 24 fields (Table 5.1). In this study, all management decisions were determined by the farmer while the role of the researcher was to record operations and collect weed and crop data.

Table 5.1 Number of fields under different tillage systems monitored during the 2008/09 season in wards 12 and 14 of Masvingo district

Tillage	No. of fields in Ward		
	12	14	Total
CONV	3	3	6
PB3-	6	3	9
PB3+	3	6	9
Total			24

5.2.3.1 Soil weed seed bank

Soil samples were collected from the 24 fields from Wards 12 and 14 in mid-November 2008 before the onset of effective rains and the resultant first weed flush. A sampling net plot was demarcated in each field at least 2 m from the field border and two crossing diagonal transects were marked out. Four quadrats measuring 1 m x 1 m and spaced 5 m apart were aligned along each transect (Plate 5.1) to give 8 quadrats per field.

Plate 5.1 Soil sampling in CF farmer's field in Ward 14 of Masvingo District in November 2008.

In CONV tillage, one soil core (5.2 cm diameter and 15 cm depth) was obtained from one random position within each quadrat. Each soil core was separated into 0 - 5; 5 - 10 and 10 - 15 cm layers and the eight cores from the same depth were bulked to give three soil samples per CONV tillage field. This gave a cumulative surface area of ~ 170 cm^2 (volume 850 cm^3) sampled per field. In CF fields, quadrats were aligned so as to include four planting basins within the area to be sampled. Two soil cores were obtained per quadrat, one from within a randomly selected planting basin and the other soil core from the inter-row area adjacent to the basin. The soil cores from each sampling position (planting basin or inter-row area) were separated by soil depth (0 - 5; 5 - 10 and 10 - 15 cm) to give six soil samples per CF field. The cumulative surface area per sampling position in each CF field was the same as that in CONV tillage fields.

The 126 soil samples were partially air dried and clods broken after which the samples were stored in a cold room at 4 ^{0}C at Matopos Research Station until analysis. In December 2008, a sub-sample of 300 g was obtained per soil sample for weed seed bank analysis. Of the remainder, 50 g of the soil per field was sent for analysis of pH (water), % organic carbon; % total N and % total P using the standard methods outlined by Anderson and Ingram (1993). The weed seed bank was analysed using the seedling emergence method, which, although it can underestimate the absolute seed bank (Kellerman, 2004) provides a relative comparison to assess tillage effects (Carter & Ivany, 2006). Plastic pots (11.5 cm x 12 cm x 15 cm) were filled with silica sand and topped with the 300 g of sampled soil. The pots were watered and emerged weed seedlings were counted daily. Once counted weeds were removed to prevent self-seeding. Every fourth week, the soil was stirred to encourage weed germination and emergence. The experiment was terminated at the end of 16 weeks when there was no seedling emergence for three consecutive weeks.

Weed seed bank data analysis

Viable and non-dormant weed seed population per soil depth for each field was estimated by summing the number of seedlings counted over 16 weeks. The seedling numbers were then converted to weed density m^{-2} based on a 5.2 cm sampling core diameter. Relative importance values (RIV) were computed as the mean of the percentage relative density and relative frequency for each weed species (Chikoye & Ekeleme, 2001) per tillage system. Relative density (%) was calculated as the mean density of each weed species divided by the total weed density for that tillage system multiplied by 100. Relative frequency (%) was calculated as the frequency of individual weed species within each tillage system divided by the total frequency of all weed species in that tillage system multiplied by 100.

Seedling emergence (m^{-2}), species richness, Shannon's evenness and diversity index was calculated for each field. Shannon-Weiner' diversity index $H^{'}$ was calculated for each field after Magurran (1988) as follows:

$$H^{'} = (N \ln N - Sum (n \ln n)) / N \qquad \textit{Equation 1}$$

where H' measures species diversity through proportional abundance of species, with a higher value signifying greater diversity; *N* is the total population density m^{-2} and *n* is the population of each weed species found in this area;

and evenness index E

$E = H' / \ln N$ *Equation 2*

where E is the relationship between the observed number of species and total number of species, with a greater value indicating greater uniformity between species abundances.

Seedling emergence data was square-root ($x + 0.5$) transformed to homogenize variances (Gomez & Gomez, 1984). Weed data from the inter-row samples was used to determine tillage and soil depth effects on weed seed bank size and composition. In CF fields, sampling position (samples obtained from within planting basin and the inter-row area) and soil depth were the treatment factors in the seed bank analysis. The seedling emergence (m^{-2}), species richness, Shannon's evenness and diversity index data was subjected to an Unbalanced ANOVA (GenStat Release 9.1) and means were separated using the least significant difference (LSD) at $P < 0.05$.

5.2.3.2 Above-ground weed flora

Weed composition and density were estimated from the 24 experimental fields from Ward 12 and 14 during the period from November 2008 to April 2009. All weeds that were present in each of the 8 quadrats that had been used for soil sampling in November 2008 were identified to species level and counted. Thereafter, one quadrat from each diagonal transect was marked out with tall pegs and maintained as a permanent quadrat for weed assessments throughout the 2008/09 cropping season. Originally, weeds were to be sampled before each hoe weeding operation but since timing of weeding varied with farmer this approach was found to be difficult to implement. Furthermore, during the second weed survey some CF farmers reported that they had delayed weeding their fields until after the weed counts had been done and thus, this approach was interfering with farmer weed management. To avoid this, farmers were advised to weed their fields except for the area under the permanent quadrats. As from the third weed survey, weed counts were done when about 50% of farmers were observed to be weeding their fields and in this way weed counts were done during the main weeding period.

In addition to the weed count done at seed bank sampling, weed counts were done at 3, 7, 11 and 19 weeks after planting (WAP) based on the median planting date. In CF fields, weed counts were done separately for area within the planting basin and inter-row area per quadrat. The average planting basin area per field was recorded in November 2008 during the first weed count using basins within the eight quadrats. Field operations were recorded in a record book by farmers with the assistance of the extension officer. Farmers were also requested to record the time that they allocated to each weeding operation in monitored field. Daily rainfall was recorded during the season and crop yields were measured at harvesting.

Field data analysis

Farmers planted maize and groundnuts in fields during the 2009/10 season. However, only one CF farmer grew groundnuts compared to two in CONV tillage. Due to the low number of fields with groundnuts under CF, only the data from maize fields (n=21) was analysed. Weed density (m^{-2}) at soil sampling and 3, 7, 11 and 19 WAP and cumulative weed density after planting (3 to 19 WAP) were determined for each field during the 2008/09 cropping season. Relative importance values were computed for each weed species. Weed density data was log (x + 1) transformed to homogenize variances and the data was analysed for tillage effects and in CF sampling position effects.

A comparison of seed bank and above-ground weed floral composition was done using Sorenson's index of similarity (CC) as follows

$$CC = [2a/ (2a+b+c)]/100 \qquad \textit{Equation 3}$$

where a = number of species in common to the weed flora and seed bank in field x

b = total number of species present in seed bank in field x

c = total number of species present in the above-ground weed flora in field x

A higher index indicates strong similarity between seed bank and above-ground weed flora (Chikoye & Ekeleme, 2001).

Weed density and similarity indices were subjected to an Unbalanced ANOVA with Ward as the blocking factor as a prior analysis of weed density data using the residual maximum likelihood model (REML) method had indicated that the random variable Ward had a greater variance component than any of the management factors that differed across fields. These procedures were done using GenStat Release 9.1. For maize grain yield, REML was used to analyse the effect of tillage on crop grain yield. The REML method was used as it accounts for more than one source of variation. Random variables that had a significant relationship with maize grain yield were used to build the REML model as the random model. The structure of the REML model finally used in the analysis of maize grain yield was:

Response variate: Maize grain
Fixed model: Constant + Tillage system
Random model: % manure use + number of weedings
Weed density, similarity index and maize grain yield means were separated using LSD at $P < 0.05$.

5.2.4 End of season farmer-feedback workshop

At the end of the 2008/09 cropping season a one-day workshop was held in August 2009 at Great Zimbabwe Hotel in Masvingo District. Twenty-two of the farmers whose fields had been monitored, the two extension officers and two CARE agronomists attended the workshop. Among the workshop objectives was for farmers to identify, using photographs, weed species found in farmers' fields and indicate whether any weed species were beneficial. Afterwards, farmers were divided into two equal sized groups of CONV and CF farmers and each group was asked to use pair wise ranking to list the most abundant weed species (Plate 5.2). The exercise was facilitated by the extension officers and CARE agronomists. The final activity was for all farmers to ranks weeds in terms of how difficult they were to control using hoe weeding.

Plate 5.2 Farmers in CF group using pair wise ranking to determine most abundant weed species in CF fields at Great Zimbabwe Hotel, Masvingo District in August 2009

5.3 RESULTS AND DISCUSSION

5.3.1 Seasonal rainfall

A total rainfall of 602 mm was received between November 2008 and April 2009 (Fig. 5.1) which was within the range expected for this part of Masvingo District (FAO, 2009). There was an early onset of the rains with 31 mm recorded on 9 November 2008 (Day 10 in Fig. 5.1). The rains, however, ceased after three days and a dry spell was experienced for five weeks. The dry soil conditions led to poor crop establishment in CF where all fields had been planted with the first rains. As a result, some (35%) CF fields had to be re-planted in mid-December 2008 when rains resumed on 15 December 2008 (day 44). In CONV tillage, only one field was winter ploughed in July 2008 and maize was planted with the first rains in this field. Of the fields that were ploughed in the summer, ploughing with the first rains was done in only one field where groundnut was initially planted. However, crop establishment was poor in these early planted crops such that farmers planted another crop within the first crop. This resulted in a maize-sorghum intercrop in winter-ploughed field and a maize-groundnut intercrop in fielded ploughed with first rains. The two remaining CONV tillage fields were ploughed and planted to maize in late December 2008 after the rains were well established. In general, CF farmers planted maize at least 11 days earlier than CONV tillage farmers during the 2008/09 cropping season. Rainfall was well distributed from late December 2008 and no mid-season dry spells were experienced between January and February 2009. Hoe weeding commenced earlier and was done more frequently (thrice) in CF compared to CONV tillage (twice). However, no additional weeding was done after the third weeding in CF during the 2008/09 cropping season (Fig. 5.1).

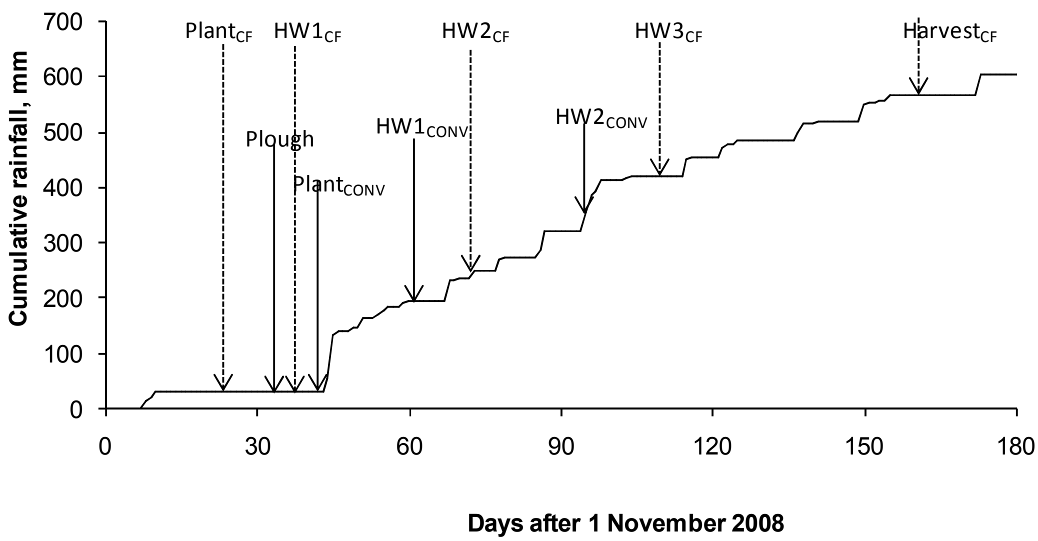


Fig. 5.1 Mean timing of field operations in CONV tillage and CF fields in relation to cumulative rainfall received between 1 November 2008 and 31 April 2009 in Wards 12 and 14 of Masvingo District. *Abbreviations*: CONV - mouldboard plough; CF - conservation farming and HW - hoe weeding

5.3.2 Adoption of CF practices by farmers

None of the monitored CF farmers whose fields were planted to maize during the 2008/09 season maintained a soil cover of at least 30% at planting. In the past four seasons all the CF farmers (n =17) had practiced maize monocropping on their CF fields. The only CF principle adopted by the monitored farmers was planting basin (PB) tillage for lengths of time varying from two to five years. Due to partial adoption of CF, the farmers previously referred to as CF3- and CF3+ will, hereafter, be referred to as PB3- and PB3+ , respectively.

5.3.3 Weed dynamics

5.3.3.1 Soil weed seed bank

Tillage system and soil depth did not have significant ($P > 0.05$) effects on total seedling density and density of individual weed species in the early summer soil weed seed bank of fields in Wards 12 and 14 during the 2008/09 cropping season. Tillage, however, had a significant ($P < 0.05$) effect on Shannon's weed species evenness (E) and diversity (H'). There was no significant ($P > 0.05$) tillage system x soil depth interaction on weed seedling density and seed bank community diversity. In the PB system position of sampling, PB years, soil depth and their 2-way and 3-way interactions did not have significant ($P > 0.05$) effects on weed seed bank size and composition.

5.3.3.1.1 Seed bank structure

A total of 18 weed species was identified in the soil seed bank with 8 weed species present in the CONV tillage seed bank compared to 14 species in each of the PB 3- and PB 3+ seed banks (Table 5.2). The annual monocot *E. indica* had the highest relative importance value (RIV) regardless of tillage system. After *E. indica*, the ranked order of weed species varied with tillage system. The grass weed *Cynodon dactylon* was the third most important species in the PB3- seed bank but was less important (RIV < 10) in CONV tillage and PB 3+. The fields that had been under PB for the longest time had *Galium spurium* as the second most important weed species in the seed bank suggesting that this weed may becoming more important with time under PB. The weed *Eragrostis aspera* that was absent from CONV tillage seed bank was a moderately important weed in the PB seed bank. The weed seed bank community under PB comprised a number rare (RIV < 10) weed species that were absent from CONV tillage seed bank (Table 5.2). The difference in importance of several weed species in the seed bank community under CONV and PB tillage systems may be suggestive of changes in weed seed bank community diversity.

