Renewable Agriculture and Food Systems

cambridge.org/raf

Research Paper

Cite this article: Mupangwa W, Thierfelder C, Cheesman S, Nyagumbo I, Muoni T, Mhlanga B, Mwila M, Sida TS, Ngwira A (2019). Effects of maize residue and mineral nitrogen applications on maize yield in conservation-agriculture-based cropping systems of Southern Africa. *Renewable Agriculture and Food Systems* 1–14. https://doi.org/10.1017/S174217051900005X

Received: 11 May 2018
Revised: 2 October 2018
Accepted: 2 January 2019

Key words:
Chlorophyll; crop–livestock interaction; immobilization; residue retention; sustainable intensification

Author for correspondence:
W. Mupangwa, E-mail: w.mupangwa@cgiar.org; mupangwa@yahoo.com

Effects of maize residue and mineral nitrogen applications on maize yield in conservation-agriculture-based cropping systems of Southern Africa

W. Mupangwa[1], C. Thierfelder[2], S. Cheesman[2,3], I. Nyagumbo[2], T. Muoni[2,4], B. Mhlanga[2], M. Mwila[5], T. S. Sida[1] and A. Ngwira[6]

[1]International Maize and Wheat Improvement Centre, ILRI Sholla Campus, P O Box 5689, Addis Ababa, Ethiopia; [2]International Maize and Wheat Improvement Centre, P.O. Box MP 163, Mount Pleasant, Harare, Zimbabwe; [3]Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, P.O. Box 8016, Windhoek, Namibia; [4]University of Zimbabwe, P.O. Box MP 167, Mount Pleasant, Harare, Zimbabwe; [5]Zambia Agriculture Research Institute, Msekera Research Station, P.O. Box 510089, Chipata, Zambia and [6]International Crops Research Institute for the Semi-Arid Tropics, Chitedze Research Station, P.O. Box 1096, Lilongwe, Malawi

Abstract

Conservation agriculture (CA) and no-till (NT)-based cropping systems could address soil degradation and fertility decline in southern Africa. A multi-location and multi-year experiment was carried out between 2008 and 2014 to assess the effects of different levels of maize residue biomass (0, 2, 4, 6 and 8 t ha^{-1}) and nitrogen (N) fertilizer (0, 30, 90 kg ha^{-1}) on maize performance under no-tillage. In some sites, different (N) fertilizer levels were superimposed to test their effects on maize grain yield and leaf chlorophyll content under different maize residue biomass levels. The different residue levels had no significant effect on maize yield in most growing seasons. Maize residue cover increased grain yield in eight out of 39 site-years across the sites used. However, in some sites, maize yield decreased with increases in residue level in cropping seasons that had average to above average rainfall. At a few sites maize yield increased with increase in residue level. Seasonal rainfall pattern influenced the effect of different residue levels on grain yield at most sites. Nitrogen fertilizer increased maize yield regardless of the residue level applied. This study demonstrates that mulching with maize residues in CA/NT systems results in limited maize yield gains – at least within the first 6 years in different agro-ecological conditions of southern Africa.

Introduction

Smallholder farming systems of southern Africa are characterized by mixed crop and livestock production (Valbuena *et al*., 2012; Duncan *et al*., 2013). Crops are multi-purpose as they are a source of food and income, but also provide residues that are used as dry season feed for livestock (Homann-Kee Tui *et al*., 2013; Mupangwa and Thierfelder, 2014). Often crop residues are left in the field after harvest and livestock graze them *in-situ* during the dry season (Rusinamhodzi *et al*., 2013). Cereal residues are also used for bedding in livestock pens (locally called kraals), construction and as a source of fuel (Jaleta *et al*., 2015). In most instances smallholders are not producing enough biomass quantities to meet livestock feed requirements in mixed farming systems (Duncan *et al*., 2013). This is mainly attributed to low crop productivity on highly degraded granitic sandy soils with low organic matter content, micronutrient deficiencies and low input use (e.g. mineral fertilizer) on smallholder farms (Twomlow *et al*., 2006; Jayne *et al*., 2010; Nyamangara *et al*., 2013).

Conservation agriculture (CA)-based crop management systems have shown great potential for improving crop productivity on smallholder farms (Kassam *et al*., 2009; Wall *et al*., 2013; Thierfelder *et al*., 2015). The CA-based cropping systems involve the use of minimum soil disturbance, crop rotation and permanent/semi-permanent soil cover through crop residue retention or cover crops which should be applied in a mutually reinforcing manner to make use of their synergistic effects within the system (FAO, 2015). The challenges to adapt CA to the circumstances of smallholder farmers have received significant attention (Giller *et al*., 2009; Andersson and D'Souza, 2014; Palm *et al*., 2014; Pittelkow *et al*., 2014). While minimum soil disturbance seems to be a CA principle that is easily adopted by farmers, residue retention and crop rotations are more difficult to achieve and are closely bound to social and economic factors in the smallholder sector (Mazvimavi and Twomlow, 2009).

Crop yield responses in CA or no-till (NT)-based cropping systems have been variable, with positive yield increases observed in some studies (Thierfelder *et al*., 2015) and yield reduction observed in others (Rusinamhodzi *et al*., 2011; Nyamangara *et al*., 2014; Kitonyo *et al*., 2018).

Table 1. Geographic location, soil types and rainfall regimes of the trial sites in Malawi, Mozambique, Zambia and Zimbabwe

Site	Latitude	Longitude	Altitude (m.a.s.l)	Soil type	Average rainfall (mm)	Average temperature (°C)	pH ($CaCl_2$)	Organic carbon (g kg^{-1})	Clay content (g kg^{-1})
UZ	−17.724	31.023	1499	*Chromic Luvisols*	840	18	5.1	16.8	400[a]
DTC	−17.607	31.141	1543	*Luvisols*	880	18.8	4.5	7.3	200[b]
Makoholi	−19.833	30.766	1204	*Arenosols*	645	28.0	4.6	0.26	3.0[c]
MFTC	−16.241	27.442	1108	*Chromic Lixisols*	748	22.2	4.8	6.0	120[d]
MRS	−13.645	32.557	1018	*Haplic Luvisol*	1030	25	5.3	10	260[e]
CRS	−13.973	33.654	1145	*Chromic Luvisols*	926	19.6	5.3	4.5	–[f]
NURS	−14.546	34.186	1223	*N/A*	936	20.4	5.8[g]	14.4	–[h]
SRS	−19.317	33.242	616	*Haplic Lixisols*	1155	24	4.8	18	350[i]

UZ, UZ farm; DTC, Domboshawa Training Centre, Zimbabwe, Makoholi, Makoholi Research Station, Zimbabwe; MFTC, Monze Farmer Training Centre, Zambia; MRS, Msekera Research Station, Zambia; CRS, Chitedze Research Station, Malawi; NURS, Ntengo Umodzi Research Station, Mozambique; SRS, Sussundenga Research Station, Mozambique.
[a]Nyamapfene (1991);
[b]Mapfumo *et al.* (2007);
[c]Thierfelder *et al.* (2014);
[d]Thierfelder and Wall (2010);
[e]Barrios *et al.* (1997);
[f]Kumwenda *et al.* (1998);
[g]Determined by the water method
[h]Matusso *et al.* (2015);
[i]Nyagumbo *et al.* (2015);

In semi-arid areas no maize yield gains were observed when up to 10 t ha^{-1} residue biomass were applied as soil cover (Mupangwa *et al.*, 2007). Elsewhere, higher maize, wheat and rice yields have been reported in CA systems with crop residue soil cover (Verhulst *et al.*, 2010; Jat *et al.*, 2013; Lal, 2015).

