Chapter 2
Crop Rotations and Residue Management in Conservation Agriculture

Leonard Rusinamhodzi

Abstract Yield increases and sustainability of conservation agriculture (CA) systems largely depend on systematic crop rotations and *in situ* crop harvest residue management coupled with adequate crop nutrition. In this chapter, the beneficial effects of crop residue management and crop rotations on maize (*Zea mays* L.) grain yield in CA systems under rainfed conditions are explained through a meta-analysis. The effects of crop residue management are most beneficial under rainfed conditions as rainfall distribution is often erratic and seasonal dry spells common. The meta-analysis was based on the weighted mean difference (WMD) effect size using the random effects model. Yield advantages of CA systems over conventional tillage systems were only significant when in rotation, under low rainfall conditions and with large N fertiliser inputs. The WMD for CA with continuous maize ranged from -1.32 to 1.27 with a mean of -0.03 t ha^{-1}, and when rotation was included the WMD ranged from -0.34 to 1.92 with a mean of 0.64 t ha^{-1}. Mulch retention under low rainfall (<600 mm) had a WMD between -0.2 and 1.0 with a mean of 0.4 t ha^{-1} while high rainfall (>1000 mm per season) reduced the yield advantage with the WMD ranging from -1.2 to 0.02 with a mean of -0.59 t ha^{-1}. CA is likely to have the largest impact in low-rainfall environments where increased infiltration of rainfall and reduced evaporative losses are achieved by retaining crop residues. However, it is in these areas that achieving sufficient crop residues is a challenge, particularly in mixed crop–livestock systems where crop residues are needed for livestock feed in the dry season. The results suggest that CA needs to be targeted and adapted to specific biophysical as well as socioeconomic circumstances of farmers for improved impact. The ability of farmers to purchase fertiliser inputs, achieve sufficient biomass production as well as produce alternative feed will allow them to practise CA and possibly achieve large yields.

Keywords Crop rotation · Crop residues · Conservation agriculture · Maize grain yield · Meta-analysis · Weighted mean difference · Rainfed conditions

L. Rusinamhodzi (✉)
CIRAD—Agro-ecology and Sustainable Intensification of Annual Crops, c/o CIMMYT Regional Office, Mt Pleasant, Harare, Zimbabwe
e-mail: leonard.rusinamhodzi@gmail.com

© Springer International Publishing Switzerland 2015
M. Farooq, K. H. M. Siddique (eds.), *Conservation Agriculture*,
DOI 10.1007/978-3-319-11620-4_2

2.1 Introduction

Systematic crop rotations and *in situ* crop harvest residue management are the pillars of conservation agriculture (CA). Yet, they are also the most pronounced barriers to its widespread practice especially on smallholder farms in the tropics. A crop rotation is the sequence of crop types grown in succession on a specific field (Wibberley 1996; Castellazzi et al. 2008). Crop rotations play a key role in CA systems where they facilitate soil fertility replenishment while at the same time minimising pest and disease build-up (Trenbath 1993). Crop rotations with leguminous crops have the potential to increase soil nitrogen (N) concentration through biological nitrogen fixation (BNF; Giller 2001). Research results have shown that synthetic fertilisers or organic manure do not solve the challenges of soil degradation and fertility decline except when used in combination (Chivenge et al. 2009, 2011). The use of mineral fertiliser is needed and should be combined with management practices that build up organic carbon and achieve sustainability in the longer term. The underlying hypothesis of this chapter is that yield increases in CA over conventional agriculture systems are underpinned by successful crop residue management and crop rotation, and such yield increases differ according to fertiliser inputs by farmers and the amount and distribution of seasonal rainfall.

The importance of crop residue retention to sustainability of crop production is widely acknowledged. *In situ* retention of crop harvest residues coupled with no tillage has the potential to increase substantially soil organic carbon (SOC) although current data and knowledge are inconclusive (Govaerts et al. 2009). However, there is consensus that consistent and sufficient C inputs are the major determinants of SOC changes in soil and not so much the type of tillage (Chivenge et al. 2007). Reduced tillage is important in reducing decomposition rates but this is only relevant if sufficient organic inputs have been applied (Chivenge et al. 2007). The absence of soil inversion may lead to SOC accumulation in the top layers of the soil (Franzluebbers and Arshad 1996). Carbon increases are expected over time if the amount of crop residue retained is more than that dissipated by the oxidation process. Current literature suggests that the importance of crop residue retention in the short term might be related to the maintenance of SOC rather than its absolute increase.