Table 5.2 Relative importance value (%) of weed species occurring in the sampled early summer seed bank under the different tillage systems in 2008 in Masvingo District. Weed species ranked according to importance in CONV tillage

Latin name	Growth form[a]	RIV (%) in tillage system		
		CONV	PB3 -	PB 3+
Eleusine indica (L.) Gaertn.	Annual monocot	55.6	55.2	51.5
Cyperus esculentus L.	Perennial monocot	27.3	32.2	29.5
Richardia scabra L.	Annual dicot	19.0	17.5	21.2
Leucas martinicensis (Jacq.)R.Br.	Annual dicot	17.8	11.9	29.0
Galium spurium L. ssp. *africanum* Verdc	Annual dicot	11.8	13.6	30.5
Cynodon dactylon (L.) Pers.	Perennial monocot	9.0	23.6	5.8
Hibiscus meeusei Exell	Annual dicot	8.9	18.0	5.8
Phyllanthus leucanthus L.	Annual dicot	8.9	-	5.8
Eragrostis aspera (Jacq.) Nees	Annual monocot	-	17.8	11.7
Sida alba L.	Perennial dicot	-	11.7	-
Amaranthus hybrius L.	Annual dicot	-	5.8	-
Corchorus tridens L.	Annual dicot	-	5.8	5.8
Gnaphalium pensylvanicum Willd	Annual dicot	-	5.8	-
Ipomea plebia L.	Annual dicot	-	5.8	-
Solanum incanum L.	Perennial dicot	-	5.8	5.8
Acanthospermum hispidum DC.	Annual dicot	-	-	5.8
Cleome monophylla L.	Annual Dicot	-	-	5.8
Commelina benghalensis L	A/P monocot	-	-	5.8

A '-' indicates that a weed species was absent in a given tillage system; [a]A/P: annual / perennial. *Abbreviations:* CONV, moudboard plough; PB3-, planting basin period of 2 or 3 years; PB3+, planting basin for > 3 years

5.3.3.1.2 Tillage effect

There was no evidence of a decline in the total seedling density of the soil weed seed bank with years under PB as seed bank size did not differ ($P > 0.05$) between CONV and PB tillage systems. The upper 15 cm soil weed seed bank was estimated 422 seedlings m^{-2} for CONV tillage, 760 seedlings m^{-2} for PB3- and 655 seedling m^{-2} in PB3+. There was also no difference in weed seed distribution through the 15 cm soil layer between CONV and PB systems. In all tillage systems most weed seed was found in the upper 10 cm soil layer. Tillage, however, had a significant ($P < 0.05$) effect on weed seed bank diversity with a two-fold increase in the Shannon's evenness and diversity indices recorded in the PB seed bank compared to that under CONV tillage (Table 5.3). This indicated an increase in weed diversity in CF systems relative to CONV tillage although the length of time a field had been under PB had no significant effect on seed bank diversity.

The greater diversity in the PB seed bank was probably due to the wider ranger of weed species in PB relative to CONV tillage (Fig. 5.2). Although the nine additional weed species found in the PB seed bank had low relative importance values their increased relative density in PB (Fig. 5.2) probably contributed to the more equitable distribution of species and higher weed diversity in PB compared to the CONV tillage seed bank (Table 5.2). The presence of these rare species only in the PB seed bank may suggest that the PB system or cultural practices associated with PB may be introducing seeds of the rare weed species to the soil seed bank. The presence of *Amaranthus hybridus* and *Corchorus tridens* in the PB seed bank only (Table 5.2) suggests that these weed species may have been introduced by application of manure as the species were found to be usually abundant in poorly cured manure by Rupende *et al*. (1998). The higher weed seed bank diversity in PB may, if reflected on the above-ground flora, facilitate weed control in PB. According to Miyazawa *et al*. (2004) high weed community diversity may enhance competition among weed species and prevent the dominance of a single weed species especially if this is a problem weed in arable fields. This would result in reduced weed/crop competition if problem weed species is replaced by less competitive weed species.

Table 5.3 Weed community diversity for the early summer weed seed bank under different tillage systems in Wards 12 and 14 of Masvingo District in 2008

Tillage system	Shannon's	
	Evenness (E) index	Diversity (H') index
CONV	0.30	0.31
PB3-	0.68	0.60
PB3+	0.65	0.81
LSD $_{(0.05)}$	0.320	0.379

Abbreviations: CONV, mouldboard plough; PB3-, planting basin for 2 or 3 years or less; PB3+, planting basin for > 3 years. LSD - least significant different; ns - not significantly different.

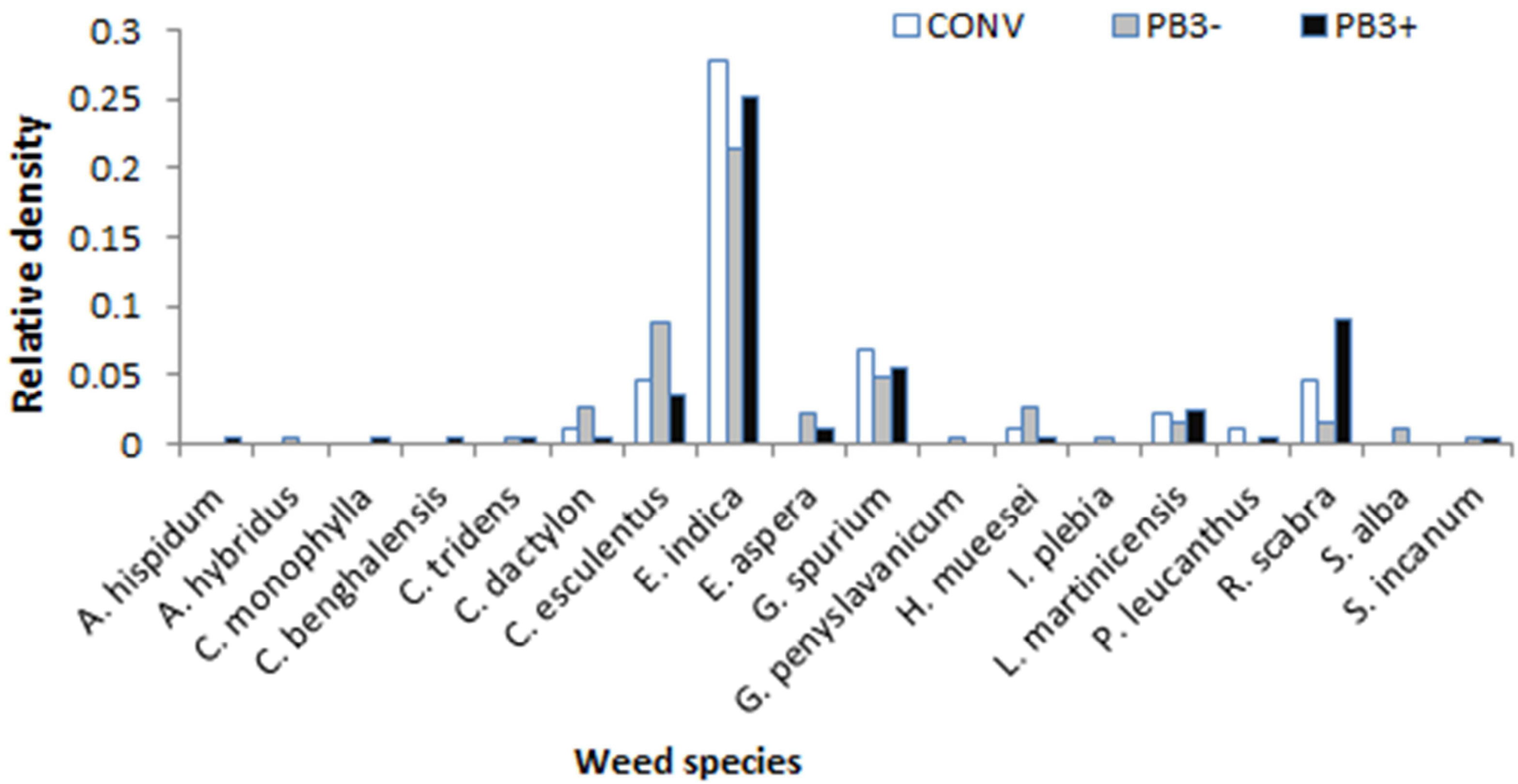


Fig. 5.2 Relative density of weed species found in the early summer seed bank of fields under three different tillage systems in Wards 12 and 14 of Masvingo District in 2008. *Abbreviations:* CONV, mouldboad plough; PB3-, planting basin for 2 or 3 years; PB3+, planting basin for > 3 years

5.3.3.2 Above-ground weed flora

5.3.3.2.1 Weed composition

Nineteen weed species were identified in maize fields during the 2008/09 season (Table 5.4) of which 15 species were also found in the soil seed bank (Table 5.2). However, *B. pilosa, D. stramonium, Digitaria* spp. and *S. asiatiaca* were not identified in seed bank while *S. alba* was not sampled in any of the fields during the maize growing period. The weed species *S. asiatica* was not present in the weed seed bank because there was no cereal host in the plastic pots used for seed bank enumeration. Most of the species that were not common to both seed bank and above-ground weed flora were usually identified in only one tillage system. Furthermore, the weed species had low RIVs showing that they were not generally important weed species in the study area. The ranking of the top five weed species based on RIV was influenced by tillage system. The top three weed species varied with tillage system but were found in all the tillage systems. In CONV tillage fields*, R. scabra* (73%) was the most important species followed by *C. dactylon* and both *L. martinicensis* and *A. hispidum*. In PB3- fields, *A. hispidum* had the highest RIV (62%) followed by *L. martinicensis* and *R. scabra*. The most important weeds in PB3+ were *R. scabra* (64%), followed by *L. martincensis* and *A. hispidum*.

However, the weed species *E. indica* which was the most important in the seed bank (Table 5.2) was not among the three most important weeds in the above-ground weed flora (Table 5.4) although it was still an important weed in all the tillage systems. In the seed bank, *A. hispidum* was identified only in PB3+ and had an RIV of less than 10 (Table 5.2) but in the field this weed was among the most important weed species in all the tillage systems. Such differences in the representation of weeds in the seed bank and above-ground flora were a reflection of the low Sorenson' similarity index recorded. All tillage systems had low similarity index of below 25 which indicated a weak relationship between weed species in above-ground flora and seed bank. This poor correlation in weed flora in soil seed bank and above-ground was also observed in studies by Chikoye and Ekeleme (2001) and Kellerman (2004) among others. Swanton and Booth (2004) state that the weed seed bank is at best a weak predictor of present above-ground flora as the transition from seed to seedling and finally to mature plant depends on many factors that may have varied between fields and the uncontrolled glasshouse where the seedling emergence method was used for weed seed bank estimation.

Table 5.4 Relative importance value (%) of weed species occurring above-ground in maize fields under different tillage systems during the 2008/09 season in Wards 12 and 14, Masvingo District. Weed species were ranked according to importance in CONV tillage

Latin name	Growth form	RIV (%) in Tillage system		
		CONV	PB3-	PB3+
Richardia scabra L.	Annual dicot	72.9	55.1	63.7
Cynodon dactylon (L.) Pers.	Perennial monocot	62.2	29.7	20.8
Acanthospermum hispidum DC.	Annual dicot	53.0	61.9	52.0
Leucas martinicensis (Jacq.)R.Br.	Annual dicot	53.0	55.2	60.4
Hibiscus meeusei Exell	Annual dicot	51.9	46.7	15.2
Ipomea plebia L.	Annual dicot	38.9	14.3	47.7
Eleusine indica (L.) Gaertn.	Annual monocot	28.0	33.9	44.9
Digitaria spp.	Annual monocot	26.2	11.4	12.4
Commelina benghalensis L	A/P monocot	25.8	29.7	40.2
Cyperus esculentus L.	Perennial monocot	13.0	5.9	13.1
Eragrostis aspera (Jacq.) Nees	A/P monocot	12.6	5.6	-
Galium spurium L. ssp. *africanum* Verdc	Annual dicot	12.6	5.6	19.2
Gnaphalium pensylvanicum Willd	Annual dicot	12.5	5.9	37.7
Amaranthus hybridus L.	Annual dicot	-	11.2	29.1
Bidens pilosa	Annual dicot	-	11.2	-
Cleome monophylla L.	Annual Dicot	-	5.6	25.1
Striga asiatica L.	Annual dicot	-	5.6	12.5

A '-' shows that weed species was absent in a given tillage system; A/P: annual or perennial; *Abbreviations:* CONV, mouldboard plough; PB3-, planting basin for 2 or 3 years; PB3+, planting basin for > 3 years

5.3.3.2.2 Weed density

There was no significant (P > 0.05) difference in the weed density measured in maize fields under different tillage systems during the 2008/09 cropping season (Fig. 5.3). The lack of a tillage effect on weed density differs from findings from other research done in southern Africa where MT systems were associated with increased weed density especially early in the cropping season (Mabasa *et al.*, 1998; Muliokela *et al.*, 2001; Mashingaidze *et al.*, 2009b; Chapter 3). The lack of significant differences in weed emergence early in the 2008/09 cropping season between PB and CONV tillage fields in Wards 12 and 14 of Masvingo District may have been influenced by differences in weed management between the tillage systems.

The PB farmers in Wards 12 and 14 performed the first hoe weeding earlier than in CONV tillage fields (Fig. 5.1). The majority (53%) of PB fields were hoe weeded within the first week after maize was planted compared to CONV tillage where hoe weeding began three weeks after planting. As a result, the first hoe weeding was done at least 15 days earlier ($P < 0.05$) in PB compared to CONV tillage during the 2008/09 cropping season. The early weeding in CF is suggestive of high weed pressure soon after planting in these fields. Bullied *et a*l. (2003) reported that MT systems may be associated with earlier weed emergence than conventional plough tillage. Research done by Shumba *et al*. (1992) and Vogel (1994) demonstrated higher weed growth soon after planting in MT systems relative to conventional plough tillage that necessitated earlier and more frequent weeding in MT systems compared to conventional tillage. As the area under the quadrats was weeded during the first hoe weeding in the majority of PB fields, the early weeding in PB probably masked any differences in weed density at 3 WAP between PB and CONV tillage. A high level of weed management has been found to diminish the differences in weed infestation between tillage systems (Locke *et al*., 2002; Chapter 3). However, the findings of this study are not conclusive it may be that PB farmers were following the CF recommendations of frequent weeding with the aim of maximising maize yield in these PB fields that received both organic and inorganic fertilisers. There is need for further weed assessments that are carried out before farmers hoe weed their fields to determine whether PB fields are associated with higher early season weed infestations than CONV tillage.

There was no significant ($P > 0.05$) difference in timing and frequency of hoe weeding between PB3- and PB3+ farmers during the 2008/09 season implying that labour requirements in PB3+ had not yet gone down even after five years of PB. Since maize residue mulching offered limited weed suppression and resulted in increased weed growth under CA (Chapter 3 and 4), there is a need to investigate the use of herbicides to reduce the labour bottlenecks experienced early in the cropping season for CF farmers. One option for reducing the costs associated with herbicide use could be banding of herbicides. Previous work done in maize grown under ripper tine on smallholder farms in Zimbabwe demonstrated that labour for hoe weeding could be significantly reduced through either full cover or banded application of 50% of the recommended rate of atrazine (Gatsi *et al*., 2001). Positive returns to land, labour and draught animal power were obtained for application of atrazine in maize grown under ripping in this case.