Crop yield responses to CA or NT-based cropping systems with maize residue soil cover are dependent on the seasonal rainfall patterns (Rusinamhodzi *et al.*, 2011; Mupangwa *et al.*, 2012; Kitonyo *et al.*, 2018). Crop yield and soil water benefits from residue cover in CA or NT-based cropping systems can be limited in different agro-ecological zones of southern Africa (Mupangwa *et al.*, 2007; Masvaya *et al.*, 2017; Kitonyo *et al.*, 2018) while significant gains can be achieved in others (Ngwira *et al.*, 2012; Mupangwa *et al.*, 2016*b*). Higher soil quality and crop yield benefits from CA or NT-based cropping systems are observed when crop residues management is associated with minimum tillage and mineral nitrogen (N) fertilizer application (FAO, 2002; Kitonyo *et al.*, 2018). However, CA or NT-based cropping systems in southern Africa are being promoted with a minimum soil cover of 30% (approximately 2–3 t ha^{-1} of crop residue biomass), which is based on findings from regions outside southern Africa (FAO, 2002). Additionally, appropriate mineral N fertilization rates for CA/NT cropping systems need to be developed for the different agro-ecological regions of southern Africa.

Negative effects of retaining crop residues have been reported especially in the initial years of conversion from conventional to CA and NT-based cropping systems (Lal, 2015; Pittelkow *et al.*, 2015). Crop residues with a wide C:N ratio (>42:1) can lead to N immobilization, depending on the soil type and rainfall regime (Giller *et al.*, 1997; Gentile *et al.*, 2009; Masvaya *et al.*, 2017). This is caused by the increased biological activity in the soil when crop residues are retained (Gentile *et al.*, 2009; Habig and Swanepoel, 2015). Mineral N immobilized during part of the season can become available as the growing season progresses (Masvaya *et al.*, 2017).

Leaf chlorophyll concentration is one index that can be used to assess soil N supply to growing plants during the growing season (Pandey *et al.*, 2000; Liu and Wiatrak, 2011). Leaf chlorophyll content in maize can vary with tillage practices used, growth stage of plants and the quality of seasonal rainfall pattern (Hlatywayo *et al.*, 2016). Previous studies have shown that maize plants grown under CA-based systems can have lower leaf chlorophyll content compared to conventionally ploughed systems (Hlatywayo *et al.*, 2016; Mupangwa *et al.*, 2016*a*).

Currently there is limited information on the appropriate quantities of maize residues and mineral N fertilizer that should be applied in CA/NT-based cropping systems to increase crop yields on smallholder farms. In this study it was hypothesized that (1) different maize residue biomass and N fertilizer levels will increase maize leaf chlorophyll content, (2) different maize residue biomass levels with or without mineral N fertilization will increase grain yield, and (3) the effect of different maize residue biomass levels on grain yield is dependent on seasonal rainfall pattern. The objectives were to determine (1) the effect of different maize residue biomass levels combined with N fertilizer on maize leaf chlorophyll content, (2) the effect of different maize residue biomass levels with or without N fertilization on maize grain yield, and (3) the effect of different maize residue biomass levels on grain yield under different seasonal rainfall patterns.

Material and methods

Description of experimental sites

The study was carried out between 2008 and 2014 across on-station trials in Malawi, Mozambique, Zambia and Zimbabwe. In Zimbabwe, the research was established at Domboshawa Training Centre (DTC), University of Zimbabwe Farm (UZ) and Makoholi Research Station (Makoholi); in Zambia at Monze Farmer Training Centre (MFTC) and Msekera Research Station (MRS); in Malawi at Chitedze Research Station (CRS) and in Mozambique at Sussundenga and Ntengo Umodzi Research Stations (noted hereafter as SRS and NURS, respectively). All sites represent predominantly rainfed maize-based farming areas and cover a wide range of soil types and climatic conditions in southern Africa (Table 1).

Experimental design and description of treatments

The experimental designs used in this study varied with experimental site and year. Monze Farmer Training Centre, MRS, SRS and NURS sites had a randomized complete block design (RCBD) throughout the period of experimentation. Domboshawa Training Centre and UZ farm had RCBD in 2008, 2009, 2010 and 2011. From 2012 to 2014 a split plot RCBD design was used at DTC and UZ sites when N sub-treatments were introduced and superimposed on the maize residue level main treatment (Table 2). Makoholi site had RCBD in 2009, 2010, 2011 and 2012. In 2013 and 2014 a split plot RCBD was used when N sub-treatments were superimposed on the different maize residue biomass levels. At CRS in Malawi, RCBD was used in 2011 only and a split plot RCBD design was used from 2012 to 2014 with the main treatment being maize residue biomass level and N rates as sub-treatments. The treatments were replicated 3–5 times depending on space available at each experimental site. The six main treatments tested at each site consisted of CA-based seeding with different levels of maize biomass residues applied at the onset of each cropping season. In all the sites, the control treatment was the one that had no maize residues applied. When N sub-treatments were introduced at DTC, UZ Makoholi and CRS sites (Table 2), the control treatment had a combination of $0\ \text{t ha}^{-1}$ residue cover and $0\ \text{kg N ha}^{-1}$. The residues treatments were:

(i). $0\ \text{t ha}^{-1}$
(ii). $2\ \text{t ha}^{-1}$
(iii). $4\ \text{t ha}^{-1}$
(iv). $6\ \text{t ha}^{-1}$
(v). $8\ \text{t ha}^{-1}$

In Malawi and Zimbabwe each maize residue level plot was subdivided into three to accommodate the N level sub-treatments. The N level sub-treatments were:

(i). $0\ \text{kg ha}^{-1}$
(ii). $30\ \text{kg ha}^{-1}$
(iii). $90\ \text{kg ha}^{-1}$

An animal traction Magoye ripper [a ripper tine attached to a beam of a conventional plough (VS 100)] or a hoe (at CRS), was used for opening planting furrows (10–15 cm deep) for all CA treatments at the onset of each rain season (Supplementary Plate 1). At UZ, basins were prepared with a hand hoe during the dry period. Maize residues from the previous harvested crop and any remaining residues applied as soil cover in the previous season were removed before applying new maize residues, weighed according to treatment, at the onset of each season in all CA treatments. The maize residues used at each site consisted of a mixture of stalks and leaves from the previous season. At all experimental sites the plot size was 7.2 m (8 rows) × 6 m.

Experimental management

Maize was spaced at 0.90 m × 0.25 m with one living plant per station giving a target plant population of $44{,}444\ \text{plants ha}^{-1}$ at all stations except CRS and NURS where plant spacing was 0.75 m × 0.25 m ($53{,}000\ \text{plants ha}^{-1}$). Planting was done after receiving the first effective rains, from mid-November to the end of December in most seasons, across the four countries. Pristine maize variety was grown at DTC, UZ, Makoholi, MFTC, NURS and SRS sites. Pan 53 and MRI 624 were grown at CRS and MRS, respectively.

