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.

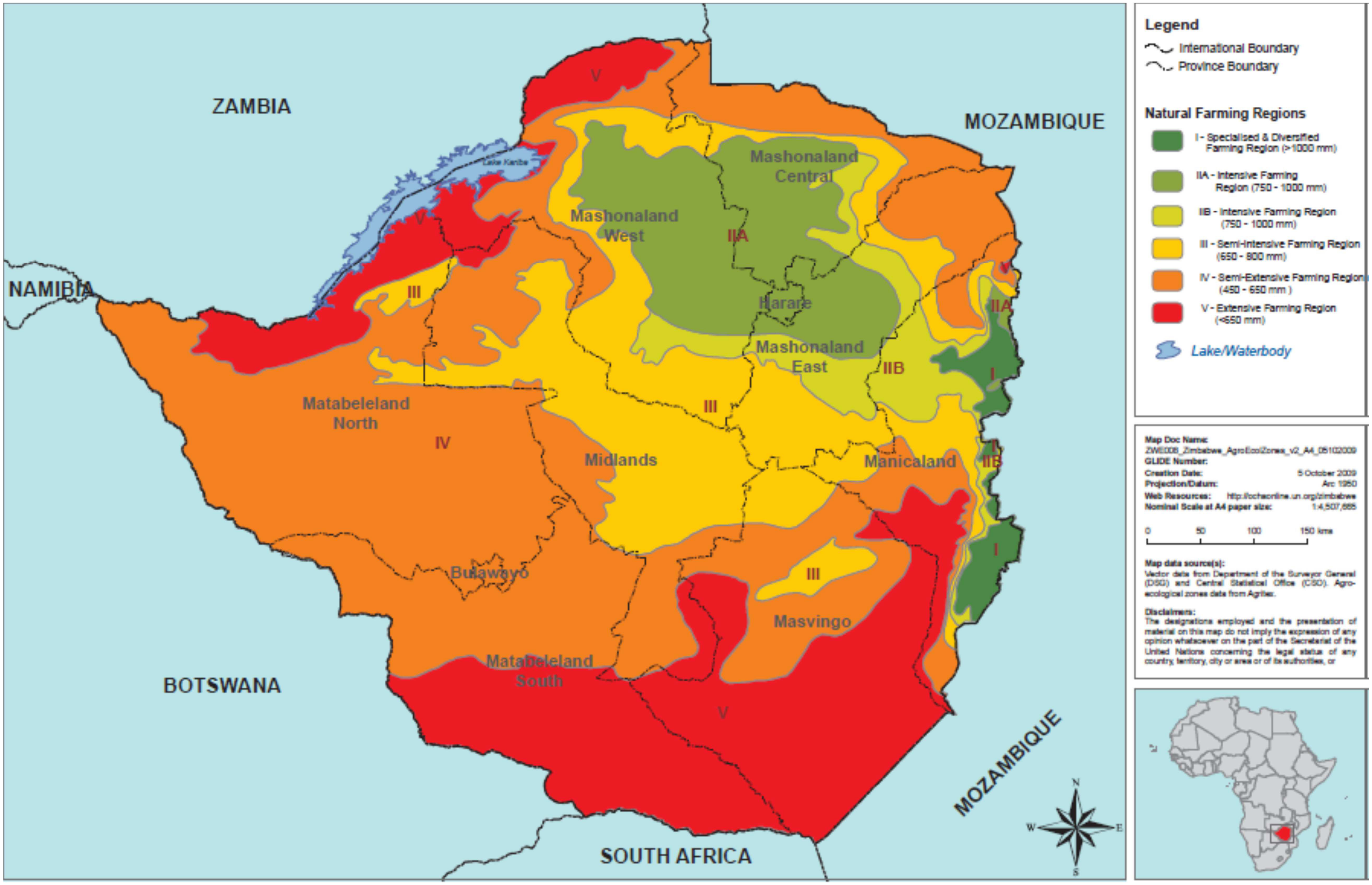

Fig. 2.1 The Natural Regions (NR) of Zimbabwe (Adopted from OCHA, 2009)

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).