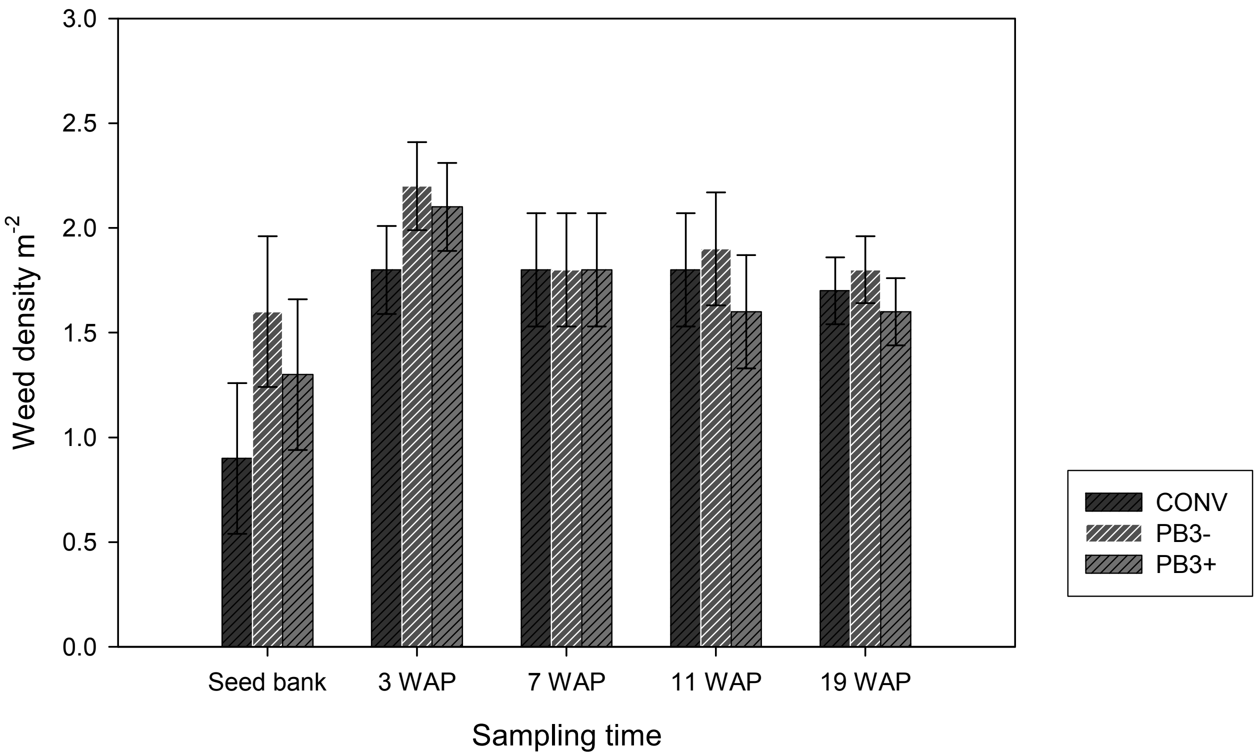


Fig 5.3 Mean weed density in maize fields at different times during the 2008/09 cropping season in Wards 12 and 14 of Masvingo district. Log (x + 1) data presented. Narrow bars present ±sed *Abbreviations*: WAP - weeks after planting; CONV, mouldboard plough; PB3 planting basin for 2 or 3 years; PB3+, planting basin for > 3 years

Although there was no significant difference in weed community diversity between PB and CONV tillage during the 2008/09 season in Wards 12 and 14, there were differences in the density of some weed species. The weed *A. hispidum* occurred in greater density in PB3- than in the other tillage systems after harvesting (Table 5.5). This weed is difficult to control as it produces multiple generations within one season (Chivinge *et al*., 1988). Since none of the PB3- farmers removed weeds at harvesting (Fig. 5.1), the increase in density of *A. hispidum* after harvesting may lead to high weed infestations in the future due to increased seed bank return. The seeds of *A. hispidum* can persist in the soil for more than 12 years (Schwerzel & Mabasa,

1986) so potentially any additional seed input can exacerbate problems in controlling this weed. Farmers in both Wards 12 and 14 performed the last hoe weeding in CF fields between late February and mid-March 2009 and this provided time for late season weeds such as *A. hispidum* to reach reproductive maturity (Plate 5.4) and subsequently replenish the seed bank before the dry season weeding was done from July. Farmers in both Wards 12 and 14 performed the last hoe weeding in PB fields between late February and mid-March 2009 and this provided time for late season weeds such as *R. scabra* to reach reproductive maturity (Plate 5.4) and subsequently replenish the seed bank before the dry season weeding was done from July. There is, therefore, a need to emphasise late season weeding in PB as farmers only confined frequent weeding to early in the cropping season. However, there is likely to be labour bottlenecks for weeding the early planted PB fields and harvesting late planted crops before livestock are set into the field.

Minimum tillage fields were, however, associated with significantly reduced density of *C. dactylon* with the effect significant ($P < 0.05$) at 7, 11 and 19 WAP (Table 5.5) relative to CONV tillage fields that had at least double the density of *C. dactylon* found in PB fields. This might be due to the smallholder farmer practices of ploughing followed by harrowing which generally propagated *C. dactylon* in fields as reported by Mabasa *et al*. (1995). The encroachment by *C. dactylon* into MT fields reported by Vogel (1994) and Makanganise *et al*. (2001) was not observed in PB fields monitored in Wards 12 and 14.

Table 5.5 Weed seedling density (m^{-2}) under maize of *A. hispidium* and *C. dactylon* under different tillage systems during different sampling periods in 2008/09 season in Wards 12 and 14 in Masvingo District

Tillage system	Weed density m^{-2} at WAP							
	A. hispidum				*C. dactylon*			
	7	11	19	Total	7	11	19	Total
CONV	3.2	1.2	1.2	4.6	1.3	1.2	1.1	1.8
PB3-	2.7	2.9	2.8	10.3	0.4	0.3	0.2	0.9
PB3+	2.1	1.0	1.2	5.1	0.2	0.2	0.2	0.3
LSD $_{(0.05)}$	ns	ns	1.47	ns	0.72	0.66	0.47	0.92

. Log (x + 1) transformed data presented *Abbreviations:* WAP – weeks after planting; CONV, mouldboard plough; PB 3-, 2 or 3 years under PB; PB 3+, > 3 years under PB; LSD - least significant difference; ns - not significantly different.

Plate 5.4 Harvested but un-weeded PB field in fifth year next to yet to be harvested conventional tillage maize crop in April 2009 in Ward 12, Masvingo District. *Abbreviations:* PB – planting basin

5.3.3.2.3 Influence of cultural practices on weeds under PB tillage

Total weed density during the 2008/09 season was between 200 and 600 weeds m^{-2} in most CONV and PB fields (Fig. 5.4). However, a few PB fields had a density of over 1 000 weeds m^{-2} which probably implied that factors other than tillage may have accounted for the high weed density in these fields. The differences in weed densities were reflected in time required for hoe weeding which ranged from 30 hours ha^{-1} to 420 hours ha^{-1} per weeding operation. Farmers identified the level of weed infestation and type of weeds as the main reasons for a lengthy hoe weeding operation. The three fields with the highest cumulative weed density (Fig. 5.4) also recorded the highest weed density at 3 WAP. The high weed infestations in these three PB fields were explained by the fact that at the time of the second weed count none of the three fields had yet received the second weeding in contrast to the other PB fields. The field with the fourth highest weed density recorded the highest weed density at seed bank sampling at which time the field had not yet been weeded. The differences in these outlier fields compared to other fields without early weeding it was highly probable that PB fields had higher weed density than CONV tillage fields early in the season as was observed at Matopos Research Station (Chapter 3).

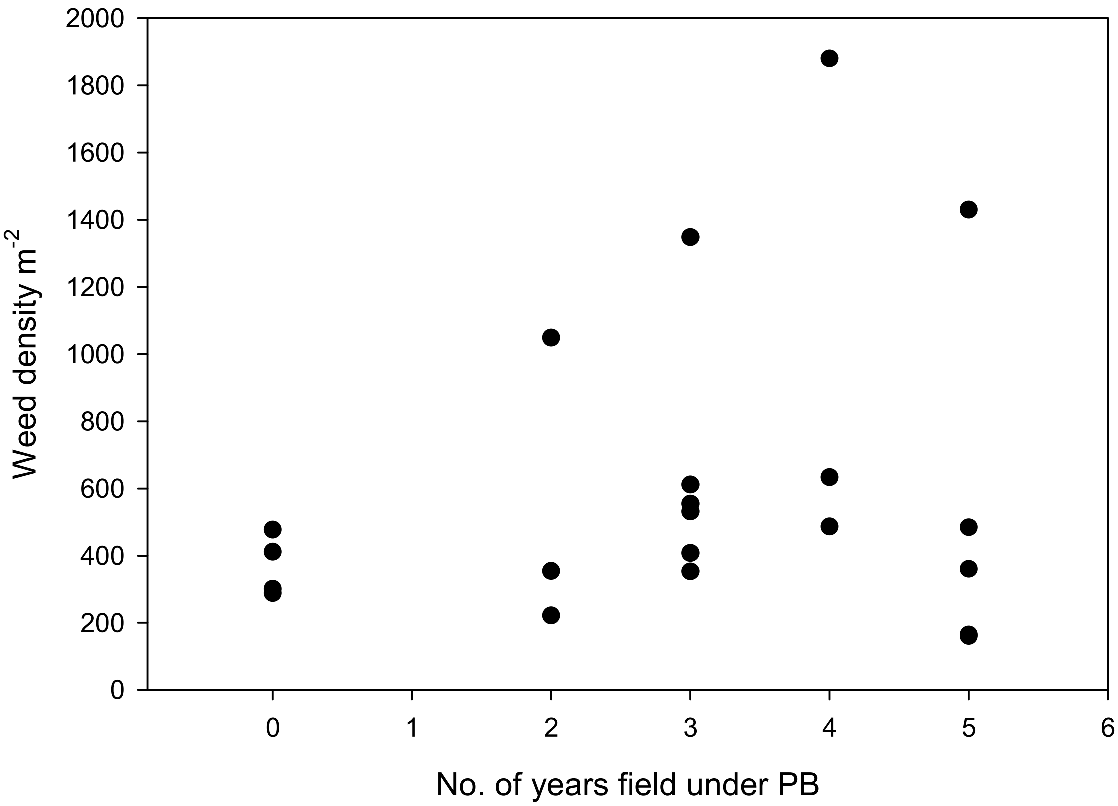


Fig. 5.4. A scatter-plot of the distribution of cumulative weed density (m^{-2}) in maize fields that had been under PB for different years in Wards 12 and 14 of Masvingo District during 2008/09 season. O (zero) years represents CONV tillage. *Abbreviation*: PB – planting basin ; CONV tillage - conventional mouldboard plough

A comparison of weeds within the planting basins and the inter-row area in PB fields indicated that planting basins had higher ($P < 0.05$) weed density throughout the 2008/09 cropping season than the inter-row area (Table 5.6). Significantly higher densities of *A. hispidum*, *E. indica*, *I. plebia* and *R. scabra* were found within planting basins than in the inter-row area (Table 5.7). A number of factors could be responsible for the higher weed density in planting basin than the inter-row area. The area within the planting basin was disturbed to a greater depth than the inter-row area and during basin preparation seeds that were previously buried may have been exposed to conditions suitable for germination resulting in increased seed germination. Secondly in PB, both organic and inorganic fertilisers are precision applied within the planting basin (ZCATF,

2009) and over time an area of high fertility may have been created in planting basins compared to the inter-row area in farmers' fields. Addition of nutrients can increase the germination of some nitroliphic weed seeds and / or lead to increased weed growth due to improvement in fertility of nutrient poor soil (Major *et al*. 2005). However, no significant relationship was found between the applied amount of compound D, AN, total and available N at planting and weed density during the 2008/09 season in this study.

Apart from improving soil fertility, addition of organic fertiliser may have also introduced weed seeds into the planting basins. Poorly processed or composted manure can be a source of additional weed seeds that will emerge during the cropping season. The weed species *A. hispidum*, *E. indica* and *R. scabra* that were found in higher numbers in planting basins in this study (Table 5.7) were among weed species that were reported to be spread in manure by Munguri *et al*. (1995) and Rupende *et al*. (1998). This together with the presence only in the PB seed bank of species such *Amaranthus hybridus* and *Corchorus tridens* that are associated with manure use (Table 5.2) suggested that the frequent use of manure in PBmay be contributing to increased weed infestations inPB. Since information on the amounts of manure applied during the 2008/09 season was not available for most farmers, the relationship between frequency of manure use in the past four seasons (2005/06 to 2008/09 seasons) and weed density during the 2008/09 season was investigated. This revealed a weak ($R^2 = 0.38$) but significant ($P < 0.05$) relationship ($y = 0.003x^2 – 0.22x + 13.11$) between weed density at 3 WAP and frequency of manure use that suggested that the annual application of manure in PB may have been associated with an increase in weed density. Although the planting basin covered less than 20% of PB fields, introduction of new seeds through manure use could have led to increased weed infestations with time in PB when some of weeds escaped control and set seed that was later dispersed to the rest of the PB field. In addition the high soil moisture content reported in PB may have resulted in more vigorous weed plants within basins that without control added to the seed bank.

An implication of the high weed density within the planting basin was that of increased interference as the majority of weeds were in close proximity to the two maize plants grown per planting basin. Rambakudzibga *et al*. (2002) reported that maize grain yield was significantly lower with E. *indica* within 20 cm of maize row than with double the *E. indica* density spaced 40 cm away from maize row. The weed species *A. hispidum*, *E. indica*, *I. plebia* and *R. scabra* thst had high density within planting basins were identified as aggressive weeds by smallholder farmers in Masvingo Province in a survey carried by Chivinge (1988). Thus, weeds within the planting basin were likely to be more competitive than those in the inter-row area. It is recommended that farmers with labour constraints must remove the weeds growing within the planting basins before the ones in the inter-row area to avert significant crop yield loss.

Table 5.6 Weed density within basin and in the inter-row area in maize grown under PB fields in Masvingo District in 2008/09

Sampled	Weed density (m^{-2}) at sampling period					
area	Seed bank	3 WAP	7 WAP	11 WAP	19 WAP	Total§
In basin	13.8	22.6	15.9	14.4	11.8	40.7
Inter-row	7.2	12.0	7.5	7.8	7.0	20.9
LSD $_{(0.05)}$	5.87	6.55	5.14	3.90	2.48	8.18

§Total: cumulative of 3, 7, 11 and 19 WAP. Square-root (x + 0.5) data presented *Abbreviations:* WAP - weeks after planting; LSD - least significant different; ns - not significantly different

Table 5.7 Density of specific weeds∞ within basin and in the inter-row area in maize grown under basin fields in Masvingo District in 2008/09

Sampled area	Weed density m^{-2}				
	A. hispidum	*E. indica*	*H. mueesei*	*I. plebia*	*R. scabra*
In basin	12.0	5.2	6.6	12.6	18.5
Inter-row	6.9	2.	3.4	5.5	9.3
LSD $_{(0.05)}$	4.8	2.3	2.2	5.9	5.2

∞ Weed species that showed significant differences; §Total: cumulative of 3, 7, 11 and 19 WAP. Square-root (x + 0.5) data presented *Abbreviations:* LSD - least significant different; ns - not significantly different

5.3.4 Maize grain yield

Planting basins produced double ($P < 0.01$) the maize grain yield obtained in CONV tillage with the highest mean maize grain yield obtained from PB3+ (mean: 2 856 kg ha^{-1}). Maize grain yield increased ($P < 0.001$) with the number of years a field had been under PB (Fig. 5) probably as a result of better crop management in soil fertility and weeding in CF. There was a positive (R^2 = 0.38; $P < 0.01$) correlation between frequency of manure use and maize grain yield that showed that fields that frequently received manure were associated with high maize grain yield. Mutiro & Murwira (2004 reported that manure increased maize yield in the second and third year of application. Planting basin fields were probably benefiting from the annual application of manure compared to CONV tillage where manure was applied after three or four seasons.

The importance of weeding early in the cropping season was demonstrated by the relationship between weed density at 3 WAP and maize grain yield (Fig. 5.6) that showed that high weed density at 3 WAP was associated with low maize grain yield. This period falls within the critical period of weed control for maize which is reported to be between 2 and 6 weeks after crop emergence (Zimdahl, 1999; Mashingaidze, 2004). Similar yield increases of above 100% have been reported before for CF relative to CONV tillage by Mazvimavi and Twomlow, (2009) and Marongwe *et al*. (2011) in semi-arid Zimbabwe. The three fields that had the highest cumulative weed density in Fig 5.4 are the same outliers in Fig. 5.6 where, despite the high weed infestations in these fields high maize yields were still obtained. The high weed infestations were a result of weed density recorded at 3 WAP before the fields were weeded. However, the fields were weeded soon after the weed counts and the third weeding was done 15 days later. This frequent weeding averted any significant yield loss in these fields. The subsequent removal of the weeds after the weed sampling was not taken into account in the regression analysis presented. The four sites with low weed densities at 3 WAP but low maize grain yield are CONV tillage fields where poor weed management and low use of fertilisers probably contributed to reduced maize grain yield compared to PB plots.