Crop residues provide soil cover which decreases run-off and soil loss especially on low slopes but it is less effective on steep slopes (Adekalu et al. 2007). In a study on a utisol in Nigeria, Adekalu et al. (2007) reported that water infiltration increased with increasing levels of mulch cover (giant elephant grass) and decreased with increasing slope. The authors suggested that to improve infiltration and reduce run-off and soil erosion, up to 90 % cover may be necessary especially if organic matter is low and sand content is high. Other researchers have suggested mulch application rates of 4–6 t ha^{-1} as adequate (Lal 1976; De Silva and Cook 2003) but what these quantities translate to in terms of soil cover for different crops is not well known (Morrison et al. 1985). Some authors suggest that mulch rates of up to 6 t ha^{-1} may completely eliminate soil loss (Fig. 2.1, Lal 1998; Adekalu et al. 2006, 2007). Understanding the interactions between the type and rate of mulch application, the

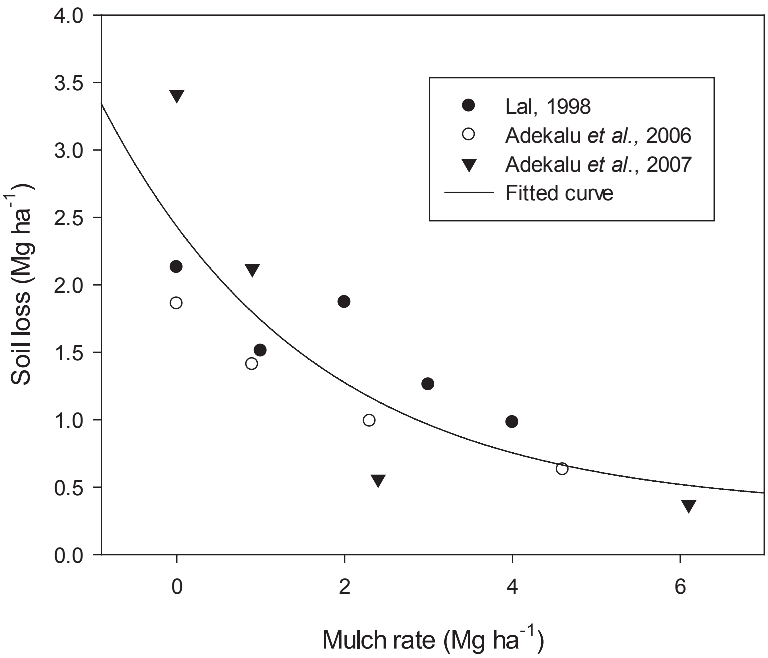

Fig. 2.1 The relationship between the amount of crop residue retained and soil loss. (Data used were reported by Adekalu et al. 2006, 2007; Lal 1998)

contribution to nutrient enhancement in soil and the potential for crop yield improvement are needed (Cook et al. 2006). Crop residues have low thermal conductivity such that mulching can reduce soil temperature for optimal germination and root development in hot environments (Lal 1978; Riddle et al. 1996). They insulate the soil surface and increase resistance to heat and vapour transfer leading to increased available soil water (Hatfield and Prueger 1996; Dexter 1997; Cook et al. 2006). Mulch is also important for intercepting rainfall energy and reduces erosion. In areas of relatively short duration and low-intensity rainfall, mulching may reduce soil water recharge; this could be crucial in areas with frequent and small amounts of rainfall because it can be intercepted before it recharges the topsoil (Sadler and Turner 1993; Savabi and Stott 1994). It has also been suggested that the crop residue thickness has a direct effect on total interception of rainfall (Savabi and Stott 1994). Thus, mulch application is not always positive and may be detrimental to crop productivity.

In cereal-based systems which dominate the tropics, most crop residues are derived from maize, millet and sorghum, which are rich in lignin and have high C/N ratios that are generally greater than 60 (Cadisch and Giller 1997; Handayanto et al. 1997). Although crop residues are often on the soil surface, they are more likely to partially incorporate and decompose as the season progresses adding to SOC (Parker 1962). However, the wide C/N ratio leads to prolonged N immobilization by microorganisms, rendering N unavailable for crop growth in the short term (Giller et al. 1997). Thus, high N inputs are required when poor-quality crop residues are used as mulch cover.