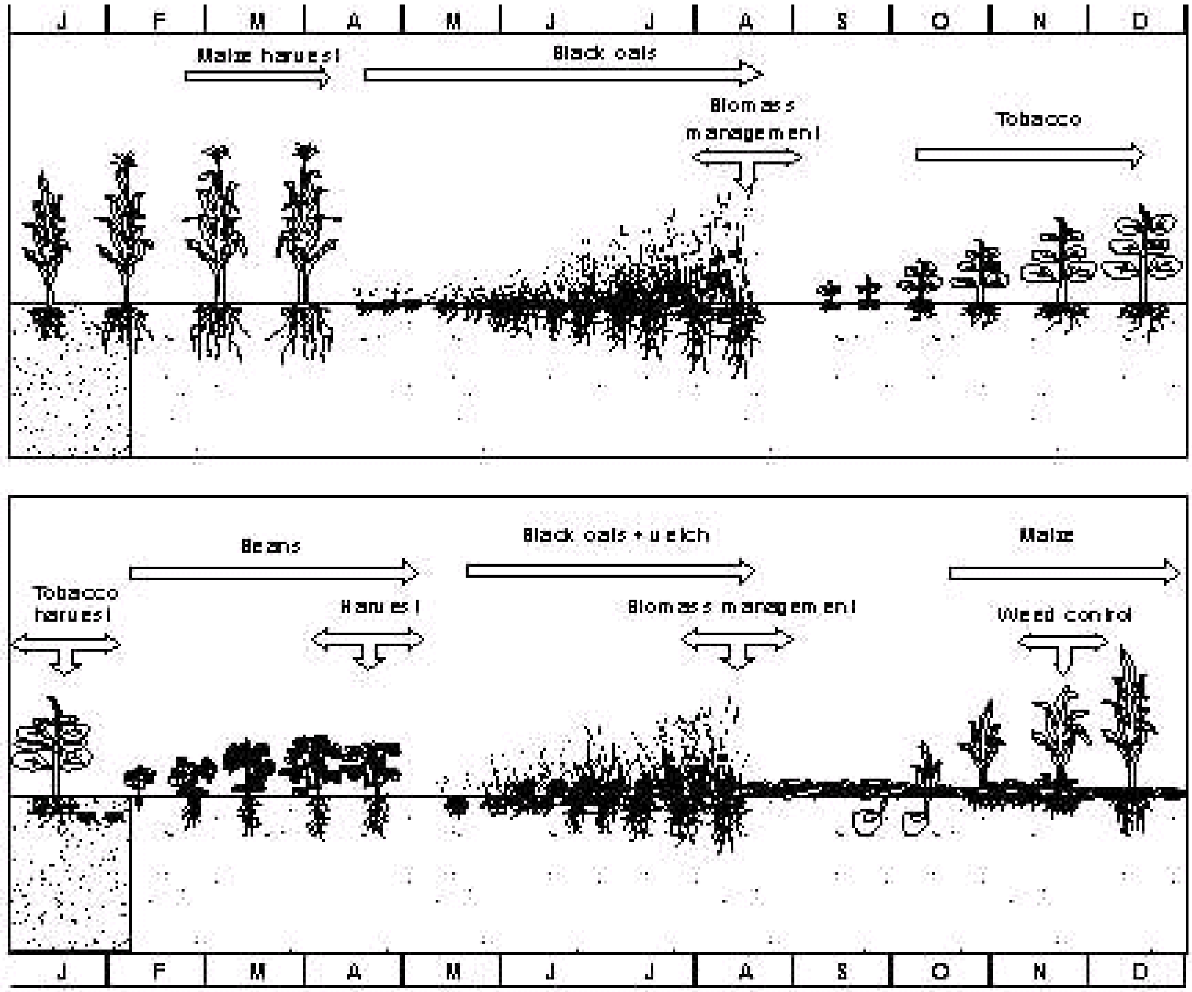

Fig. 2.2 A diversified crop rotation to maintain soil fertility and break pest lifecycle (FAO, 2012)

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).