Basal fertilizer was applied during seeding at all experimental sites used in this study but the amount depended on the experimental layout and the formulation of the fertilizer available in the respective country. Fertilization rates used in the study were based on the national recommendations for each country. Plant nutrients supplied by basal and topdressing fertilizers used at all sites are summarized in Table 3. For the years without N sub-treatments, blanket topdressing fertilizer was applied at $250\ \text{kg ha}^{-1}$ in Malawi and Zimbabwe. However, after the introduction of N fertilizer levels in Malawi and Zimbabwe, topdressing was applied in the form of urea (46% N) and ammonium nitrate (34.5% N) so that the amount of N supplied would add up to that required for sub-treatments 2 and 3 accordingly. In Mozambique and Zambia topdressing fertilizer was applied at a rate of $200\ \text{kg ha}^{-1}$. At all sites and in all seasons, topdressing was applied 5 and 7 weeks after crop emergence. Nutrient analyses in maize residues used for soil cover were done for DTC and UZ sites only. Total N in maize residues averaged $9.6\ \text{g kg}^{-1}$ and $11\ \text{g kg}^{-1}$ at DTC and UZ sites, respectively (Mhlanga, 2015). Phosphorus content in the maize residues was 0.22% at UZ and 0.61% for DTC.

Initial weed control in CA treatments was done using glyphosate [N-(phosphono-methyl) glycine] applied at $2.5\ \text{l ha}^{-1}$ ($1.025\ \text{l ha}^{-1}$ active ingredient) at seeding followed by manual hoe weeding whenever weeds reached 0.1 m height or 0.1 m in radius for those with a stoloniferous growth habit. Pests such as maize stalk borer (*Busseola fusca* Fuller) were controlled by applying Dipterex (*Trichlorfon*) whenever necessary at a rate of $1.6\ \text{kg ha}^{-1}$ applied in granular form into the maize funnel.

Table 2. The period each experimental site was used and the treatments applied in each year in Malawi, Mozambique, Zambia and Zimbabwe

Site	Years site was used	Maize residues applied	Nitrogen sub-treatments applied
UZ	2008–2014	2008–2014	2012–2014
DTC	2008–2014	2008–2014	2012–2014
Makoholi	2009–2014	2009–2014	2013–2014
MFTC	2011–2014	2011–2014	Not applied
MRS	2012–2014	2012–2014	Not applied
CRS	2011–2014	2011–2014	2012–2014
NURS	2013–2014	2013–2014	Not applied
SRS	2010–2014	2010–2014	Not applied

Data collection

Daily rainfall during the growing season

Daily rainfall was collected manually using a plastic rain-gauge mounted at 1.5 m above ground level. Rainfall collected over a 24 h period at each site was recorded every morning at 08.00.

Table 3. Plant nutrients (kg ha^{-1}) supplied through basal and topdressing fertilizer at each experimental sites used in Malawi, Mozambique, Zambia and Zimbabwe in years with and without nitrogen sub-treatments

Year	Site	N (from basal)	N (from topdressing)	P	K	S
Without sub-treatments	UZ	11.6	86.25	10.1	9.6	0
	DTC	11.6	86.25	10.1	9.6	0
	Makoholi	11.6	86.25	10.1	9.6	0
	MFTC	16.3	92	14.2	13.5	0
	MRS	16.3	92	14.2	13.5	0
	CRS	23	115	9.2	0	4
	NURS	12	92	10.5	10	0
	SRS	12	92	10.5	10	0
With sub-treatments	DTC	11.6	30 and 90			
	UZ	11.6	30 and 90			
	Makoholi	11.6	30 and 90			
	CRS	23	30 and 90			

UZ, UZ farm; DTC, Domboshawa Training Centre, Zimbabwe, Makoholi, Makoholi Research Station, Zimbabwe; MFTC, Monze Farmer Training Centre, Zambia; MRS, Msekera Research Station, Zambia; CRS, Chitedze Research Station, Malawi; NURS, Ntengo Umodzi Research Station, Mozambique; SRS, Sussundenga Research Station, Mozambique.

Maize leaf chlorophyll content

In vivo chlorophyll content of maize plant leaves was measured using a portable chlorophyll meter (SPAD-502, Minolta, Tokyo, Japan) at DTC and UZ sites. Leaf chlorophyll content was measured weekly from five randomly selected and permanently tagged plants per plot on the uppermost extended leaf of each plant. Measurements were taken starting from 7 weeks after seeding until the early reproductive stage of the maize crop. One measurement for chlorophyll content was taken from each tagged leaf on each day measurements were taken.

Maize grain yield

Maize grain yield was measured from a net plot consisting of four rows by 5 m. Field weight of cobs was recorded before taking ten cobs for moisture correction and to determine the shelling percentage of the maize. The maize cobs were air-dried for 5 weeks before measuring grain moisture content. Grain moisture content was recorded using a grain moisture meter (mini GAC® moisture tester DICKEY-John, USA). Maize grain yield was calculated to a hectare basis at 12.5% moisture content.

Statistical Analyses

Leaf chlorophyll content under different maize residue biomass and N treatments

For DTC and UZ sites, the effect of different residue biomass and N levels on the chlorophyll content of maize leaves was explored. The mean of chlorophyll content measured during peak vegetative stage was used in the analysis. As indicated in Equation 1, N rate was modeled as sub-plot factor, while residue biomass level was fitted as the main plot factor in a split plot design using R (R Core Team, 2017).

$$\boldsymbol{Y}_{\mathrm{ijk}} = \alpha + \beta \mathrm{ML}_i + \delta \mathrm{RF}_j + \mu \mathrm{NR}_{k(i)} + \boldsymbol{\sigma}(\mathrm{ML}:\mathrm{RF})_{\mathrm{ij}} + \gamma(\mathrm{ML}:\mathrm{NR})_{\mathrm{ik}} + \boldsymbol{\varepsilon} \quad (1)$$

Where Y_{ijk} is transformed or untransformed chlorophyll content of maize leaves, ML_i is the i^{th} level of mulch, RF_j is the j^{th} amount of seasonal rainfall and NR_k is the k^{th} level of N. $\mathrm{NR}_{k(i)}$ is the k^{th} rate of N nested within the i^{th} mulch level. Constants α, β, γ, μ, σ and τ are coefficients of main and interaction effects, while ε is the residual of the model.

Maize yield responses to different residue levels

The linear mixed model was applied to assess the effect of maize residue biomass levels on grain yield in each season from 2008 to 2011. In each season residue biomass levels were modeled as fixed factor and replicate as a random factor. The yield data were analyzed using GenStat Release version 6.1 (Payne *et al.*, 2002). To explore more extensively the effect of different residue biomass levels on maize yield across the years of experimentation, generalized linear mixed model (GLMM) was applied using R (R Core Team, 2017). Residue biomass levels, seasonal rainfall and duration of mulching were modeled as fixed effects, while replications were modeled as random effects. All the variables were modeled nested within seasons. Separate models were fitted for different countries and sites within countries to account for high between country and inter-site variabilities using R (R Core Team, 2017). We log-transformed or square-root-transformed when data did not satisfy the parametric assumption (Equation 2).

$$\boldsymbol{Y}_{\mathrm{ijkl}} = \alpha + \beta \mathrm{ML}_i + \gamma \mathrm{DR}_j + \delta \mathrm{RF}_k + \mu \mathrm{YR}_{l(\mathrm{ij})} + \boldsymbol{\sigma}(\mathrm{ML{:}RF})_{\mathrm{ik}} + \varepsilon \quad (2)$$

Where, Y_{ijkl} is transformed or untransformed maize grain yield, ML_i is the i^{th} level of mulch (t/ha), DR_j is the j^{th} duration of mulching (years), RF_k is the k^{th} amount of seasonal rainfall (mm). $\mathrm{YR}_{l(\mathrm{ij})}$ is the i^{th} level of mulch and the j^{th} duration of mulching nested within the l^{th} season. Constants α, β, γ, δ, μ and σ are coefficients of main and interaction effects, while ε is the residual of the model.