This chapter collates and performs a meta-analysis on existing literature on the effect of crop rotations and crop residue management on maize grain yield under CA. Meta-analysis allows combined quantitative analyses of experimental yield data reported in the literature and estimation of effect sizes (Glass 1976; Rosenburg et al. 2000; Ried 2006; Borenstein et al. 2009). The analysis increases the statistical power available to test hypotheses and can help unravel differences in responses between treatments under different environments (Gates 2002; Borenstein et al. 2009). The effect size for each individual study is considered an independent estimate of the underlying true effect size, subject to random variation. All studies contribute to the overall estimate of the treatment effect whether the result of each study is statistically significant or not thus reducing publication bias. Data from studies with more precise measurements or larger studies (many cases) are given more weight, so they have more influence on the overall estimate (Gates 2002). However, meta-analysis has potential weaknesses due to publication bias and other biases that may be introduced in the process of locating, selecting and combining studies (Egger et al. 1997; Noble 2006). Publication bias arises when researchers, reviewers and editors submit or accept manuscripts for publication based on the direction or strength of the study findings (Dickersin 1990). This means that studies reporting contradictory or neutral results are likely to be omitted from publications. To reduce publication bias, data searches were carried out online to find results from all parts of the world under rainfed conditions. Some researchers were also contacted to provide some grey literature. Moderators, i.e. factors likely to influence effect sizes such as mean annual precipitation (MAP) and N fertiliser input, were identified during data collation and the random effects model was used during the analysis (Ried 2006).

2.2 Meta-analysis

Maize grain yield data were obtained from studies on the effect of crop residue management and crop rotation. Due to the voluminous nature of the search results, meta-analysis was restricted to rainfed conditions in semiarid and subhumid environments where the effects of mulch on crop productivity would be better assessed. Data searches were predominantly online and obtained from refereed journals, book chapters or peer-reviewed conference proceedings. The following keywords and their combinations were searched: crop rotations, legumes, CA, mulch cover, no tillage, maize yield, corn yield, subhumid, semiarid and rainfed. The treatments from which maize grain yield data were collated are described in Table 2.1. Nutrient inputs needed to be the same across the treatments tested in each study. Unpublished data or grey literature was obtained from researchers working on CA. Result moderators or factors likely to influence the meta-analysis outcome such as annual rainfall and N input as reported in the literature were included in the analysis. Fifty publications met the selection criteria and were used in the meta-analysis (Table 2.2).

Table 2.1 Tillage treatments used in the meta-analysis

Tillage management option	Short description
Conventional tillage (CT)	Mouldboard ploughing without crop residue retention. The most widely practised tillage technique used by communal farmers with animal draught power in southern Africa
No tillage + mulch (NTM)	Practice of minimising soil disturbance plus previous crop residues to achieve soil cover after planting. Weed control is accomplished primarily with herbicides
No tillage + mulch + rotation (NTMR)	As described above for NTM. Main crop of maize in a rotation sequence with legumes such as soybean (*Glycine max* L.) or cowpea (*Vigna unguiculata* (L.) Walp)

The meta-analysis procedure and calculation followed that described by Rusinamhodzi et al. (2011) as presented below. Data required for the meta-analysis were in the form of treatment mean ($\bar{X}$), standard deviation ($SD_{\bar{X}}$), and number of replicates (n) mentioned in the experimental design. Several authors presented statistical data in different formats such as standard error $SE_{\bar{X}}$ and coefficient of variation ($CV\%$). These were converted to standard deviation ($SD_{\bar{X}}$) using the following equations: $SD_{\bar{X}} = SE_{\bar{X}} \times \sqrt{n}$ and $SD_{\bar{X}} = \left(\frac{CV\%}{100}\right) \times \bar{X}$. Effect size was obtained by computing the weighted mean difference (WMD) using the random effects model (DerSimonian and Laird 1986; Borenstein et al. 2009). The mean difference (Eq. 2.1) in yield between the treatment and control was used due to its ease of interpretation and the relevance for comparing potential gains (Ried 2006; Sileshi et al. 2008). To obtain overall treatment effects across studies, the differences between treatment and control were weighted (Eq. 2.3). The weight given to each study was calculated as the inverse of the variance (Eq. 2.2). The random effects model assumed that the true effect of CA on crop yield varied from site to site and from season to season; thus, contributions of each study to the overall effect size were considered independent. Nitrogen input and amount of seasonal rainfall were chosen as the most important moderators and their effect tested on the magnitude of the responses (mean differences). Nitrogen input and MAP classes were categorized as reported by Rusinamhodzi et al. (2011) with MAP classes as low (<600 mm), medium (600–1000 mm) and high (>1000 mm), and N fertiliser input as low (<100 kg ha^{-1}) and high (>100 kg ha^{-1}):