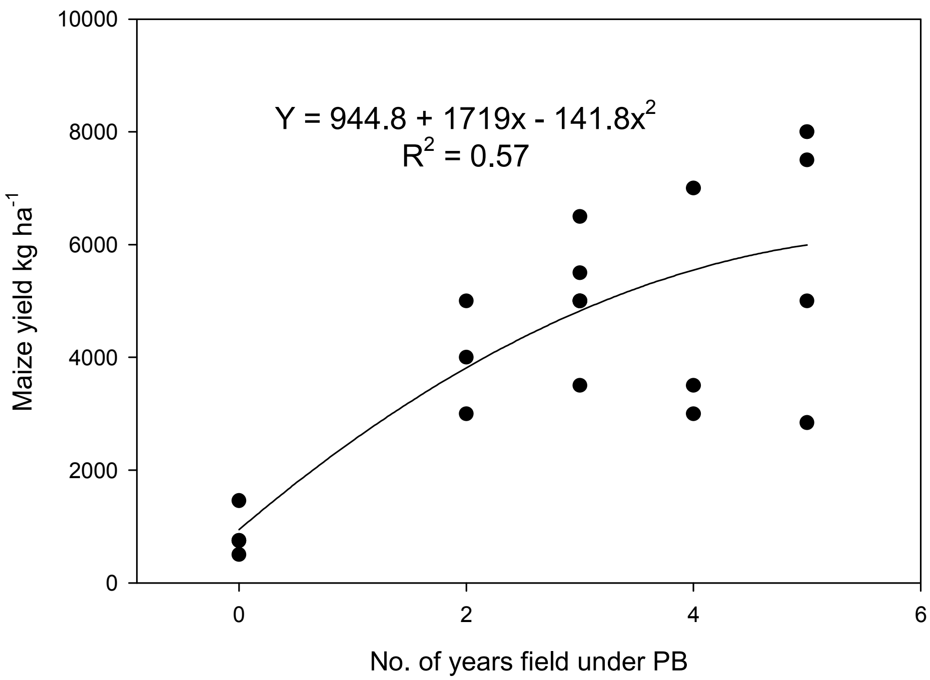


Fig. 5.5 Relationship between the number of years a field had been under PB and maize grain yield obtained from farms in Wards 12 and 14 of Masvingo District during the 2008/09 season. *Abbreviations*:PB– planting basin

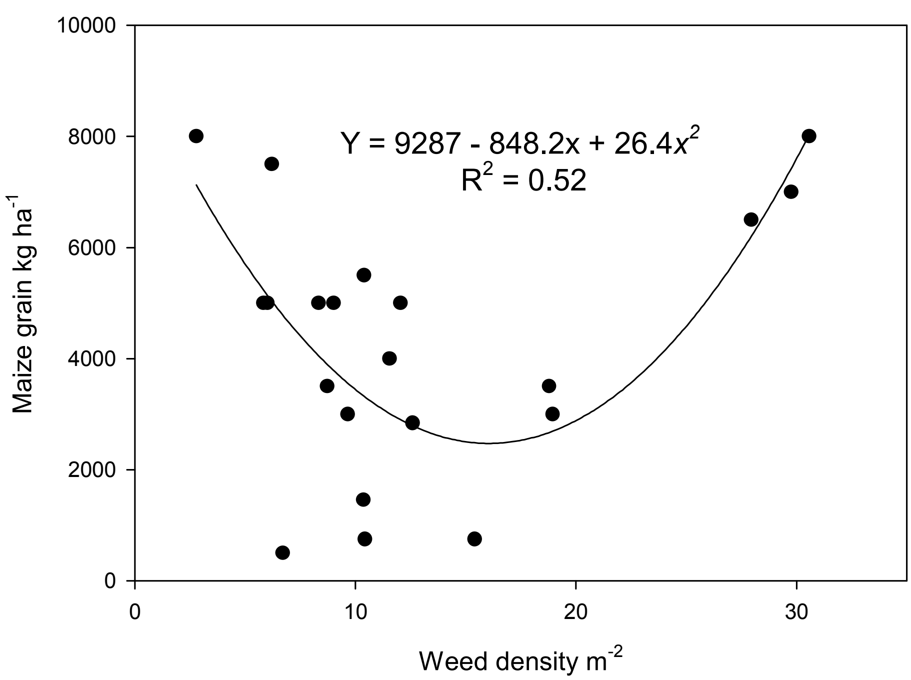


Fig. 5.6 Relationship between weed density at 3 weeks after planting and maize grain yield obtained from farms in Wards 12 and 14 of Masvingo District during the 2008/09 season

5.3.5 Farmer perceptions

5.3.5.1 Constraints to crop production

The same four factors were identified as the main constraints to crop production in Wards 12 and 14 by both CONV and PB farmers in November 2008 at the start of the study (Table 5.8). Most of the farmers in the CONV tillage group did not receive seeds and fertiliser from CARE and identified lack of inputs as the major constraint that often resulted in 50% or less of available land being cropped. Labour especially for weeding was the second most important constraint to CONV tillage farmers as most did not have implements such as cultivators to use for weeding. Farmers close to Lake Mutirikwi (Ward 14) identified hippos as a major constraint resulting in abandonment of some outer fields. The ranking of constraints in PB was low rainfall > input availability > labour > pests. The area under PB was equivalent to the inputs most farmers received from CARE International. When CONV tillage farmers were asked why they had not adopted CF, they cited the unavailability of fertiliser as the main reason. Most farmers perceive that without fertilisers there would be limited yield benefits to PB. Under the low areas committed to PB weeds could be managed with available family labour. These findings are in contrast to Marongwe *et al*. (2011) who observed that the high labour requirement, especially for weeding, was the main constraint under PB on most smallholder farms in Zimbabwe. Although not the most important constraint, labour availability was identified as a constraint suggesting that even if more inputs became available for use under PB, labour requirements would ultimately limit the area under PB. There is, therefore, a need to address both the issue of input availability and alternative weed control strategies to reduce the labour required for land preparation and weeding under PB. This would result in an increase in the area under smallholder PB and given the higher yields reported under PB, is likely ensure food security for most smallholder households.

Table 5.8 Constraints to crop production ranked in order of importance by CONV tillage and PB farmers in Wards 12 and 14 of Masvingo District in November 2008

Rank	Conventional tillage farmers	Planting basin
1	Lack of inputs.	Low rainfall.
2	Labour especially for weeding.	Input availability.
3	Pests such as hippos, cut worms.	Labour for digging basins, weeding and collecting forest litter.
4	Rainfall availability.	Pests such as termites, hippos, baboons.

5.3.5.2 Important weeds

The ranking of the important weed by CONV tillage farmers (Table 5.9) was in agreement with results from the field (Table 5.4). However, in PB only 3 of the weeds ranked as the most abundant by farmers were also identified as the most important weed species in monitored fields. Conservation farmers ranked *C. dactylon* as the second most abundant species in their fields (Table 5.9) although field studies had revealed the species to be less important in PB compared to CONV tillage. The low weed sampling intensity (2 quadrats per field) used in this study may be the reason for the difference in the ranking of *C. dactylon* from field monitoring and by farmers using pairwise ranking. The weed usually occurs in patches which were probably missed in some fields due to inadequate sampling.

Based on farmer observations, there appeared to be no marked shift in weed species in fields where CONV tillage was replaced by PB as the same weed species were identified as the most abundant in both systems. This agrees with results from the observational field study done during the 2008/09 season. The farmers were aware of the biological adaptations of the weed species and the limitations in their current weeding methods that allowed these weed species to persist in large numbers in their fields (Table 5.9).

The weed *C. dactylon* was identified as the most problematic weed in both CONV tillage and PB fields (Table 5.10) probably because of the difficulties faced by farmers in effectively controlling it using hoe weeding. The species *C. dactylon, R. scabra* and *A. hispidum* that were identified by farmers as difficult to control and problematic were among the most important weed species in fields during the 2008/09 season. Although the density of *L. martinicensis* was high in PB the weed was not identified as a problematic weed by farmers. However, not all the 20 weed species were undesirable as over 70% of identified weeds were reported to be beneficial to farmers. Among the benefits was use of species such as *Amaranthus* species, *B. pilosa*, *C. monophylla* and *C. tridens* as relish. The tubers of *C. esculentus* were also reported to be consumed by farmers. Some weeds were reported to have medicinal properties with *A. hispidum* and *O. latifolia* used to treat sores and *B. pilosa* identified as a traditional asthma treatment. The grass weed *E. indica* was used to make compost by farmers. Some weeds provided food for different types of livestock found on the farm. The species *L. martinicensis*, *I. plebia* and *C. benghalensis* were fed to rabbits and pigs while *R .scabra* and *Digitaria* spp. were fed to livestock including cattle. Some farmers reported not weeding fields after harvesting so that their livestock could graze on the weeds during the dry season. Since farmers often left out some of these beneficial weed species during hoe weeding, the use of herbicides such as glyphosate that indiscriminately kill all weeds may not be suitable under smallholder conditions. This may explain the observation made by Baudron *et al*. (2007) that some smallholder farmers are reluctant to use herbicides.

Table 5.9 Ranking of the five most abundant weeds in CONV and PB fields in Wards 12 and 14 of Masvingo District, August 2009

Weed	CONV rank	PB rank	Reasons given for ranking by farmers
C. dactylon	1	2	1. It is found in all crops and all types of fields. 2. Weed spreads during weeding and grows more vigorously than before. 3. It is not easily controlled by hoe weeding. 4. Plant has deep roots which help in spreading it so difficult to kill. 5. It regenerates easily in wet soil.
R. scabra	2	1	1. Weed produces a high number of seed. 2. Species has early vigorous growth and found in large numbers. 3. It is difficult to kill when weeding and re-grows if it rains. 4. Seed dispersed by wind and water.
A .hispidum	3	-	1. It has high seed production. 2. Weed can re-grow if it rains soon after weeding.
Digitaria spp.	4	4	1. It spreads rapidly through the field. 2. It can re-grow if it rains after weeding. 3. It has high seed production. 4. Difficult to weed due to dense root system.
H. mueesei	5	5	1. It has a high seed production. 2. It has a dense root system which makes it difficult to uproot and weed.
L. martinicensis	-	3	1. Weed has high seed productivity. 2. Seed dispersed by run-off water and wind. 3. It is also spread by livestock.

Abbreviations: CONV - conventional moudboard plough; PB – planting basin

Table 5.10 The five most difficult to control weeds ranked by farmers in Wards 12 and 14 of Masvingo District in August 2009

Number	Weed	Reasons given for ranking by farmers
1	*C. dactylon*	1. It spreads during weeding process 2. It has a deep root so difficult to kill. 3. If soil is wet, it re-grows soon after weeding. 4. It multiplies by both seed, stolons and tubers
1	*E indica*	It has a dense root system so difficult to uproot.
3	*R. scabra*	1. It re-grows if it rains soon after weeding. 2. Weed has vigorous growth
3	*Digitaria* spp.	1. It spreads using stolons. 2. It grows rapidly.
5	*H. meeusei*	1. It has a deep root system so difficult to uproot. 2. It can re-grow if it rains after weeding. 3. Difficult to weed due to dense weed system.

5.4. Conclusion

The minimum tillage system of planting basins was the only CF practice adopted by farmers in Ward 12 and 14 of Masvingo district. There was no evidence of a decline in weed density in both the soil seed bank and above-ground weed flora with years the field had been under PB in Wards 12 and 14 of Masvingo District. Although weed density did not significantly ($P > 0.05$) differ between PB and CONV tillage throughout the 2008/09 cropping season, the earlier hoe weeding carried out in PB compared to CONV tillage suggested higher early season weed growth in PB relative to CONV tillage. The first hoe weeding was done at least 15 days earlier ($P < 0.05$) in PB than in CONV tillage. In addition, three post-planting weedings were done in PB compared to only two in CONV tillage. This increased weeding effort may be one of the reasons PB was practiced on less than 50% of the cropped area on the majority of farms despite the higher crop yields obtained in PB. At least double the maize grain was obtained from PB compared to CONV tillage (mean: 1 052 kg ha^{-1}) with yield observed to increase with number of years the field had been under PB. Improvements in soil fertility and weed management likely contributed to the increased maize grain yield under PB. The decrease in maize grain yield with increased weed density at 3 WAP highlighted the importance of early season weed control. However, farmers did not identify labour for weeding as the most important constraint in PB probably because farmers were using PB on small acreages that were equivalalent to the seed and fertilisers provided by NGOs. There is need to determine whether weed density in PB was higher than in CONV by carrying out weed assessment before farmers weed fields over a number of seasons. Further research needs to be done on the economic feasibility of herbicide use to reduce the weeding burden early in the cropping season. There is also a need to determine weed seed viability in manure as the annual application of manure in PB may have introduced additional weed seeds and new weed species in some PB fields.

CHAPTER 6

WEEDS IN COMPOST APPLIED IN SMALLHOLDER CONSERVATION FARMING

ABSTRACT

The use of composted cattle manure and plant litter to improve soil fertility in conservation farming (CF) may create a weed management problem if poorly composted materials are used. In a study carried out during the 2009/10 cropping season in Wards 12 and 14 of Masvingo District, compost samples were collected during storage in August 2009 and at time of field application in December 2009 from six randomly selected CF farms to determine the effect of composting on weed seedling emergence. The weed spectrum in compost applied to CF fields was also assessed on an additional 10 farms selected randomly from farms that were monitored for weed emergence during the 2008/09 cropping season. Weed seed viability in compost was determined using the weed seedling emergence method. On four out of six farms, composting markedly ($P < 0.05$) reduced weed seedling emergence by at least 60% with an associated decline in density of the most important weed species *Eleusine indica, Cynodon dactylon* and *Amaranthus hybridus*. However, on most farms composting did not completely eliminate viable weed seeds with emergence of between 3 and 142 weed seedlings kg^{-1} of mature compost observed. This translated to potential addition of weed seedlings that ranged from 18 000 to 852 000 ha^{-1} at the current farmer compost application rate of 6 t ha^{-1}. The variation in weed seedling emergence from the composts probably reflected the differences in compost storage on the different farms. Heap stored cattle manure had 57% more ($P < 0.05$) weed seedlings and double the *C. dactylon* density than pit stored compost suggesting that pit storage was more effective than heap storage in reducing weed seed viability. However, it is unlikely that labour constrained households will carry out all the recommended pit composting practices as CF is already associated with high labour requirements for basin preparation and weeding.

Key words: Conservation farming, compost storage, cattle manure, plant litter, weed composition

6. 1 INTRODUCTION

The use of organic nutrient sources is being widely promoted to smallholder farmers practicing conservation farming (CF) in Zimbabwe (Twomlow *et al*., 2008; ZCATF, 2009). Smallholder farmers in southern Africa commonly use animal manure (Materechera, 2010) and partially decomposed tree litter (Mafongoya & Dzowela, 1998) to amend soils. The benefits of using composted manure have been reported widely and include improvement in the soil physical environment, contribution to long-term soil organic matter buildup, supply of nutrients and essential trace elements (Simpson, 1986; Zingore, 2006). However, the use of manure is limited by the severely low quantities available on most smallholder farms and its poor quality characterised by high soil content and low N (Nzuma *et al*., 1999; Murwira *et al*., 2004).