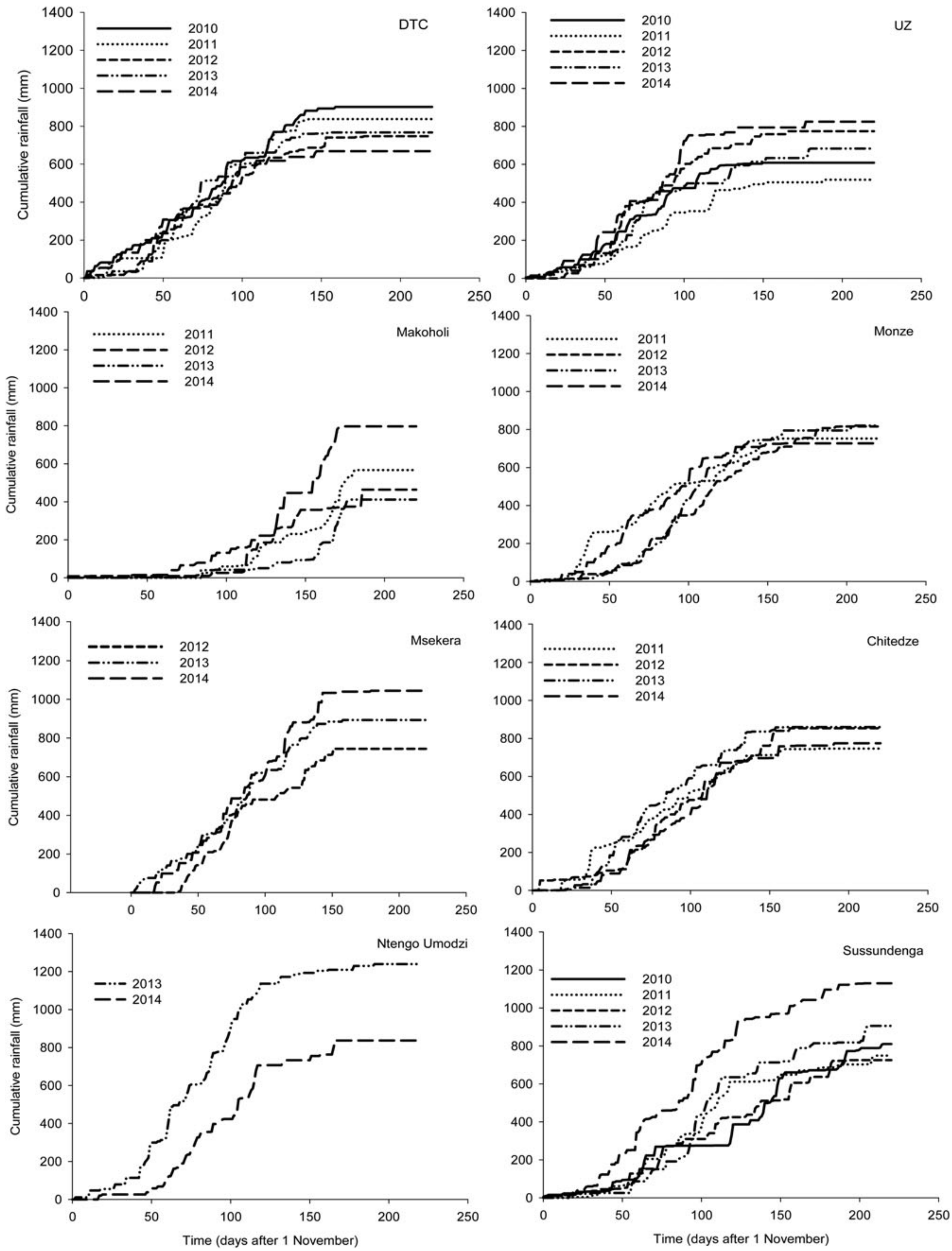

Fig. 1. Cumulative rainfall distribution in some of the growing seasons at experimental sites in Malawi, Mozambique, Zambia and Zimbabwe between 2008 and 2014.

Table 4. The effects of different residue levels (t ha^{-1}) and N fertilization (kg N ha^{-1}) on maize leaf chlorophyll content (Spad units) at Domboshawa Training Centre (DTC) and University of Zimbabwe (UZ) sites in 2013 and 2014 growing seasons

Site	Treatment	2013	2014
DTC	0	23.7	41.9
	2	23.7	40.9
	4	22.9	40.8
	6	23.1	40.8
	8	22.8	41.0
	P-value	0.68	0.92
	SED	0.92	0.79
	0	19.2	36.2
	30	22.1	41.2
	90	28.4	45.8
	P-value	<0.001	<0.001
	SED	0.58	0.53
UZ	0	34.3	44.4
	2	32.0	42.7
	4	31.0	40.9
	6	32.9	40.3
	8	33.8	39.7
	P-value	0.58	<0.001
	SED	0.76	0.94
	0	32.9	34.9
	30	32.8	42.8
	90	32.7	47.0
	P-value	0.14	<0.001
	SED	0.60	0.62

Maize yield responses to different residue levels and N fertilizer

To assess the effect of different residue biomass and N levels on grain yield at DTC, UZ, Makoholi and Chitedze in 2012, 2013 and 2014, residue biomass level and N fertilizer were modeled as fixed factors and replicates as random factor in a linear mixed model in each season using GenStat Release version 6.1 (Payne *et al.*, 2002). To explore more extensively the effects of different residue biomass levels with N fertilizer superimposed across different years, the GLMM with a split plot design was used to assess the effects of these treatments on maize yield using R (R Core Team, 2017). Duration since the mulching treatment started, seasonal rainfall amount, residue and N levels were modeled as fixed effects (Equation 3). Replication and site were modeled as random effects.

$$Y_{\mathrm{ijkl}} = \alpha + \beta \mathrm{ML}_i + \gamma \mathrm{DR}_j + \delta \mathrm{RF}_k + \mu \mathrm{NR}_{l(i)} + \sigma(\mathrm{ML} : \mathrm{RF})_{\mathrm{ik}} + \tau(\mathrm{NR} : \mathrm{RF})_{\mathrm{lk}} + \varepsilon \quad (3)$$

ere Y_{ijkl} is transformed or untransformed maize grain yield, ML_i is the i^{th} level of mulch, DR_j is the j^{th} duration of mulching, RF_k is the k^{th} amount of seasonal rainfall, and NR_l is the l^{th} rate of N. $\mathrm{NR}_{l(i)}$ is the l^{th} N level nested within the i^{th} mulch level. Constants α, β, γ, δ, μ, σ and τ are coefficients of main and interaction effects, while ε is the residual of the model.