$$\text{Mean difference (MD)} = \text{mean}_{\text{treated}} - \text{mean}_{\text{control}} \tag{2.1}$$

$$\text{weight}_i = \frac{1}{\text{variance}_i} = \frac{1}{\text{SD}_i^2} \tag{2.2}$$

$$\text{Weighted mean difference (WMD)}_{\text{overall}} = \sum_{i=1}^{i=n} (\text{weight}_i * \text{MD}) / \sum_{i=1}^{i=n} \text{weight}_i \tag{2.3}$$

$$\text{CI}_{95\%} = \text{mean}_{\text{overall}} \pm (1.96 * (\text{variance}_{\text{overall}})^{0.5}) \tag{2.4}$$

Table 2.2 Site information for experiments used in the meta-analysis

Country	Treatments	Reference
Madagascar	CT, NT, NTR	Djigal et al. (2012)
USA	CT, NT	Wilhelm and Wortmann (2004)
USA	CT, NT	Karlen et al. (1991)
USA	CT, NT	Griffith et al. (1988)
USA	CT, NT, NTM	Linden et al. (2000)
Nigeria	CT, NT, NTM	Lal (1997)
Zimbabwe	CT, NT	Vogel (1993)
Zimbabwe	CT, NT	Moyo (2003)
Zimbabwe	CT, NT	Nehanda (2000)
USA	CT, NT	Olson et al. (2004)
USA	CT, NT	Wilhelm et al. (1987)
Australia	CT, NT	Thiagalingam et al. (1996)
USA	CT, NT	Iragavarapu and Randall (1995)
India	CT, NT, NTM	Acharya and Sharma (1994)
Brazil	CT, NT	Sisti et al. (2004)
China	CT, NTM	Jin et al. (2007)
USA	CT, NT	Karunatilake et al. (2000)
Italy	CT, NT	Mazzoncini et al. (2008)
Canada	CT, NT, NTM	Dam et al. (2005)
Mexico	CT, NT, NTM	Fischer et al. (2002)
USA	CT, NT	Rice et al. (1986)
India	CT, NTR	Ghuman and Sur (2001)
USA	NT, NTR	Karlen et al. (1994b)
USA	CT, NT, NTR	Ismail et al. (1994)
Zimbabwe	CT, NT	Nyagumbo (2002)
USA	CT, NT	Dick and Van Doren (1985)
Zimbabwe, Zambia	CT, NT	Marongwe et al. (2011)
Malawi	CT, NT, NTR	Ngwira et al. (2012a)
Malawi	CT, NT, NTR	Ngwira et al. (2012b)
Malawi, Mozambique, Zambia, Zimbabwe	CT, NT, NTR	Thierfelder et al. (2012a)
Zimbabwe	CT, NT, NTR	Thierfelder et al. (2012b)
Malawi	CT, NT, NTR	Thierfelder et al. (2013a)
Zambia	CT, NT, NTR	Thierfelder et al. (2013c)
Malawi, Mozambique, Zambia, Zimbabwe	CT, NT	Thierfelder et al. (2013b)
Zimbabwe	CT, NT	Thierfelder and Wall (2012)
Kenya	CT, NT, NTM	Paul et al. (2013)
Nigeria	CT, NT	Osuji (1984)
Zimbabwe	CT, NT, NTR	Mupangwa et al. (2007)
Zimbabwe	CT, NT, NTR	Mupangwa et al. (2012)
Nigeria	CT, NT	Mbagwu (1990)
Kenya	CT, NT, NTR	Kihara et al. (2012)

CT conventional tillage, *NT* no tillage, *NTM* no tillage with mulch

$$\text{Variance}_{\text{overall}} = \frac{1}{\sum_{i=1}^{i=n} \text{weight}_i}. \tag{2.5}$$