In CF, farmers are encouraged to supplement locally available organic soil amendments with small quantities of inorganic fertilisers (Twomlow *et al*., 2008). This practice is reported by Nyamangara *et al*. (2009) to improve synchonisation of nutrient release and subsequent uptake by crop. Furthermore, both organic and inorganic fertilizers are precision applied into planting basins so as to concentrate nutrients in the root zone of the crop and limit access of weeds to nutrients. However, given that the conservation agriculture manual does not include training on composting (ZCATF, 2009) and that only a small number of smallholder farmers use recommended composting techniques (Murwira *et al*., 2004) there is a strong possibility of increased weed infestation in CF fields through the use of poorly managed composts.

The frequent use of composts to ameliorate soil fertility recommended in CF may, therefore, inadvertently exacerbate smallholder farmers' weeding burden. Svotwa *et al*. (2009) reported that smallholder organic farmers in Zimbabwe cited increased weed infestation in fields where composts were used as one of their main crop production challenges. Sub-optimal composting practices were identified as the main reason for the presence of viable weed seed in composts by Zarborski (2011). The high temperatures of between 50 and 70 ^{0}C that are critical for reducing the number of viable weed seeds in compost (Egley, 1990; Dahlquist *et al*., 2007) may not be attained during the thermophilic stage of active composting under sub-optimal composting conditions. In addition to exposure to high temperature, microbial activity and emission of various chemicals including acetic acid and ammonia in compost can result in high weed seed mortality (Larney & Blackshaw, 2003; Menalled *et al*., 2005). Hence, the composting process should create conditions that are phytotoxic to weed seeds so that there is minimal introduction into field of seed of both old and new weed species that may result in future weed management problems.

The aim of this study was to determine the effect of composting practices used by farmers in Wards 12 and 14 of Masvingo District on weed seedling emergence and to assess the weed spectrum in compost applied in CF fields during the 2009/10 season. In this study, compost refers to any soil amendment obtained from the thermophilic decomposition of locally available organic waste including animal manure, plant litter and household wastes.

6.2 MATERIALS AND METHODS

6.2.1 Sample collection

Availability sampling was used to collect a total of six composts from farms in Wards 12 and 14 of Masvingo District during the dry season in August 2009. The six farmers were part of the 23 farmers whose fields had been monitored for weed emergence during the 2008/09 season (Chapter 5). The compost was collected from heaps either outside the kraal or in fields and pits depending on the farm. Samples were obtained from four random spots in pit or heap at a depth of 50 cm from the surface to give a composite sample of 1 kg. In November 2009, at the beginning of the 2009/10 cropping season, samples of the compost applied to CF fields was obtained from 16 farms including the six from August 2009 and were collected from pits or heaps (Plate 6.1) using the same procedure outlined above. However, due to limited amounts available on some farms composite samples ranged from 0.6 to 1 kg. Information on general field management including application dates and rates of composts were captured in record books given to farmers at the beginning of the 2009/10 season. Semi-structured interviews were carried out for the six farmers with paired compost samples to elicit detailed information on handling and storage of compost used by farmers.

Plate 6.1 Storage of compost with composted cattle manure heaped outside cattle kraal at farm 1(left) and pit stored compost at farm 2 in November 2009 in Ward 12 of Masvingo District

6.2.2 Weed composition determination

The compost samples from each farm were gently hand pulverized and sub-samples of 200 g per farm were each placed in a plastic pot in an uncontrolled greenhouse at Matopos Research Station. A weed seedling emergence trial was set up as a randomized complete block design with 5 replications per site for August 2009 samples and 3 replications for November 2009 samples.

The lower number of replications for November 2009 compost samples was as a result of some samples being less than 1 kg. In addition, 50 g of the applied compost from eight farms including the six farms where samples were collected in both August and November 2009 were sent for analysis for pH (water), total N and P (%), OC (%) and available N (%). The compost samples were watered daily and stirred monthly to encourage weed emergence in the greenhouse. Weed seedlings were identified and counted weekly until there was no further weed emergence. The samples obtained in August 2009 are hereafter referred to as immature compost samples as they were assumed to have been still undergoing composting at time of sampling. The November 2009 samples were sub-samples of compost applied to CF fields by farmers and will be referred to as mature compost.

6.2.3 Statistical analysis

Relative importance values were calculated for all weed species identified in immature and mature compost in order to rank weed species according to importance.

RIV = (Relative frequency + Relative density) / 2 *Equation 1*

All weed species with an RIV of 10 or less were considered rare (Chikoye & Ekeleme, 2001) and dropped from further analyses. Weed seedling data was Log (x + 1) transformed to homogenize variances and was subjected to an Un-balanced design Analysis of Variance (GenStat 9.1). For the six farms with immature and mature compost, the stage of maturity of compost and farm were the treatments. Farm was the treatment factor for the 16 mature composts. In addition, the mature composts were grouped according to type of storage used (heap or pit) and this was used a treatment factor in ANOVA.

6.3 RESULTS AND DISCUSSION

6.3.1 Effect of composting on weeds

6.3.1.1 Weed spectrum

In both the immature and mature composts, the three most important weed species were *Eleusine indica, Cynodon dactylon* and *Amaranthus hybridus* (Table 6.1). More (15) weed species were identified in the immature than mature composts (10 species). Of the important species, *Galinsoga parviflora* and *Gallium asparium* were absent from mature composting suggesting that composting was effective in reducing the seedling density at most farms. However, *E. aspera* was absent in immature samples but was identified as an important weed in mature compost samples (Table 6.1). Interestingly the RIV values of *E. indica, C. dactylon* and *A. hybridus* in mature compost were higher than in immature compost indicating that consistently high weed seedling numbers of these species were recorded in the mature compost across farms. This suggests that the compost used on the six farms during 2009/10 season were potential sources of viable weed propagules of these species. The three weed species were also found to be dominant in heaped manure by Rupende *et al*. (1998) and Munguri *et al*. (1995) in sub-humid Zimbabwe. Makanganise and Mabasa (1999) characterize *E. indica* and *A. hybridus* as weeds associated with manured fields in Zimbabwe.

One of the uses of *E. indica* identified by farmers in the study area was as one of the main grasses used for compost making (Chapter 5). Since the late season weeding was delayed to the dry season when weeds had probably seeded in CF (Chapter 5) addition of weeds such as *E. indica* likely introduced weed seeds to composts. It is recommended that farmers add weeds to compost that have not reached the reproductive stage to minimize introduction of weed seeds to compost. The prevalence in compost of the weed species *E. indica* and *C. dactylon* that were also identified as being among the most difficult to control weed species by farmers in the study area (Chapter 5) may have serious consequences for future weed management. This is because prevention of seed addition to the soil weed seed bank has long been identified as one of the central strategies of sustainable long-term weed management (Dekker, 1999; Swanton & Booth, 2004).

Table 6.1 Relative importance value (%) of weed species occurring in fresh and mature compost obtained from farms in Wards 12 and 14 of Masvingo District during 2009. Weed species are ordered according to abundance in immature compost

Latin name	Growth form	Compost (RIV %)	
		Immature	Mature
Eleusine indica (L.) Gaertn.	Annual monocot	50	66
Cynodon dactylon (L.) Pers.	Perennial monocot	38	43
Amaranthus hybrius L.	Annual dicot	30	48
Galium spurium L. ssp. africanum Verdc	Annual dicot	18	-
Galinsoga parviflora Cav.	Annual dicot	18	-
Cyperus esculentus L.	Perennial monocot	9	9
Dactyloctenium aegptyium	Annual monocot	9	-
Heterophylla hirta	Annual dicot	9	-
Hibiscus meeusei Exell	Annual dicot	9	9
Leucas martinicensis (Jacq.)R.Br.	Annual dicot	9	9
Portulaca oleracea	Annual dicot	9	-
Richardia scabra L.	Annual dicot	9	-
Setaria monophylla	Annual	9	9
Sida alba L.	Perennial dicot	9	-
Digitaria spp.	Annual monocot	1	-
Eragrostis aspera (Jacq.) Nees	Annual monocot	-	17

A '-' indicates that a weed species was absent in a given tillage system.

6.3.1.2 Weed seedling emergence

The number of total, monocot, dicot, *A. hybridus*, *C. dactylon* and *E. indica* weed seedlings significantly ($P < 0.05$) varied between the six farms. There were significant ($P < 0.05$) differences in the density of total, monocot, dicot and the population of the three most important weed species between the immature and mature compost. However, in all cases the farm and maturity factor effects were confounded within the highly significant ($P < 0.001$) farm x compost maturity interaction (Figs 6.1 and 6.2).

Mature compost obtained from four of the six farms had at least 60% ($P < 0.05$) less weed seedlings than immature compost (Fig. 6.1). The greatest reduction in weed seed viability was obtained from farm 1 where the mature composted cattle manure (Plate 6.1) had only a third of the density of weed seedlings found in the immature compost. The cattle manure at farm 1 was removed from the kraal in August 2009 and, thus, the immature compost had been heaped for less than a month at time of sampling (Appendix A). However, storage of the manure in a heap for three months reduced weed seed viability of both monocots and dicots (Fig. 6.1) including *E. indica*, *C. dactylon* and *A. hybridus.* The immature composted kraal manure had high numbers of *A. hybridus* whose seeds according to Costea *et al*. (2004) still maintain viability even after rumen digestion and elimination from the animal. The seeds may have been ingested by cattle and excreted in cow dung which was later used for composting However, heap composting for three months markedly reduced weed seed viability of *A. hybridus* such that no weed seedlings emerged in the mature composted kraal manure.

Pit composting reduced weed seedling emergence of both dicot and monocot weeds that included the species *E. indica* and *C. dactylon* at farms 2, 3 and 4 (Fig. 6.1 and 6.2). The species *A. hybridus* had low density in both immature and mature composts stored in pits probably because low amounts of cattle manure were added to the compost. The immature compost at site 4 had the lowest number of weed seedlings with no weed emergence observed in the mature compost. The level of reduction in weed seedling emergence on composting varied between farms 2, 3 and 4 probably reflecting the differences in composting procedures. Only the farmer at farm 4 received training on composting from a local NGO in 2000 and this probably contributed to production of compost that was largely free of viable weed seeds. The immature compost at farm 4 had been stored in pit for three months when sampling was done and this may explain the low weed emergence observed. The period of composting, size of pits, materials used for composting and management varied between the three farms (Appendix B) and this probably contributed to the differences observed on the effect of composting on weed seedling emergence. A reduction in weed emergence on composting has also been reported by Cudney *et al.* (1992), Rupende *et al*. (1998) and Menalled *et al.* 2005. High temperatures, increased microbial activity, toxic gases and acids produced during composting have been reported to reduce weed seed viability (Egley, 1990; Eghball & Lesoing, 2000; Dahlquist *et al*., 2007).

However, pit composting was associated with high weed seedling emergence in mature relative to immature compost at farms 5 and 6 (Fig. 6.1 and 6.2). Mature compost obtained from farm 6 had at least 2-fold ($P < 0.05$) the density of total and monocot weeds compared to the immature compost. The seedlings of *E. indica*, *C. dactylon* and *A.hybridus* did not emerge in the immature compost but emerged in high numbers in the mature compost from farm 6 with a similar observation recorded for *C. dactylon* in compost from farm 5 (Fig. 6.2). The composts from farms 5 and 6 received the least management compared to those obtained from farms 2, 3 and 4 (Appendix B). The farmer at farm 6, although trained on composting by a local NGO in 2000, reported that the recommended composting procedure was too labour intensive and had opted to collect partially decomposed forest litter from an anthill in the Lake Mutirikwi Game Reserve and place in a shallow pit for four months until field application. According to the farmer there was no need to dig a deep pit, add water and other compost making aids such as anthill soil or N fertiliser. This low management of compost pit was in contrast to management at farm 4 where the farmer followed most of the recommended composting practices outlined in the AGRITEX/ZFU, (1999) soil fertility management manual. According to Zarborski (2011) improperly assembled and maintained compost piles may not reach the high temperature that is lethal for most weed seeds. Furthermore, temperatures of above 40 ^{0}C but below 50 ^{0}C were observed to promote germination of some weed species (Egley, 1990; Dahlquist *et al*., 2007) and this was attributed to these sub-lethal temperatures breaking seed-coat enhanced dormancy. The compost at farms 5 and 6 may have created conditions that relieved dormancy of weed seeds during composting and this was observed as high weed seedling emergence in the mature compost.

On the overall both heap and pit composting reduced weed seed viability. However, the extent of reduction in weed seedling number in mature compost depends on how the compost was managed.

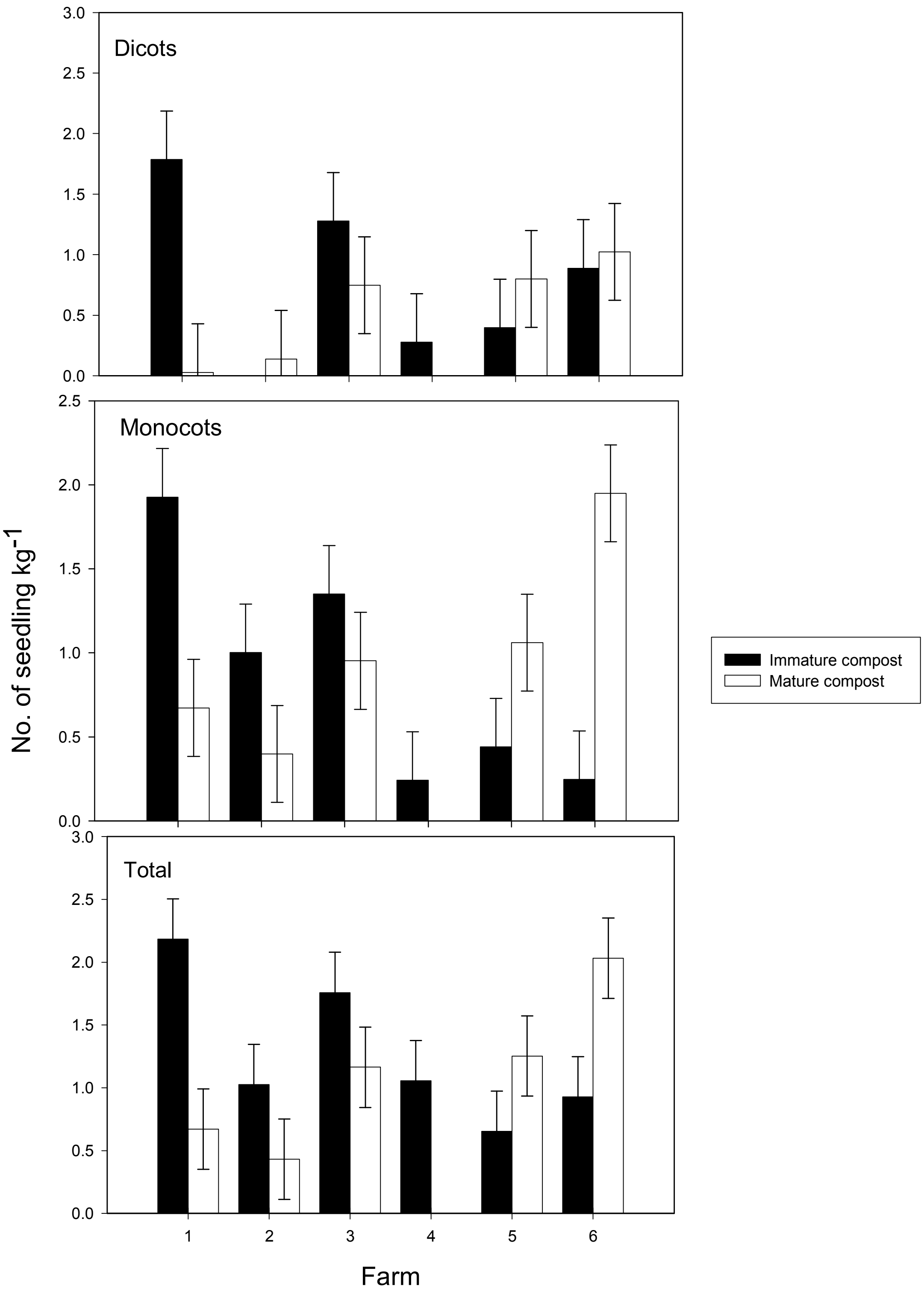


Fig 6.1 Farm x compost maturity interaction on the number of weed seedlings that emerged from composts obtained from farms in Wards 12 and 14 of Masvingo District during 2009/10 season. Narrow bars represent ± SED. Log (x + 1) transformed data presented