Results

Seasonal rainfall patterns

Seasonal rainfall was dominated by amounts of less than 10 mm per day at all sites during experimentation. The 10–20 mm per day was the next dominant rainfall range and these daily amounts were mainly distributed between December and February in each growing season (Fig. 1). Rainfall amounts of more than 40 mm per day were recorded on a few occasions and one rainfall event of 100 mm, received at DTC in 2011, was the highest daily amount recorded during experimentation. Most dry spells (i.e. consecutive days with no rain) occurred during the late flowering and grain filling stages of the maize crop grown at experimental sites. The longest dry spell lasted 39 days in 2011 at Monze in Zambia and the shortest dry spell was 16 days at Ntengo Umodzi in Mozambique. At the semi-arid Makoholi site, each season experienced at least one 14 day dry spell between 2011 and 2014.

Leaf chlorophyll content at DTC and UZ sites

At DTC site, different residue biomass levels had no significant effect on leaf chlorophyll content at flowering stage of maize in 2013 and 2014 seasons (Supplementary Table 3; Table 4). Nitrogen fertilization significantly increased leaf chlorophyll content during the flowering stage in both seasons (Table 4). In 2013 residue biomass levels and N fertilization had no significant effect on leaf chlorophyll content at UZ site (Supplementary Table 3; Table 4). In 2014 the residue biomass level × N interaction had a significant ($P = 0.04$) effect on leaf chlorophyll content at UZ site (Supplementary Table 3). In that season leaf chlorophyll content decreased with increase in residue biomass level at 0 kg N ha^{-1} treatment (Fig. 2). Under 2, 4, 6 and 8 t ha^{-1} residue biomass levels, N fertilization increased leaf chlorophyll content. At 4, 6 and 8 t ha^{-1} maize residue level, 90 kg N ha^{-1} treatment had higher leaf chlorophyll content compared with 30 kg N ha^{-1}.

Maize yield responses to different residue levels

Maize residue soil cover increased grain yield in six out of 28 site-years across the sites. At DTC site, maize residue biomass cover significantly influenced grain yield in 2010 and 2011 only (Fig. 3). Grain yield was higher in the first two seasons (2008 and 2009) compared with the follow-up seasons, a trend showing a decrease in yield over time (Fig. 3). In 2011, which was the fourth season of experimentation and characterized by poor rainfall distribution, grain yield increased with increase in residue biomass level applied. Across the years, 2 t ha^{-1} residue biomass level had the lowest ($P = 0.033$) grain yield compared with the other treatments (Supplementary Table 4; Fig. 3). There was no residue biomass level × rainfall interaction across the years at DTC. In 2008, different residue biomass levels suppressed yield while in 2009 grain yield increased with increase in soil cover levels up to 4 t ha^{-1} at the UZ site (Fig. 3). Across the years different residue biomass levels × rainfall interaction significantly ($P = 0.022$) influenced grain yield (Supplementary Table 4; Fig. 3). At

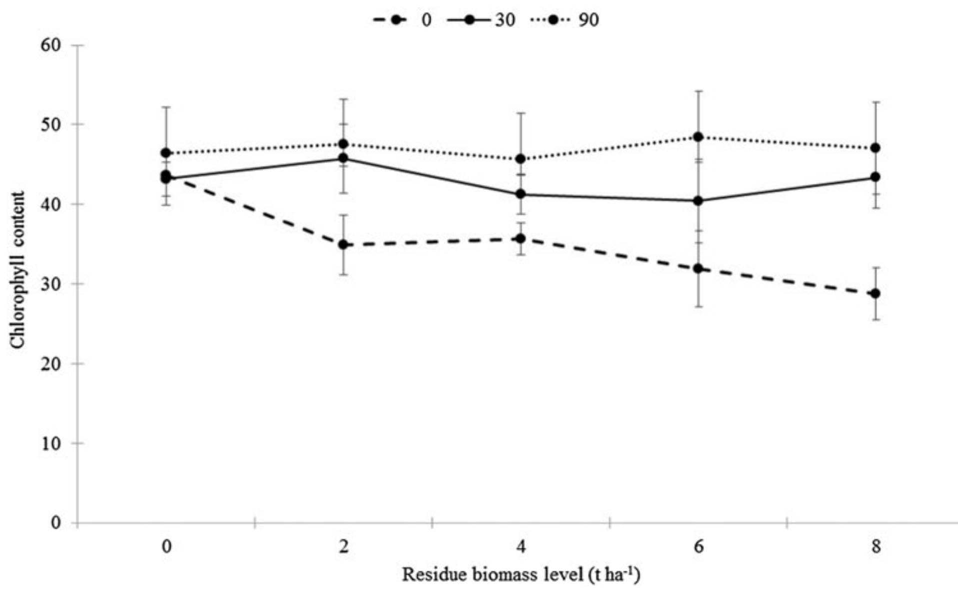

Fig. 2. Effects of maize residue biomass and N interaction on leaf chlorophyll content in 2014 season at the UZ site, Zimbabwe. Vertical bar represents standard error of means (SE) ($n = 30$).

Makoholi grain yield was influenced ($P = 0.029$) by residue level × rainfall interaction. Grain yield was higher under 6 and 8 t ha^{-1} treatments compared with 0, 2 and 4 t ha^{-1} in 2010 and 2011 seasons. However, in 2012 different residue biomass levels had no significant effect on grain yield.

At MFTC and MRS in Zambia residue level × rainfall interaction significantly influenced grain yield across the years (Supplementary Table 4). In 2011, a growing season characterized by rainfall concentrated in the first 2 months, 6 and 8 t ha^{-1} residue levels suppressed grain yield compared with 0, 2 and 4 t ha^{-1} treatments at MFTC (Fig. 3). However, grain yield increased with increase in residue level in 2014, a year that had low seasonal rainfall. Maize yield decreased ($P < 0.001$) with an increased duration of experimentation (Supplementary Table 4; Fig. 3). The effect of different residue biomass levels on grain yield depended on the seasonal rainfall at MRS. In 2013 season with >800 mm of rainfall, 4 t ha^{-1} treatment had significantly higher yield compared with 2 and 6 t ha^{-1} soil cover. Grain yield decreased with increase in residue level in 2014 which received >1000 mm seasonal rainfall. Grain yield decreased with time at both sites, a trend which was similar to results from sites in Zimbabwe. In Malawi, residue biomass levels had no significant effect on yield (Supplementary 5; Fig. 3). There were no linear relationships between grain yield and residue biomass levels applied at MFTC, MRS and CRS.

In Mozambique, residue biomass levels influenced ($P = 0.003$) grain yield at Sussundenga in 2011 only (Fig. 3). In that year 4 t ha^{-1} treatment had significantly lower yield compared with 2 and 6 t ha^{-1} treatments. Across the years different residue biomass levels had a similar effect on grain yield. At NURS, residue cover increased maize yield in one out of 2 years. The residue biomass levels × rainfall amount interaction had a significant effect on grain yield (Supplementary Table 5). In 2013 with 1240 mm of rainfall, 8 t ha^{-1} significantly reduced grain yield. In 2014 with lower seasonal rainfall, yield increased with increased soil cover from 2 to 8 t ha^{-1} (Fig. 3). Overall grain yield increased with mulching across the two seasons.