2.3 Yield Data from Different Mulch and Crop Rotations

The WMD of CA with continuous maize cropping was almost zero but ranged from −1.32 to 1.27 t ha^{-1} (Fig. 2.2). Including the rotation into the CA system increased the WMD which ranged from −0.34 to 1.92 t ha^{-1} with a mean of 0.64 t ha^{-1}. Retention of mulch alone without crop diversification does not necessarily lead to improved crop productivity. The overall effect of mulch on crop productivity could be considered neutral in this case. These results agree with Kapusta et al. (1996) who observed no significant yield difference between no tillage and conventional ploughing on poorly drained soils after 20 years of continuous no tillage. Similarly, Dam et al. (2005) reported that, after 11 years, maize yields were more affected by the amount of rainfall and temperature across years than tillage and crop residue management. Rotations especially with legumes often have positive effects on maize yield across soil fertility regimes (Karlen et al. 1991, 1994a). The larger yield in rotation compared with continuous monocropping was attributed to reduced pest infestations, improved water-use efficiency, good soil quality as shown by increased organic carbon, greater soil aggregation, increased nutrient availability and greater soil biological activity (Van Doren et al. 1976; Hernanz et al. 2002; Kureh et al. 2006). In the Highlands of Madagascar, Djigal et al. (2012) observed CA systems that supported comparable or better yields in the long term than conventional tillage if crop rotation was correctly managed.

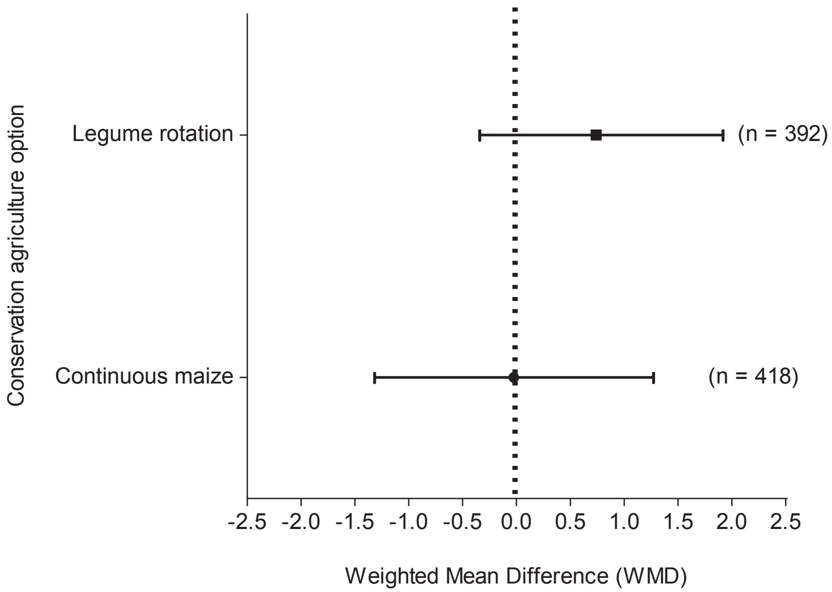

Fig. 2.2 The weighted mean difference (*WMD*) for continuous maize under conservation agriculture (*CA*) and for maize in rotation with legumes under CA. The WMD were computed as the difference in yield of the CA options over continuous maize cropped using conventional tillage

Subgroup analysis of continuous maize production with mulch suggested that the amount of seasonal rainfall and fertiliser inputs are important yield moderators. The most yield advantage (WMD between −0.2 and 1.0 t ha^{-1}) from mulch retention was obtained in environments where seasonal precipitation did not exceed 600 mm, with an overall effect of 0.4 t ha^{-1} (Fig. 2.3). The yield advantages from mulch application decreased with increasing seasonal rainfall as expected; above 600 mm, there was no yield advantage from mulch retention over conventional tillage. The retention of mulch increases rainfall infiltration into the soil and reduces evaporative losses resulting in waterlogging. In other studies, yields under CA practices were 5–20% less than under conventional tillage practices in wet years, but 10–100% higher in relatively dry years (Hussain et al. 1999). Similarly, Lueschen et al. (1991) reported larger crop yields with CA practices than conventional tillage in a relatively dry year.