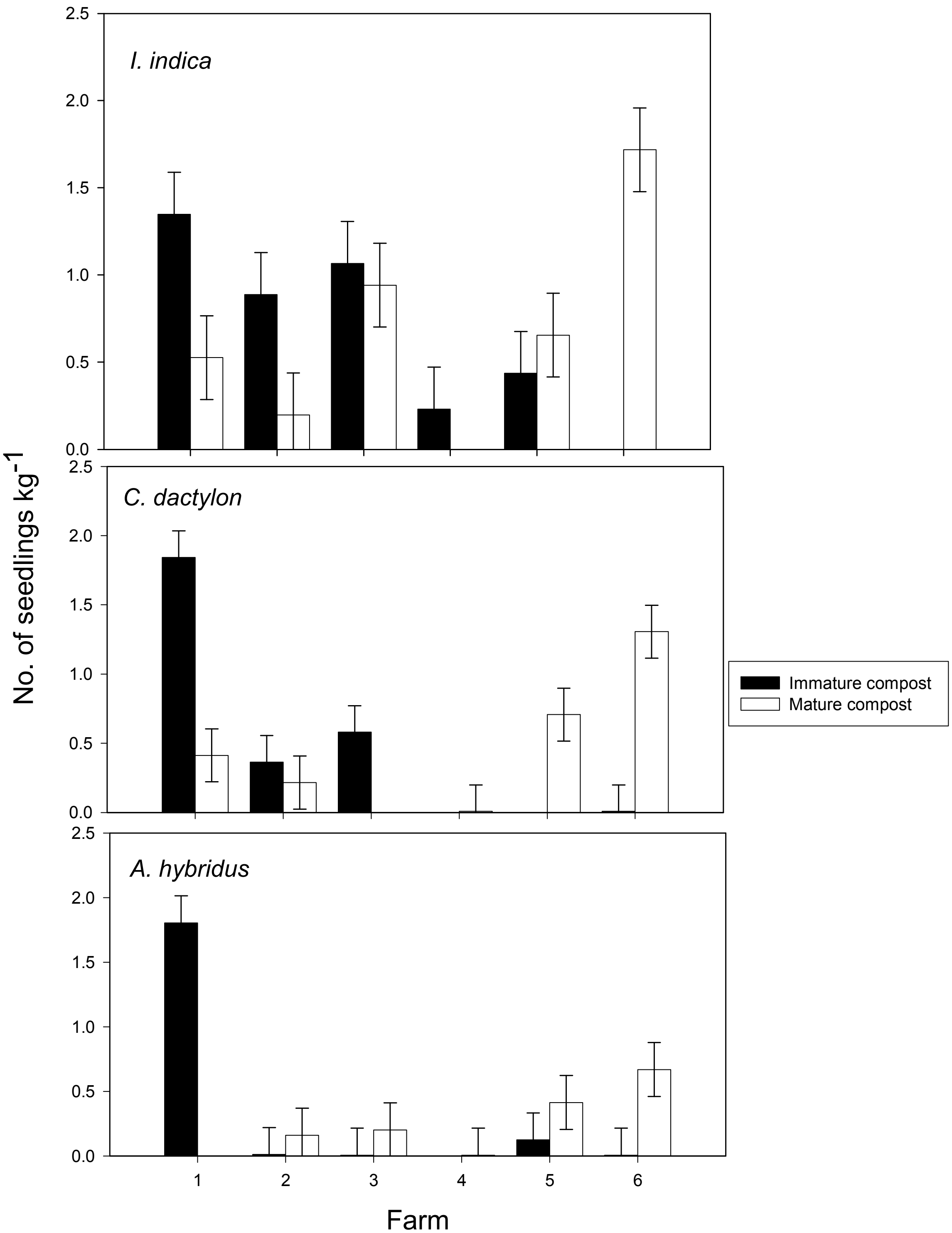


Fig 6.2 Farm x compost maturity interaction on the number of weed seedlings of *E. indica*, *C. dactylon* and *A. hybridus* that emerged from composts obtained from farms in Wards 12 and 14 of Masvingo District during 2009/10 season. Narrow bars represent ± SED. Log (x + 1) transformed data presented

6.3.2 Weeds in applied composts

6.3.2.1 Weed species composition

The most important weed species in composts applied to CF fields during the 2009/10 season were *E. indica*, *C. dactylon* and *A. hybridus* (Table 6.2) reflecting the findings obtained from the smaller sample of farms used to compare immature and mature compost (Table 6.1). Grass species were the prevalent weeds in compost applied in CF fields which may be a result of the widespread use of grass weeds as composting material by farmers. Although there was variation in relative importance values of weed species identified in heap and pit stored compost, the ranking of the four most important weed species remained the same (Table 6.2).

Table 6.2. Relative importance value (%) of weed species occurring in heap and pit stored composts applied on farms in 2009 in Wards 12 and 14 of Masvingo district. Weed species are ordered according to abundance in heap stored compost

Latin name	Growth form[a]	Compost storage (RIV %)	
		Heap	Pit
Eleusine indica	Annual monocot	66	68
Cynodon dactylon	Perennial monocot	65	40
Amaranthus hybridus	Annual dicot	19	33
Cyperus esculentus	Perennial monocot	15	11
Phyllanthus leucanthus	Annual dicot	7	-
Sida alba	Perennial dicot	7	-
Hibiscus meeusei	Annual dicot	-	6
Ipomea plebia	Annual dicot	-	6
Leucas martinicensis	Annual dicot	-	6
Acalypha crenata	Annual dicot	-	6
Corchorus tridens	Annual dicot	-	6
Digitaria spp.	Annual monocot	-	6
Setaria monophylla	Annual	-	6
Citrullus lanatus var. *lanatus*	Annual Dicot	-	6

A '-' indicates that a weed species was absent in a given tillage system

6.3.2.2 Effect of farm

There were significant ($P < 0.05$) differences in the number of total, dicot and monocot weed seedlings that emerged from mature compost obtained from the different farms in 2009 (Fig. 6.3). Mature compost obtained from farms 6, 11 and 12 had the highest ($P < 0.05$) number of weed seedlings whereas those from farms 4, 8 and 13 recorded no weed seedlings emergence. Significantly higher density of *E. indica* and *C. dactylon* emerged from composts obtained from farms 6, 11 and 12 (Fig. 6.4) which translated into the higher monocot weed seedling numbers recorded at these farms (Fig. 6.3) compared to composts obtained from the other farms. This suggests that although compost was also introducing dicot weed species such as *A. hybridus* greater numbers of monocot weed species such as the more difficult to control *E. indica* and *C. dactylon* were introduced in fields.

Compost used at farms 6, 7, 10, 11, 12 and 16 had high weed seedling emergence (Fig. 6.3) indicating that this compost likely introduced weed seeds to fields were it was applied. Since the average manure application rate used by farmers in CF fields in 2009 was 6 t ha^{-1} (equivalent to 2 handfuls of compost $basin^{-1}$), the compost from farm 12 potentially introduced about 852 000 weed seedlings ha^{-1} compared to introduction of no viable weed seeds by composts at farms 4, 8 and 13. These differences may have been as a result of how composts were handled and stored at the different farms.

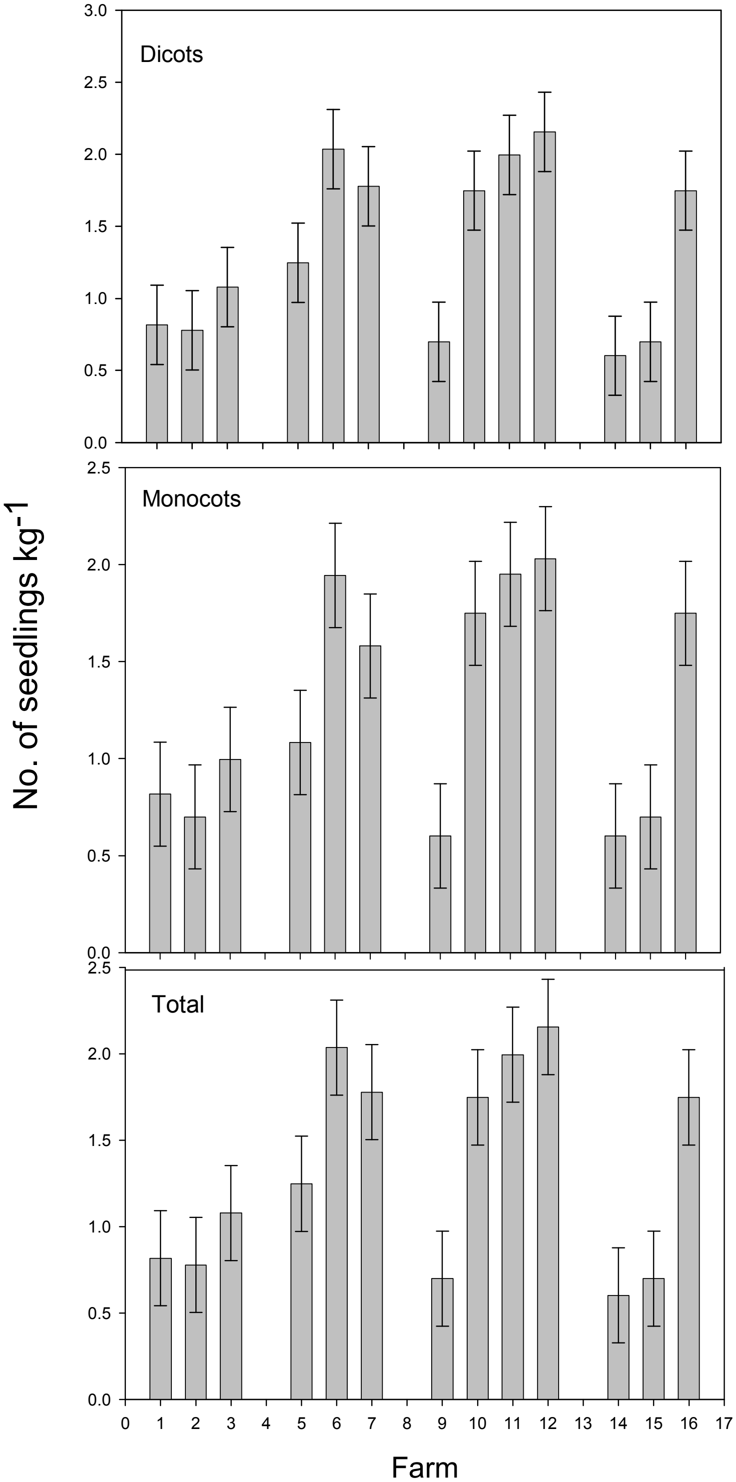


Fig 6.3 Number of total, monocot and dicot weed seedlings that emerged from composts applied to different fields in Wards 12 and 14 of Masvingo District during 2009/10 season. Narrow bars represent ± SED. Log (x + 1) transformed data presented

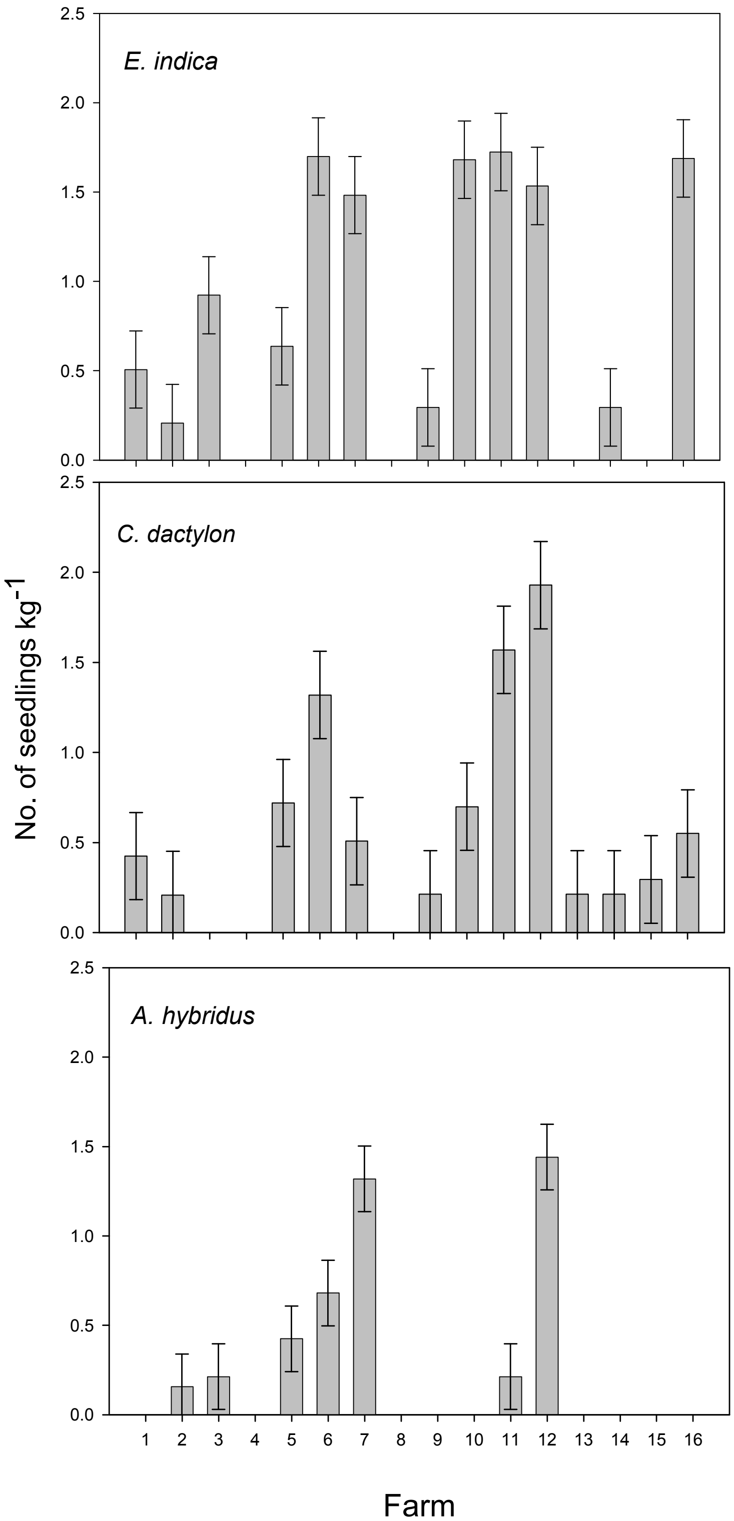


Fig 6.4 The number of weed seedlings of *E. indica*, *C. dactylon* and *A .hybridus* that emerged from composts applied ondifferent farms in Wards 12 and 14 of Masvingo District during 2009/10 season. Narrow bars represent ± SED. Log (x + 1) transformed data presented

6.3.2.3 Effect of storage method

The marked differences in weed seedling emergence from mature composts (Fig. 6.3 and 6.4) used during the 2009/10 season were likely due to handling of composts which varied between farms (Appendix A and B). During the 2009/10 season, the majority (56%) of farmers stored composts in pits while the remainder used heap storage. Where pit storage was used, the composting material comprised mainly forest litter, maize residues and mostly mature weeds to which were added small quantities of anthill soil, cattle manure and sometimes AN fertiliser depending on the farm (Appendix B). This was probably because the majority of CF farmers had limited access to cattle manure due to low livestock ownership as this group was made up of the early adopters of CF in Wards 12 and 14 (PB3+ in Chapter 5). On farms where there was access to cattle manure, harvested maize residues were added to kraal as cattle feed (Plate 6.1 at farm 1). This group comprised mainly late CF adopters (PB3-) and CONV tillage farmers. On four of the six farms, the cow dung mixed with maize residue was removed from kraals beginning from July 2009 and heaped outside kraal for a period of between 3 and 6 months before field application (Appendix A). However, on two farms the deep stall method was used where cattle manure was left in kraal until a month before field application after which it was heaped in field for a month. The differences in composting may have affected weed seed viability in heap and pit stored composts.