Maize yield responses to different residue levels combined with N fertilizer

Maize residue cover increased grain yield in two out of 11 site-years. At DTC site, residue biomass levels significantly ($P = 0.005$) influenced grain yield in 2014 and 4–6 t ha^{-1} treatments had the lowest yield (Table 5). The 4 and 6 t ha^{-1} treatments had lower yield compared with the 0 t ha^{-1} control. Across the years, residue level and rainfall interaction influenced grain yield at DTC (Supplementary Table 6). Grain yield was not affected by residue levels in 2012 and 2013 which received 748 and 767 mm rainfall that was below the average for DTC (Tables 1 and 5; Fig. 1). However, grain yield decreased with increase in residue biomass level in 2014 which also received below average rainfall (668 mm). Nitrogen fertilizer increased grain yield across residue biomass levels in each year and across the years (Table 6; Supplementary Table 6). The 90 kg N ha^{-1} treatment had higher grain yield compared with 30 kg N ha^{-1} in all the three seasons.

At UZ site, residue levels increased maize yield in two out of three years. There were significant residue biomass level × rainfall and residue biomass level × N interaction effects on grain yield (Supplementary Table 6). In 2012 with 774 mm of rainfall, 8 t ha^{-1} treatment had significantly lower grain yield compared with the other residue biomass levels (Table 5). In 2013 and 2014, with 684 and 825 mm of rainfall, grain yield increased with increase in residue biomass level (Table 5). The residue biomass level × N fertilization interaction significantly influenced grain yield in 2014 (Fig. 4). Under 0 t ha^{-1} treatment, grain yield decreased with increase in residue biomass level. Under the same residue treatment, 30 and 90 kg N ha^{-1} had a similar effect on maize grain yield. Under 2, 4, 6 and 8 t ha^{-1} treatments 30 and 90 kg N ha^{-1} had higher grain yield compared with the 0 kg N ha^{-1} control. There was a yield gain achieved by increasing N rate from 30 to 90 kg ha^{-1} under the 6 t ha^{-1} residue level treatment (Fig. 4). There was a significant residue biomass level × N interaction across the years at the UZ site (Supplementary Table 6; Fig. 5). Without N fertilization 6 and 8 t ha^{-1} residue

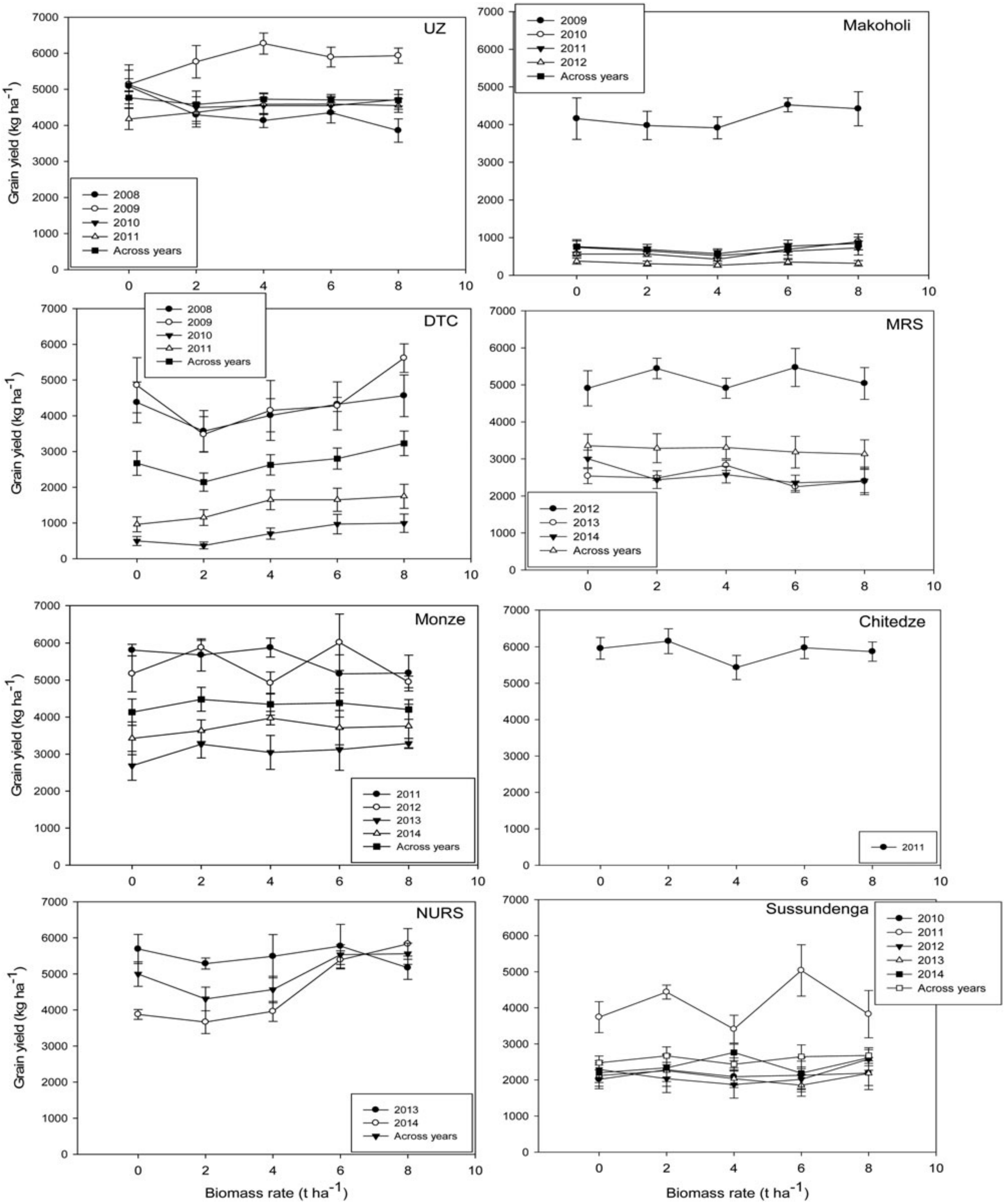

Fig. 3. Maize grain yield responses to different residue levels from 2008 to 2014 at Domboshawa Training Centre (DTC), University of Zimbabwe (UZ), Makoholi, Monze, Msekera, Chitedze, Ntengo Umodzi and Sussundenga experimental sites. Vertical bars represent standard error of means (SE) for each year ($n = 5$) and across years.

levels had significantly lower grain yield compared with the unmulched control treatment. With 30 kg N ha^{-1}, significant grain yield gain was achieved under 2 t ha^{-1} soil cover compared with the control treatment. The 90 kg N ha^{-1} had significant grain yield gains under 2, 4 and 6 t ha^{-1} treatments compared with the unmulched control. Generally, grain yield decreased with increased duration of experimentation (Supplementary Table 6; Tables 5 and 6). At Makoholi site, different residue

Table 5. Effects of different maize residue biomass levels on grain yield (kg ha^{-1}) at the Domboshawa Training Centre (DTC), University of Zimbabwe (UZ), Makoholi and Chitedze (CRS) experimental sites in 2012, 2013 and 2014, and across growing seasons