Retention of mulch requires a concomitant increase in N inputs to ensure larger yields. WMD for systems where N input was less than 100 kg ha^{-1} indicated that conventional systems would yield more than CA options tested (Fig. 2.4). When N fertiliser input was raised beyond 100 kg ha^{-1}, the WMD had a yield advantage for CA over conventional tillage. The results agree with Vanlauwe et al. (2014) who identified adequate nutrient management in CA systems as another critical factor, i.e. the need for a fourth principle. Similarly, Díaz-Zorita et al. (2002) reported that maize yields increased more with nitrogen fertilisation than tillage under subhumid

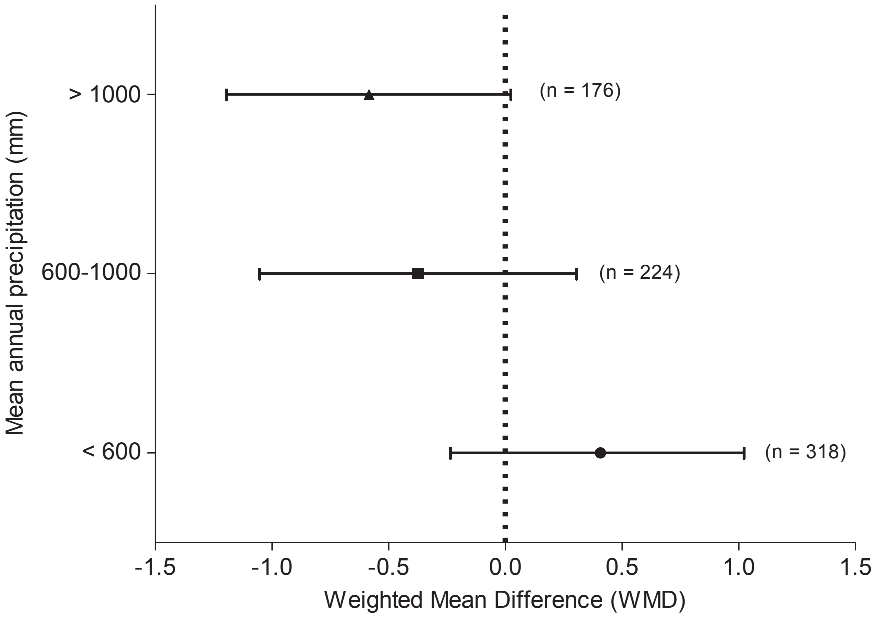

Fig. 2.3 The weighted mean difference (WMD) for continuous maize under conservation agriculture (CA) under different rainfall categories. The WMD were computed as the difference in yield of the CA over continuous maize cropped using conventional tillage

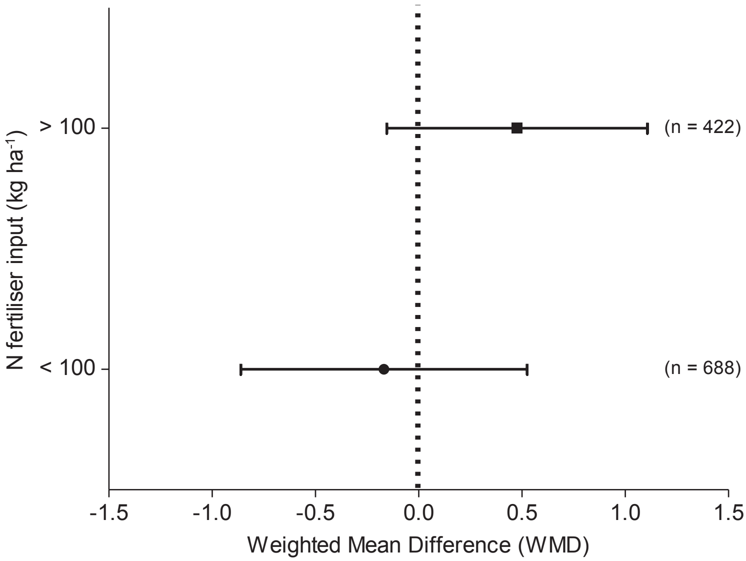

Fig. 2.4 The weighted mean difference (WMD) for continuous maize under conservation agriculture (CA) under different N fertiliser categories. The WMD were computed as the difference in yield of the CA over continuous maize cropped using conventional tillage

and semiarid regions of Argentina. The most notable crop residues in semiarid areas are those of maize, millet and sorghum of poor quality due to high C/N ratios, generally greater than 60, which immediately immobilizes N (Cadisch and Giller 1997; Handayanto et al. 1997). Thus, high N inputs are required when poor-quality crop residues are used as mulch.