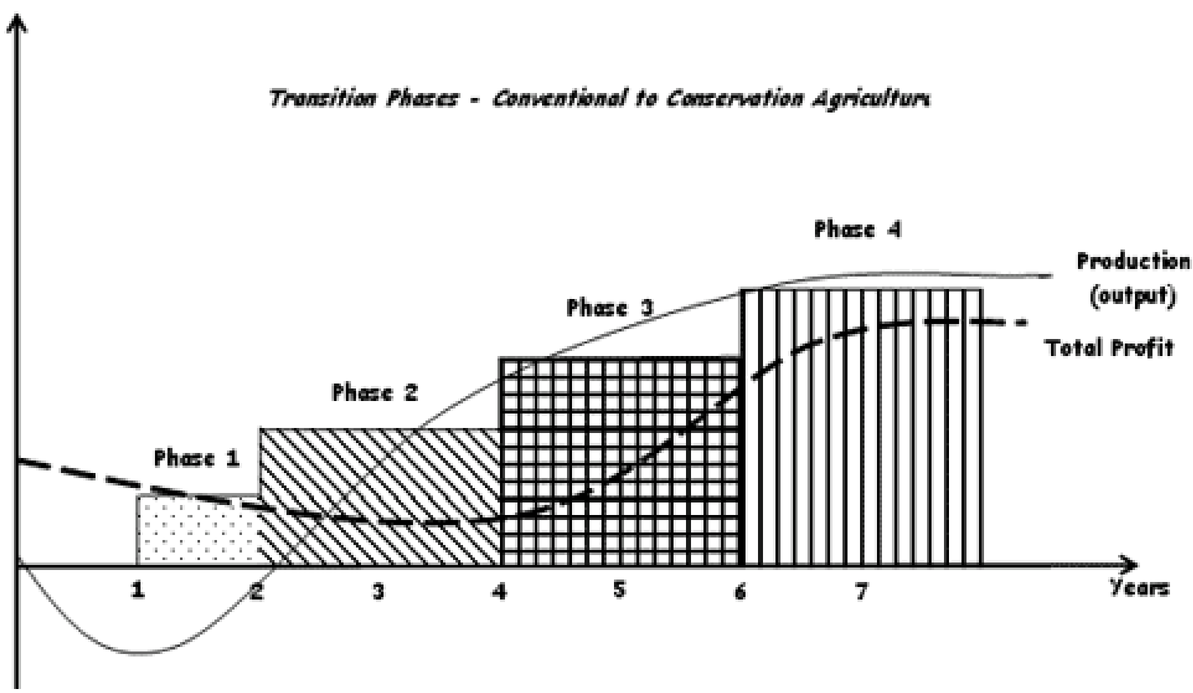

Fig. 2.3 The theoretical transition phases from conventional practice to CA (FAO, 2012b)

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.

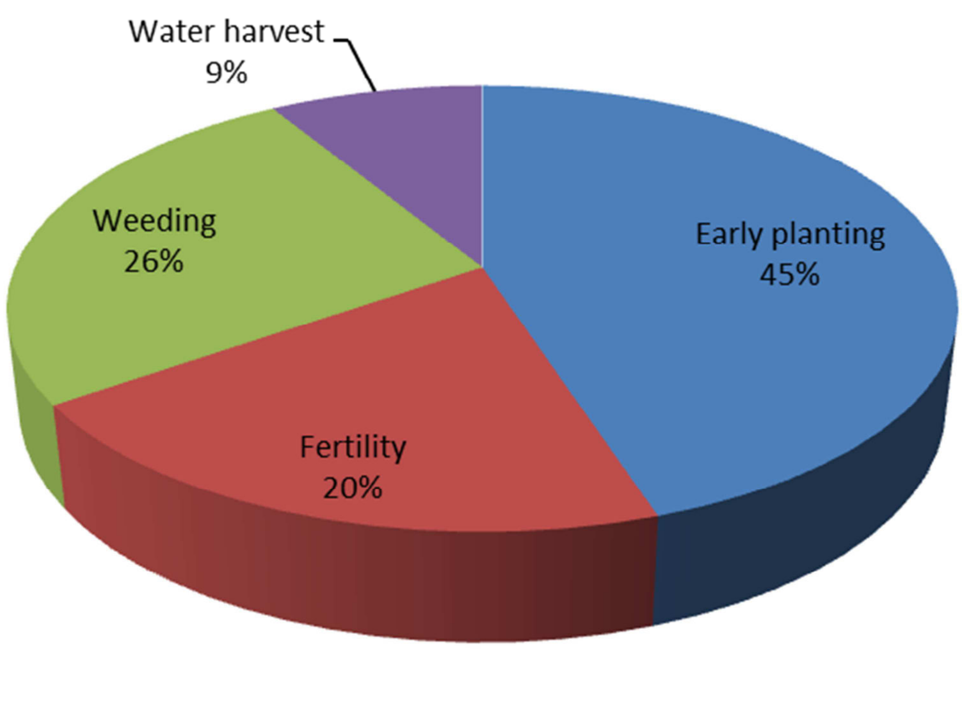

Fig. 2.4 Proportion contributed to increased maize grain yields on smallholder farmers' CF fields in southern Zambia (Adopted from GART, 2008)

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.