Heap stored composted cattle manure had significantly ($P < 0.05$) higher numbers of monocots with double the number of *C. dactylon* seedlings which ultimately translated to 57% more weed seedlings compared to pit stored compost (Table 6.3). There was, however, variation in weed seedling emergence from composted cattle manure obtained from the different farms which may have been due to differences in heaping period and size of heaps. The importance of heaping period in reducing weed seed viability is highlighted by the decline ($P < 0.01$) in weed seedling emergence with heaping period with lowest emergence recorded in composts heaped for three months (Fig. 6.5). The composted cattle manure obtained from farms 11 and 16 where the deep stall method was used was among the composts with high weed seedling emergence (Fig 6.3) probably because heaping for one month may have been insufficient to reduce weed seed viability. The high weed population in manure heaped for more than three months may have been due to dispersal of wind-blown weed seeds into un-protected heap or introduction of mature weeds after the active composting stage was complete. Zarborski (2011) reports that finished compost can be re-contaminated with weed seeds if weeds continue to be added especially after the active composting stage.

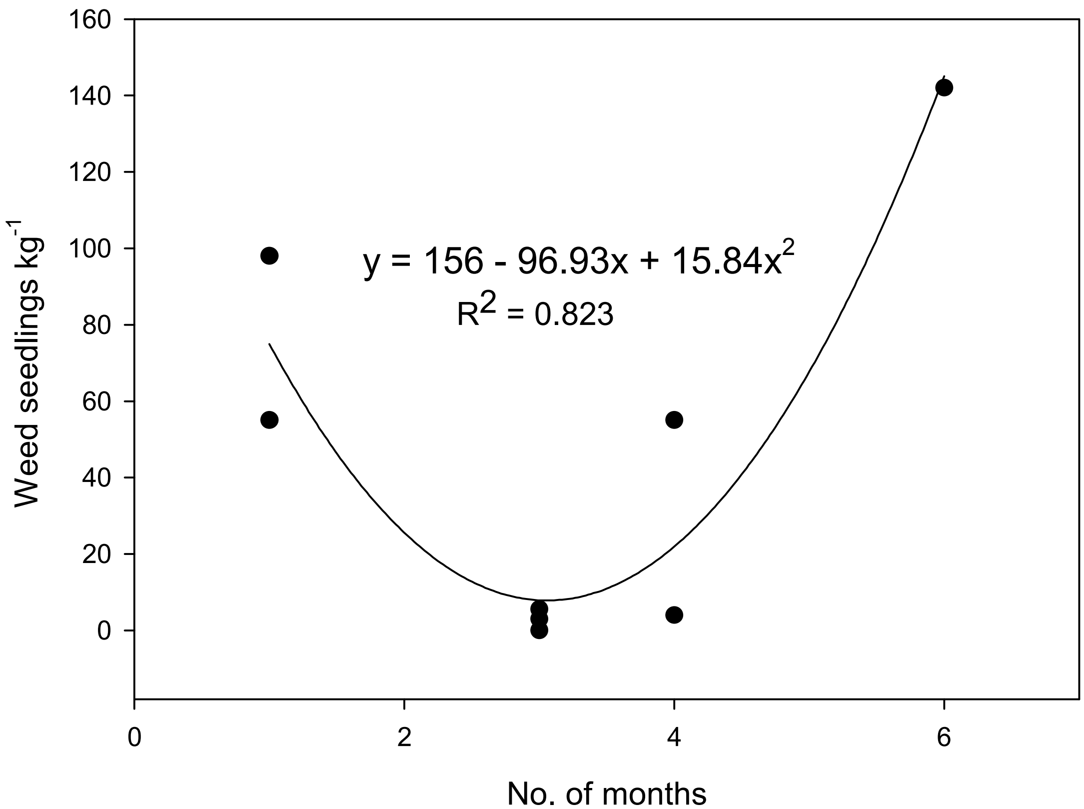


Fig. 6.5 Relationship between period of heaping and weed seedlings in composted cattle manure applied on farms in Wards 12 and 14 of Masvingo District during 2009/10 season

There is, therefore, a need to train farmers on composting cattle manure using heaps as according to N'Dayegamiye and Isfan (1991); and Rupende *et al.* (1998) the size of the heap and period of heaping have an effect on temperatures attained within compost pile and consequently the number of weed seeds that still remain viable in mature compost. The results from this study confirm the observation made by farmers in sub-humid Zimbabwe that heap stored cattle manure was associated with more weeds than compost stored in pits (Mutiro *et al*. 2004). The higher prevalence of *C. dactylon* in compost especially heap stored composted cattle manure (Table 6.3) is of concern in CF as the perennating structures are unlikely to be destroyed by the shallow hoe weeding carried out in these systems. Without access to systemic herbicides perennial grasses are likely to become a serious problem in CF for smallholder farmers.

Although pit stored compost had significantly lower weeds than heap stored compost, on most farms the mature pit stored compost still contained viable weed seeds. The compost stored in pits obtained from farms 6 and 7 had the highest weed seedlings compared to that from other farms (Fig. 6.3 and 6.4). At both farms, forest litter was used as the main plant material and it may be that forest litter required a longer composting period than the 4 months done at both farms. Furthermore, the composts from these farms were the least managed compared to those obtained from the other farms (Appendix B) and the resulting composting process may have allowed weed seeds to remain viable. Therefore, improperly handled compost was potentially a vector of weed seeds in CF fields where composts were applied annually. The compost used at farm 7 may have added over 650 000 weed seedlings ha^{-1} if applied at a rate of 6 t ha^{-1} and the farms whose composts had intermediate emergence may have added between 30 000 and 66 000 weed seedlings ha^{-1} compared to compost from farm 4 where no weed seedlings emerged. This highlights the importance of following recommended composting practices so that compost with low weed seed viability is applied in CF fields.

However, pit composting is labour intensive (Mutiro & Murwira, 2004) and most labor-constrained households are unlikely to be able to carry out all the recommended composting practices. For CF farmers there is likely to be demand for labour during the dry season for composting and basin preparation among other non-farm activities. In addition, farmers also need to decide on how to allocate the scarce crop residue among livestock feeding, mulching and composting. The high labour demands associated with basin preparation, composting and weeding in CF may result in some farmers taking the approach of the farmer from farm 6 who although trained on composting, had for the past three years opted to collect partially decomposed forest litter as this method was less labour demanding than pit composting.

However, the compost produced had high population of viable weed seeds which may have emerged in CF fields and increased the amount of labour required for hoe weeding.

Table 6.3 Weed emergence in heap and pit stored compost applied on farms in Wards 12 and 14 of Masvingo District during 2009/10 season

Compost storage	No. of weed seedlings kg^{-1} fertiliser					
	Total	Monocot	Dicots	*A. hybridus*	*C. dactylon*	*E. indica*
Heap	1.1	1.1	0.4	0.3	0.7	0.5
Pit	0.7	0.6	0.4	0.2	0.3	0.8
LSD (0.05)	0.45	0.43	ns	ns	0.33	ns

Log (x + 1) transformed data presented *Abbreviations:* LSD - least significant difference; ns - not significantly different.

6.3.2.4 Compost quality

Both heap and pit stored compost had an N% of less than 0.6% indicating that the compost used in Wards 12 and 14 was of poor nutrient quality. There was no significant difference in nutrient quality between heap and pit stored composts with levels of P and K being generally low in both. Nutrient loss in composts may have occurred when material was heaped outside pits or in fields without being covered (Appendix A and B). Nitrogen could have been lost through volatilization and leaching when the compost was exposed to hot, dry winds, sun and sometimes rains. The handling and storage of both manure and composts may have contributed to their low nutrient status suggesting the need for further training of farmers on composting.

6.4 CONCLUSION

Composting was effective in reducing ($P < 0.05$) weed seedling emergence by at least 60% in four out of six farms. There was also a significant reduction in the density of the most important weed species *E. indica*, *C. dactylon* and *A. hybridus* at these farms on composting. However, on most farms composting did not eliminate weed seeds and compost application may have potentially resulted in emergence of between 18 000 and 852 000 weed seedlings ha^{-1} at the compost application rate of 6 t ha^{-1} used on most CF fields in the study area. The variation in weed seed viability in compost applied to fields was probably a reflection of different composting practices used at the 16 farms. The majority of CF farmers practiced pit composting of mainly plant litter while farmers with access to cattle manure stored it in heaps. Heap stored composts had 57% more ($P < 0.05$) weed seedling emergence and double the *C. dactylon* density than pit stored compost suggesting that pit storage was more effective at reducing weed seed viability. Therefore, frequent use of compost as recommended in CF may lead to increases in weed infestation and density of the problematic *E. indica* and *C. dactylon* weed species where poorly stored compost is used. There is, therefore, a need to include training on composting in CF programs so as to improve nutrient quality and reduce the number of viable weed seeds.

CHAPTER 7

GENERAL DISCUSSION

7.1 Introduction

The low area under conservation agriculture (CA) on smallholder farms in southern Africa may be due to the need for more intensive weed management in CA compared to conventional tillage. Farmers, agriculture extension and research agents in the region have reported increased weed infestations on fields reported to be under CA relative to mouldboard ploughed fields. However, proponents of CA claim that weeds are only a problem where minimum tillage is adopted without the other CA principles of permanent organic soil cover and diversified crop rotations. Furthermore, they argue that with good management weeds decline within three years of CA adoption leading to more sustainable weed management in the long-term. Research presented in this thesis provides important new information on weed population dynamics under practices recommended by the Zimbabwe Conservation Agriculture Taskforce (2009) and under actual smallholder farmer practice in semi-arid areas of southern Zimbabwe.

7.2 Conservation agriculture

7.2.1 Tillage effect on weed and crop growth

A series of investigations were carried out on a long-term CA experiment to determine the effect of tillage on weed growth (Chapter 3) and weed community composition (Chapter 4). The view that weed infestations decreased within three years under recommended CA practices was not substantiated in this study. The MT systems of planting basins and ripper tine were associated with greater early season weed growth than CONV tillage in both the fifth and sixth years of CA. The weed infestations were observed as high weed emergence (cowpea phase) and growth (sorghum phase) in MT a week before crops were planted (Chapter 3). This would necessitate an early weeding in CA to provide a clean seedbed for the crop that is likely to exacerbate existing labour peaks experienced by farmers at the beginning of the season. The majority of smallholder farmers are likely to postpone weeding until after most fields are planted given the erratic nature of rainfall in semi-arid area. Delayed weeding is reported to be the major cause of loss in maize yield on smallholder farms (Rambakudzibga *et al*., 2002).

The increased weed growth in MT systems was maintained during the first four weeks after planting (WAP) in both cowpea and sorghum (Chapter 3). Corresponding results of high weed growth early in the cropping season in MT were also reported in the maize phase of the rotation in the fourth year of CA in the same study (Mashingaidze *et al*., 2009b). This indicated that conditions conducive for weed emergence and subsequent growth existed under MT systems within the first weeks after planting regardless of the crop grown. Since this period falls within the period in which weed control is required to avert significant crop yield losses for most crops, early and frequent weeding may have been needed in CA even after four years. In fact, MT systems required double the weeding (a week before planting and a week after planting) done in CONV tillage to reduce weed biomass at 4 WAP to levels comparable to CONV tillage. Since weed biomass measures the increase in individual weed size, the high weed biomass under MT indicates high biomass accumulation by weeds and, therefore, increased competition. Larger weeds have a greater impact on crop plants through competition and also have a better chance of achieving reproductive maturity and setting seed (Miyizawa *et al*., 2004). That CA had increased weed infestations early in the cropping season after three dry season weedings leads to questions on the effectiveness of hoe weeding in controlling weeds under MT systems.

The observed proliferation with the first rains of the cropping season of perennial and annual weeds with deep roots such as *Alternanthera repens*, *Boerhavia diffusa* and *Setaria* spp. (Chapter 3) demonstrates that dry season weeding using hand hoes was largely ineffective against these weeds. The high weed biomass observed a week before planting in the sorghum phase of the rotation despite three dry season weeding arose from poor weed control of these weed species. The frequency of weeding carried out in this study especially early in the cropping season is impractical given the labour shortages in smallholder agriculture. The use of herbicides such as glyphosate can reduce the early season weeding burden and more effectively control perennial weeds in CA. Systemic herbicide would be useful for controlling weeds such as *Portulaca oleracea* whose weed density was observed to increase under CA when the maize mulch rate was below 8 t ha^{-1} (Chapter 4). However, issues such herbicide availability, limited capital for purchasing knapsack sprayers, herbicides and protective clothing, and training of both extension agents and farmers on the safe use of herbicides still remain. Research carried out on a low cost weed wipe made in Zambia for use in CA found that weed control was poor especially in the presence of crop residue (Mashingaidze *et al.*, 2009a). There is need to carry out studies that include herbicide application combined with different levels of hoe weeding under CA to investigate the economic feasibility of using herbicides in CA. If herbicide use is profitable then the use of a subsidy scheme between smallholder farmers and agro-dealers can be set up. The use of herbicides for early season weed control would minimise the labour bottlenecks common early in the cropping season. However, there is a need to train both extension workers on weed species identification, the proper handling of herbicides and management of herbicide resistant weeds. This can be done using participatory research approaches including field demonstrations and Farmer Field Schools. The knowledge intensiveness of herbicide use may be an impediment to herbicide use by most of the older farmers. On the other hand, the promotion of herbicides will be inappropriate for the resource-poor farmers who at present have limited cash investment for seed and fertiliser.

However, MT systems were associated with poor crop establishment in both cowpea and sorghum that reduced grain yields (Chapter 3). Cowpea yield was especially low in MT systems and close to the Zimbabwe national yield average of 300 kg ha^{-1}. There is a need to re-visit the CA practice of maintaining the spacing recommended for maize when growing legumes and small grains. The recommended spacing of these crops is usually narrower than that for maize. The crop canopy in cowpea and sorghum developed slowly due to the poor crop stand and afforded weeds a chance to emerge and grow as was observed early in the cropping season. The increased weed growth would necessitate frequent weeding in crops that are largely viewed as minor crops in smallholder farming. Given the markets for these crops it is highly unlikely that smallholder farmers would carry out more than one post-plant weeding let alone consider applying herbicides to control weeds in the crops. From the viewpoint of weed management, the inclusion of crops such as cowpea in CA rotation while diversifying management practices would actually result in high weed seed return as most farmers are likely to weed crop only once after planting. However, in this study the below optimum crop densities probably contributed to the increased weed growth observed under CA. Intercropping of cowpea with maize has been reported to suppress weeds and effectively reduced hoe weeding from thrice to once per season (GART, 2008).