2.4 Constraints to Systematic Crop Rotations

Poorly developed markets, minimal household food contributions and limited land sizes are the major impediments to successful crop rotations by smallholder farmers. Widespread poverty prevents farmer access to credits and inputs such as fertiliser, seed and pesticides (Graham and Vance 2003; Sanginga and Woomer 2009). Specialized agrifood markets such as those in Laos limit the integration of grasses and legumes into diversified crop rotations (Lestrelin et al. 2012). Limited landholdings are becoming a major problem due to the rising population pressure—a classic example is in Malawi where land sizes are often below 1 ha limiting the number of crops farmers can grow in a season (Ellis et al. 2003; World Bank 2007). Soil fertility decline is another major challenge in the field where deficiencies of phosphorus (P), potassium (K), sulphur (S) and micronutrients such as zinc (Zn), molybdenum (Mo) and boron (B) may limit legume growth and N_2 fixation (O'Hara et al. 1988). P availability is often regarded as the most limiting factor (Giller and

Cadisch 1995). At the farm level, it is important that grain legumes provide multiple benefits especially as a food and are acceptable to farmers (Giller 2001). Formal seed systems are poorly developed with limited varieties of maize seed available, often open-pollinated varieties. Most farmers use retained seed, informal seed exchanges with other farmers and seed bought from local markets. They see their local seed as better adapted to their conditions but lack of quality uniformity means they are less preferred at the market (cf. Rohrbach and Kiala 2007). Widespread adoption of legume production will be achieved by strengthening seed systems, improving farmer access to input markets for improved, short-season and disease-resistant varieties and P fertiliser and output markets for better prices and trade terms.

2.5 Constraints to Crop Residue Management

A comprehensive appraisal of the benefits and constraints related to crop residue management has been explored (Erenstein 2002; Lal 2005). Major constraints to successful crop residue management in CA systems are related to the small baseline crop productivity and other alternative economic uses of crop residues such as livestock feed, fuel, bedding in kraals (animal paddocks) during the rainy season and construction (fencing and thatching) for some farming households (Mazvimavi et al. 2008; Erenstein 2011; Rufino et al. 2011; Johansen et al. 2012). Crop and livestock production are closely integrated in mixed smallholder farming systems in much of the tropics (Thornton and Herrero 2001; Rufino et al. 2011). Crop residues are needed to provide livestock feed during the dry season where feed is severely limited while manure is needed for crop production (Rufino et al. 2011; Rusinamhodzi et al. 2013). The application of livestock manure has been shown to increase crop productivity especially targeted to responsive fields (Zingore et al. 2008; Rusinamhodzi et al. 2013). Such yield benefits derived from manure, whose quantity and quality partly depends on crop harvest residues (Nzuma and Murwira 2000; Lekasi et al. 2003; Rufino et al. 2007), suggest that farmers face trade-offs in crop residue management and it might be beneficial for them to follow the manure production pathway than apply crop residues as mulch (Naudin et al. 2012; Valbuena et al. 2012; Rusinamhodzi 2013). Moreover, livestock provides a source of cash income and spreads the risk (Sumberg 2002; Rufino et al. 2006). In most situations, alternative grazing does not exist as communal rangelands are often degraded and characterized by poor-quality fodder (Rufino et al. 2011). Although development agents have made potential legume, grass and other agroforestry trees available for use as a fodder, farmers reject them because they do not contribute directly to food security despite the enormous labour inputs required (Giller 2001). The unimodal nature of the cropping seasons suggest that farmers concentrate all their limited resources to major food production and other crops are considered much later in the season leading to small productivity.

On the other hand, the availability of crop residues is not a technological panacea. The overall effect depends on the local biophysical and socioeconomic environ-

http://www.springer.com/978-3-319-11619-8

Conservation Agriculture
Farooq, M.; Siddique, K. (Eds.)
2015, XIX, 665 p. 40 illus. in color., Hardcover
ISBN: 978-3-319-11619-8