Year	Treatment	DTC	UZ	Makoholi	CRS
2012	0	1299	4906		5057
	2	1513	5178		4969
	4	1253	4907		4373
	6	1733	4933		4602
	8	1696	4058		4678
	P-value	0.355	0.111		0.635
	SED	297	442		503
2013	0	419	2127	1225	5314
	2	788	3232	1067	5279
	4	540	3892	1083	4763
	6	611	3612	1037	5231
	8	731	3652	1355	5151
	P-value	0.364	<0.001	0.143	0.491
	SED	201	297	145	343
2014	0	5558	2657	1311	4462
	2	4920	3270	1237	4274
	4	4175	3468	1251	3182
	6	4215	3559	1335	4197
	8	4631	3240	1647	4123
	P-value	0.005	0.024	0.838	0.166
	SED	416	271	290	556
Across years	0	2425	3255	1225	4950
	2	2407	3893	1189	4841
	4	1989	4089	1237	4106
	6	2186	4035	1169	4677
	8	2353	3650	1289	4650
	P-value	0.850	0.011	0.8050	0.050
	SED	320	461	454	518

biomass levels had no significant effect on grain yield in 2013 and 2014 seasons and across years (Supplementary Tables 6 and 5). Nitrogen fertilization increased grain yield with 90 kg N ha^{-1} having a higher yield than the 30 kg N ha^{-1} treatment (Table 6).

At Chitedze residue biomass level × rainfall interaction had a significant ($P = 0.0217$) effect on grain yield across the years (Supplementary Table 6). Grain yield was lowest in 2014 with 775 mm of rainfall compared with 2012 and 2013 that had 854 and 860 mm, respectively (Table 5; Fig. 1). Across the 3 years, 4 t ha^{-1} treatment had significantly lower grain yield (4106 kg ha^{-1}) than 4950 and 4841 kg ha^{-1} from 0 to 2 t ha^{-1} residue biomass levels, respectively. Grain yield increased with N application and, 30 and 90 kg N ha^{-1} had a similar effect on grain production in all seasons (Supplementary Table 6; Table 6). The relationship between maize grain yield and mineral N rates applied was significant ($P < 0.05$) but weak at the four experimental sites.

Discussion

Effect of residue biomass levels and N fertilizer on maize leaf chlorophyll content

Chlorophyll content varied depending on the quantity of maize residues and N fertilizer applied. On DTC sandy soil, 2–8 t ha^{-1} maize residue biomass amounts had a similar effect on leaf chlorophyll content without N fertilization. This suggests that there was no significant N immobilization as residue cover increased on the sandy soil despite differences in the rainfall pattern experienced during the two seasons. However, with and without N fertilization, maize leaf chlorophyll content decreased with increase in maize residue biomass level at UZ clay soil in 2014, a season that was characterized by incessant rains during the maize vegetative and flowering stages. A significant decrease in leaf chlorophyll with 6 and 8 t ha^{-1} residues suggests that more soil N was immobilized at higher maize residue biomass levels compared with 2 and 4 t ha^{-1} treatments. A study by Hlatywayo

Table 6. Effects of N fertilizer (kg N ha^{-1}) on maize grain yield (kg ha^{-1}) at the Domboshawa Training Centre (DTC), University of Zimbabwe (UZ), Makoholi and Chitedze (CRS) experimental sites in 2012, 2013 and 2014, and across growing seasons

Year	Treatment	DTC	UZ	Makoholi	CRS
2012	0	952	3552		3736
	30	1429	4764		5016
	90	2116	6074		5467
	P-value	<0.001	<0.001		<0.001
	SED	230	343		389
2013	0	446	2407	810	4676
	30	487	3213	1135	5146
	90	920	4289	1516	5578
	P-value	0.003	<0.001	<0.001	0.004
	SED	156	230	112	266
2014	0	3007	1815	772	3226
	30	5222	3510	1332	4388
	90	5871	4399	1961	4530
	P-value	<0.001	<0.001	<0.001	0.004
	SED	322	210	224	430
Across years	0	1468	2596	788	3875
	30	2380	3829	1214	4855
	90	2969	4898	1738	5191
	P-value	<0.001	<0.001	<0.001	<0.001
	SED	232	454	280	165

et al. (2016) showed that maize leaf chlorophyll content is lower in CA systems compared with conventional tillage particularly early in the cropping season.

The presence of crop residues on the soil surface induces increased microbial activity in the soil (Habig and Swanepoel, 2015). As the maize residues decomposed, microorganisms extracted available soil N for the decomposition process to happen. Thus, the higher the maize residues applied, the more available soil N was immobilized. The C:N ratio of maize residues ranges between 52 and 75:1 (Sakala *et al.*, 2000) and soil N is required to decompose such low-quality material because more N is needed to go with the surplus C in such material (Hadas *et al.*, 2004; Gentile *et al.*, 2009). Studies by Gentile *et al.* (2009) showed that plant materials with C:N ratio of greater than 42 often cause immobilization of soil N by microorganisms. More N from external sources or from rotations with leguminous crops may therefore be required to offset the effects of N immobilization on plant growth.

The effect of different residue levels on leaf chlorophyll content varied between sand and clay soils. The decrease in leaf chlorophyll content with an increase in soil cover and without N fertilization was more evident on clay soil compared with sands. Soil type is often one of the determinants for which decomposers (e.g. bacteria and fungi) will be present in a given soil environment (Girvan *et al.*, 2003). Clay soil tends to have more microorganisms because it has higher organic matter content than light textured soils (Berg and Smalla, 2009). The soil at the UZ site had the highest SOC and clay content (Table 1). The increased immobilization in the clay soil at UZ site suggests the presence of a higher population of decomposers in the soil, hence the increased demand for available soil N to degrade the maize residues (Verhulst *et al.*, 2010). In Malawi, Sakala *et al.* (2000) observed a longer duration of N immobilization in a heavy textured soil after incorporating maize residues compared with sandy soil. Soil N immobilization could be reduced by removing part of the harvested crop residues without compromising the yield of the next crop, mixing cereal and legume residues as mulch to regulate release of N during the cropping season, and application of more N containing fertilizers (Sakala *et al.*, 2000; Rusinamhodzi *et al.*, 2011; Mupangwa and Thierfelder, 2014).

Fertilization with mineral N increased leaf chlorophyll content, suggesting more soil N was available for plant uptake. This is consistent with results from Muchow and Davis (1988) who observed increased maize leaf N content in response to mineral N fertilization. On sandy soils, the decrease in chlorophyll content without N fertilizer at higher maize residue biomass levels was not evident in this study. Reduced N immobilization with increases in maize residue biomass levels at DTC could be a reflection of low microbial populations under the low organic carbon status of the sandy soils (Table 1). Organic C is the source of food and energy for soil micro-organisms and soils with low organic carbon often have low populations and limited species richness of soil micro-organisms (Habig and Swanepoel, 2015). With immobilization occurring due to maize residue biomass soil cover, the supply of N to growing plants is reduced, therefore it is paramount that available soil N be increased through external nutrient sources, particularly on clay soils.