7.2.2 Maize residue mulch effect

Suppression of weed growth is one of the benefits attributed to the retention of crop residue as soil surface mulch in CA. However in this study, maize residue mulching offered only limited weed suppression that was observed only in sorghum early in the cropping season (Chapter 3). Maize residue mulching reduced the density of some weed species including *P. oleracea* and may be useful in reducing the density of this weed early in the cropping season in CA where frequent early season weed control is not possible (Chapter 4). However, this required maize mulch rates of 8 t ha^{-1} which are unlikely to be retained by most smallholder farmers due to problems of crop residue availability in semi-arid areas.

However, during the course of the study maize residue mulching, especially under the intermediate rate of 4 t ha^{-1}, was consistently associated with increased mid- to late- season weed emergence in both cowpea and sorghum crops, and weed biomass accumulation in the sorghum phase of the rotation at the highest maize mulch rate of 8 t ha^{-1} (Chapter 3). The present findings indicate that weeds benefited from the moist conditions and moderate temperatures under the mulch during dry periods of the season. In addition, mulches trapped seeds of wind-dispersed weed species resulting in their increased density under mulch. Weed species such as *Conyza albida, Eleusine indica, Gnaphalium penysvalvicum, Leucas martinicensis, S. pinnata* and *Setaria* spp. were observed to emerge in greater numbers from mulched than un-mulched soil surfaces (Chapter 4). For *L. martinicensis, Setaria* spp., *Urochloa panicoides, S. pinnata* and *B. diffusa* the increased density on mulching was observed only MT systems suggesting that these species will emerge in greater numbers under CA. In both crops, the intermediate maize mulch rate of 4 t ha^{-1} had significantly higher weed density than 8 t ha^{-1}. A number of reasons were responsible for the increased weed infestations under the intermediate mulch rate. The thicker layer at a maize mulch rate of 8 t ha^{-1} may have reduced weed emergence through increased shading. Moisture conservation may have been greater at maize mulch rate of 4 t ha^{-1}

than 8 tha^{-1} as Mupangwa *et al*. (2007) reported that maximum soil water content was observed at the 4 t ha^{-1} maize mulch rate. This increased in density of some weed species under the intermediate maize mulch rate contributed to its reduced weed diversity (Chapter 4). This led to a CA community dominated by the competitive *Setaria* spp. group with difficult to control weeds such as *E. indica* increasing under the 4 t ha^{-1} maize mulch rate.

The findings of this study demonstrated that retention of moderate rates of maize stover increased mid-season weed growth and necessitated late season weed control in CA under semi-arid conditions. Furthermore, mulching was not associated with increased crop yield after four years of CA. In fact, mulching reduced sorghum yield as a result of the increased weed growth under the maize mulch (Chapter 3). However, the many significant interactions of maize mulch rate with factors such as tillage, season and even level of weed management indicate that the effect of mulching on weed and crop growth are complex. This cautions against making generalised statements as is often done in CA as the influence of mulching is season – and management specific.

7.2.3 Hoe weeding intensity

In this study, a high weeding effort was still required in the fifth and sixth years of CA (Chapter 3) demonstrating the need for intensive hoe weeding even after the three years weed pressure and weeding effort were claimed to decline under CA. This was because MT systems had high early season weed infestations and maize residue mulching increased mid- to late- season weed growth (Chapter 3) which necessitated frequent weeding throughout the cropping season to keep CA fields weed-free. The high weeding intensity of four hoe weedings during the season significantly reduced weed density and biomass which translated into improved growth of both cowpea and sorghum. In fact, the significantly greater sorghum grain yield obtained under the high weeding intensity than low weeding intensity highlighted the need for frequent weeding after six years of CA in order to avert crop yield loss. Therefore, even under recommended CA practices a high weeding intensity was required which did not substantiate the claims that weed infestation and weeding effort to control them were high only in the initial years of CA.

Although hoe weeding was less effective at controlling perennial weeds species during the dry season (Chapter 3), it was effective against most weed species found at Matopos Research Station (Chapter 4). Frequent hoe weeding significantly reduced the density of a number of weed species including *Commelina benghalensis, E. indica* and *Setaria s*pp. (Chapter 4). This demonstrated when done early hoe weeding can control weeds such as *C. benghalensis* and *E. indica* that are often identified by smallholder farmers as difficult to control using hoe weeding (Chapter 5). Delayed weeding on smallholder farms probably allows the weed species to form structures such as tubers and deep fibrous root system that make their removal difficult using hoes. Hoe weeding could also be used to reduce the density of the dominant *Setaria* spp. Previous studies also report that when done early, hoe weeding is as effective as any of the mechanical methods of weed control used in smallholder agriculture (Riches *et al*., 1998)

However from the viewpoint of smallholder farmers, the four within cropping season hoe weedings plus at least one dry season weeding done as was done in this study may be too labour demanding for most smallholder farmers. Therefore, the requirement for weeding effort ven after six years of recommended CA practices may ultimately limit the area that can be committed under CA on smallholder farms in Africa. There is, thus, need to explore the used of herbicides to supplement hoe weeding if CA is to be adopted on a wide-scale by smallholder farmers in semi-arid areas.

7.3 Conservation farming

7.3.1 Weeds in conservation farming

The CF farmers in Masvingo District were neither retaining the minimum soil cover of crop residue of 30% at planting nor rotating their maize crop with a legume or other crop in the past four seasons (Chapter 5). During the 2008/09 season, there was no evidence of a decline in weed density with time under CF. Weed density was found not to be significantly different between PBand CONV tillage. However, CF fields were weeded earlier and more frequently (thrice) than CONV tillage systems (twice). The first hoe weeding in PB was done at least 15 days earlier than in CONV tillage with the majority of PB fields weeded within the first week after maize was planted (Chapter 5). This suggested higher weed growth in PB than in CONV tillage. Since the area within the quadrats were weeded at the first weeding (Chapter 5), it is highly possible that the early weeding in PB masked the differences in weed density at 3 WAP between PB and CONV tillage. High levels of weed management have been observed to diminish the differences in weed infestation between tillage systems (Chapter 3; Locke et al., 2002). Observations from PB farmers who had not weeded fields before the first and second weed counts showed PB fields to have more than treble the weed density under CONV tillage.

Hoe weeding was done thrice during the cropping season and once in the dry season translating to four hoe weedings per year in PB compared to only twice in CONV tillage. However, none of the PB farmers carried out a late season weeding prior to or at harvesting. The lack of weeding allowed late season weeds such as *Acanthospermum hispidum* that was observed to increase in PB3- to reproduce and return seed to the soil weed seed bank. The frequency of weeding recorded in PB in this study agrees with findings of Mazvimavi *et al*. (2011) from a survey of CF in Zimbabwe that showed that most fields were weeded between twice and thrice during the cropping season. The higher hoe weeding demand in PB compared to CONV tillage may be the reason for the low area under PB on most farms in Wards 12 and 14 of Masvingo District. During the 2008/09 season less than 50% of the cropped area was under PB on most farms in the study area.

Shortage in inputs such as fertiliser and seed was identified as a more important constraint in PB than labour availability. Most smallholder farmers had under PB an area that was equivalent to the seed and fertiliser that was received from CARE International. Without fertiliser CONV tillage farmers did not adopt CF/PB as they believed that the yield benefits would be minimal. Grabowski (2011) reports that although farmers in Mozambique were aware of the benefits of CA, the majority of farmers had small areas under CA. These smallholder farmers identified lack of inputs as the main reason for the low area under CA. Labour requirements were an additional constraint to the farmers in Masvingo District. However, under the low acreage committed to PB weeds could still be managed with available family labor. Planting basins out-yielded CONV tillage with the higher yields obtained in fields that had been under PB for the longest time (Chapter 5). The increased yields in PB were a result of improvements in soil fertility and weed management. The decrease in maize grain yield with increase in weed density at 3 WAP highlighted the importance of early season weed control in PB. If the yield benefits associated with PB are to be realised over large areas in smallholder agriculture, there is need to improve farmer access to inputs and investigate the use of low cost herbicide options such as banding to facilitate the widespread adoption of CF by labour-constrained smallholder farmers in southern Africa.

Therefore, PB was still associated with earlier and frequent weeding than CONV tillage suggesting that weed pressure may have been high early in the season in MT. Frequent hoe weeding was probably effective in diminishing the high weed infestation in PB. Weed species composition in PB was similar to that in CONV tillage. As weed density and the labor requirements did not decline with time under PB, the use of herbicides may facilitate the wide adoption of PB by labour-limited smallholders. However, weed composition in PB fields was quite variable suggesting that other management practices could have influenced in weed infestations in PB fields.

7.3.2 Influence of management practices

The positive correlation between frequency of manure use and weed density at 3 WAP and the increase in weed density within planting basins suggested that poorly stored compost introduced viable weed seeds to PB fields (Chapter 5). Although both pit and heap composting reduced the number of viable weed seeds in composts, composts applied in PB fields during the 2009/10 cropping season on most farms still contained viable weed seed (Chapter 6). Weed seedling emergence varied between farms from 0 to 142 seedlings kg^{-1} of compost reflecting possibly the differences in how the composts were stored (Appendix A and B). The weeds *E. indica*, *C. dactylon* and *Amaranthus hybridus* that were identified in the soil seed bank and in the above-ground-flora in fields (Chapter 5) were of high relative importance weeds in the applied composts (Chapter 6). This suggests that these species could have been introduced into fields through frequent use of poorly stored compost. A compost application rate of 6 t ha^{-1} would have introduced on average 6 weed viable seeds to each planting basin. This was probably one of the reasons for the increased weed emergence within planting basins observed during the 2008/09 season (Chapter 5).

Weed seedling emergence varied between composts obtained from the different farms probably due to differences in handling and storage. Pit stored compost had a lower weed seedling emergence than heap stored compost suggesting that pit storage was more effective at reducing weed seed viability. However, pit composting is more labour intensive than heap storage. Considering that PB tillage is already associated with high labour demands throughout the year it is unlikely that all the recommended pit composting practices will be followed on the majority of smallholder farms. Most PB farmers were untrained on composting and this may have resulted in the minimal reduction in weed seed viability and poor nutrient status of applied composts.

7.4 Conclusions

This study was the first to characterise weed population dynamics in details under recommended and actual smallholder farmer CA practices in semi-arid southern Africa. The focus of the on-station study were legume (cowpea) and small grain crops (sorghum) that are recommended for rotation with the staple maize crop under CA in semi-arid areas as these crops are drought tolerant. Agronomic or weed research on non-maize crop is limited from southern Africa. Important and new research findings were obtained from the study that will contribute to increased understanding of the behavior of weed species under the different management practices recommended in CA. This information will guide future research in developing low-cost weed management strategies for resource-limited smallholder farmers practicing CA in semi-arid areas in the region.

- Contrary to the widely held belief of CA promoters, weed growth under the recommended CA practices for smallholder farmers in Zimbabwe was higher than in CONV tillage early in the season after more than three years of CA practice. This finding has important implications for weed management as labour bottlenecks are common under smallholder agriculture early in the season and often result in delayed weeding and crop yield loss.

- The MT systems of PB and RT promoted in smallholder CA had poorer cowpea and sorghum grain yield than CONV tillage as a result of the sub-optimal crop populations in these tillage systems.

- Under the three-year maize-cowpea-sorghum rotation, maize residue retention and frequent hoe weedings practices in this study, there was no evidence of a shift to more difficult to control weed species with adoption of CA. However, the weed species *P.oleracea* may be a problem weed under CA when maize residue of 4 t ha^{-1} or lower are retained.

- Maize residue mulching offered limited benefit in CA. Retention of maize residue mulch especially at 8 t ha^{-1} was associated with limited weed suppression early in the season in sorghum. Contrary to expectations based on previous research findings, maize residue mulching and in particular the rate of 4 t ha^{-1} increased mid- to late season weed density and biomass in both cowpea and sorghum. This higher weed growth under mulch decreased sorghum grain yield.

- The effort required to manage weeds under CA was still double that required under CONV tillage on smallholder farms even after three years of recommended CA practice. Early and frequent hoe weeding (four times within the crop growing season) was still required in both the fifth and sixth years of CA to reduce weed growth and improve both cowpea and sorghum grain yields.

- On most smallholder farms, PB was the only CF component practiced by farmers in Wards 12 and 14 of Masvingo District. There was no evidence of a decline in weed density and intensity of hoe weeding with years a field had been under PB. Hoe weeding was done earlier and more frequently in PB relative to CONV tillage suggesting high early season weed infestations in PB.

- Poorly stored composts were identified as one of the recommended CF practices that exacerbated weed infestations in most PB fields through the introduction of viable weed seeds. Pit storage was more effective in reducing weed seed viability in composts.

7.5 Recommendations for future research

- There is need for research on use of herbicides combined with different hoe weeding frequencies to reduce weeding burden early in the cropping season. The economic feasibility of using full cover and band application of herbicides including glyphosate and atrazine should be explored to reduce the cost for resource-poor smallholder farmers. Farmer Field Schools and demonstration plots can be used to train farmers and extension workers on weed identification and proper use of herbicides.

- More research should be done on biology and ecology of weed species as this is not available for most species in southern Africa. Information on weed biology and ecology can assist in making predictions on behavior of individual species or a group of related species when there is a change in management practices.

- Improvements in CA should include the development of appropriate crop spacing for small grain and legume crops in CA as the current wide spacings can compromise yields. The option of intercropping legumes should be explored including identification of suitable varieties, optimum spacing and planting density.

- There is also a need to train CA farmers on composting so as to improve nutrient quality and reduce weed seed viability.

- Detailed research is required to determine the mechanisms behind the effect of crop residue mulching on weed and crop growth on different soil types. There is a need for long-term research on CA to be carried out on contrasting soils and under researcher management and farmer management to more effectively evaluate weed population changes in the long-term.

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APPENDICES

Appendix A. Handling of heap stored cattle manure on farms during the 2009/10 season in Wards 12 and 14 of Masvingo District

Farm	Storage	Material added	Heaping period (months)	Cover
1[§]	Heap	Maize stover, dry weeds	3	None
11	Deep stall	Maize stover	1	None
12	Heap	Maize stover, grass weeds	6	None
13	Heap	Maize stover	3	None
14	Heap	Maize stover	3	None
15	Heap	Maize stover	4	None
16	Deep stall	Maize stover	1	None

[§] paired immature and mature samples obtained.

Appendix B. Handling of pit stored compost on farms in Wards 12 and 14 of Masvingo District during the 2009/10 season

Farm[§]	Storage	C source	N source	Water	Cover	Turned	Period (m)
2	Pit 2.5 m deep	30 cm layers of maize stover, forest litter.	Poultry and goat manure, household wastes.	Added	Anthill soil and ash.	No	14
3	Pit	Crop stover, weeds	Kraal manure, household wastes.	Added	Soil	No	7
4	Pit 1 m(depth)* 4 m * 4 m	Forest and fruit tree litter, maize stover.	Kraal manure, green grass, ammonium nitrate (AN).	Added	AN	No	15
5	Pit	Forest litter, crop stover.	Household wastes.	Rainfall	None	Yes	7
6	Shallow pit	Forest litter.	None	None	None	No	4
7	Pit	Forest litter, maize stover.	None	Added	None	No	4
8	Pit	Maize stover and cobs.	Household wastes.	Added	None	No	7
9	Pit	Maize stover, weeds.	Household wastes.	Added	None	No	8
10	Pit	Maize stover, forest litter.	Household wastes, green grass weeds.	Added	Ash	No	4

[§] paired immature and mature samples obtained from site 2