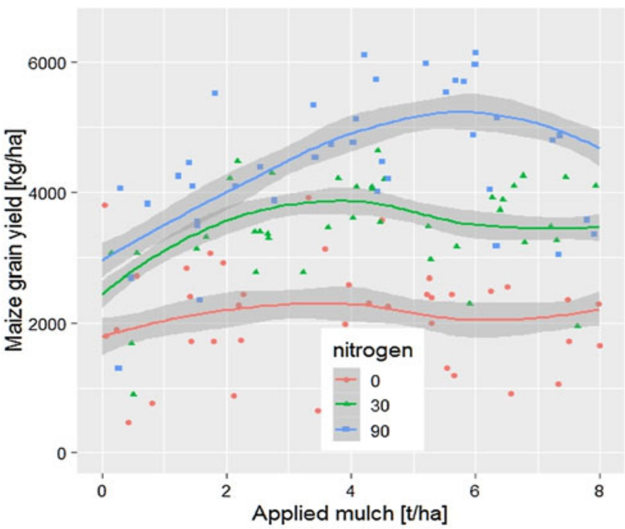

Fig. 4. Interaction effects of residue biomass levels and N fertilizer on grain yield at University of Zimbabwe site in 2014 growing season.

When N sub-treatments were applied, 30 kg N ha^{-1} reduced N immobilization that could have occurred under 2–8 t ha^{-1} treatments on the sandy soil. This implies that increasing N level to 90 kg ha^{-1} might not bring additional gain towards plant growth under the rainfall and soil conditions experienced at DTC in 2012–2014 seasons. On the clay soil, 30 kg N ha^{-1} was not adequate to reduce N immobilization at higher maize residue biomass levels when soil moisture was not limiting. Additional N is therefore required to offset N immobilization on heavy textured soil in seasons with normal to above normal seasonal rainfall amounts. This was confirmed with 90 kg N ha^{-1} treatment that still showed significantly lower chlorophyll content at 6–8 t ha^{-1} compared with the 0–4 t ha^{-1} maize residue biomass levels. The importance of rainfall distribution on responses to N, especially on the clay soil, was confirmed by chlorophyll content results from 2013 and 2014 seasons that had almost similar seasonal rainfall totals. Unlike in 2013 season, rainfall pattern in 2014 had short dry spells between December and March, and this could have created favorable conditions for maize plant growth but also for soil microbes to be active and take up more available soil N, resulting in increased competition for the nutrient.

Effect of different residue levels and N on maize yield

Maize yield responses to mulching were quite variable and rainfall-dependent at some of the experimental sites. In a few instances grain yield decreased with increase in maize residue biomass level, a result that is consistent with leaf chlorophyll content results at DTC and UZ. Higher maize residue biomass levels induced an increased demand for soil N by decomposers in the soil thereby depriving growing maize plants of N. Maize is sensitive to N availability during the vegetative and reproductive growth stages (Lemaire *et al.*, 1996). During these maize growth stages immobilization was observed and this was reflected by low chlorophyll content in the January–March period during the growing season. Chlorophyll content is often related to crop yields (Wood *et al.*, 1993) and reduced N supply, reflected by low chlorophyll content, therefore retards plant growth resulting in low yields (Blackmer and Schepers, 1996).

Maize yield responses to different residue biomass levels were limited across the different agro-ecological regions used in the study. Grain yield responses were site and rainfall dependent, and there were no responses to soil cover in the majority of the growing seasons. The results concur with the findings of Kitonyo *et al.* (2018) from a study conducted under the sub-humid conditions of Kenya. With such limited positive maize yield responses to crop residue soil cover, the practice of mulching in CA/NT systems could be targeted at improving soil quality and fertility, and biodiversity as well as conserving the soil resource base through reduced erosion (Muchabi *et al.*, 2014; Mloza-Banda *et al.*, 2016; Martinsen *et al.*, 2017). Additionally, for mulching purposes at the farm, testing alternative strategies for providing soil cover could be explored for the smallholder CA/NT-based cropping systems (Mupangwa *et al.*, 2016*a*). In the reported study, maize yield responses to residue biomass cover could have been limited because no rotations or intercropping of maize with legumes were included during experimentation.

Different maize residue biomass levels had no significant effect on grain yield at semi-arid Makoholi and Monze sites which naturally receive low seasonal rainfall. Based on the rainfall received at those sites, particularly Monze, soil moisture was not the major limiting factor for maize growth in the majority of the seasons, hence no yield benefit was derived from maize residue biomass cover. Other studies from sub-Saharan Africa confirm this lack of response to mulching even in cropping seasons with erratic

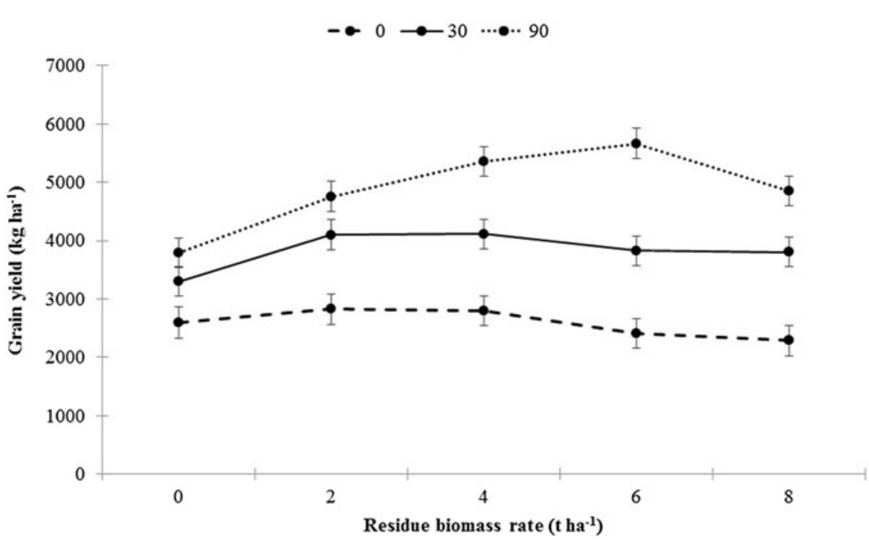

Fig. 5. Interaction effects of residue biomass levels and N fertilizer on grain yield across three cropping seasons at University of Zimbabwe. Vertical bar represents standard error of means (SE) ($n = 9$).

rainfall patterns (Mupangwa *et al*., 2012; Corbeels *et al*., 2014; Masvaya *et al*., 2017). The general decline of grain yields with increased duration of experimentation observed at all sites could partially be explained by differences in seasonal rainfall patterns. However, Masvaya *et al*. (2017) suggest that this could be due to reduced N mineralization because of minimum soil disturbance and mulching practices under NT systems.

Lack of maize yield increases due to residue biomass mulching at Sussundenga can be attributed to the early removal of crop residues by termites in most seasons. Maize residues were all degraded by termites before the middle of the cropping season. Nyagumbo *et al*. (2015) highlighted that high termite activity is a major challenge in CA systems that are being promoted on smallholder farms in some sites of central Mozambique where SRS is located. At the UZ clay soil site with close to 1000 mm seasonal rainfall, maize yield decreased with increase in maize residue biomass level, further highlighting the fact that soil N immobilization can have a great impact on maize production in some seasons depending on the seasonal rainfall pattern.

Maize yield was increased by N fertilization regardless of the amount of maize residue biomass cover applied. Nitrogen is a critical nutrient for plant growth and maize requires more N during vegetative and reproductive growth phases (Muchow, 1988; Muchow and Davis, 1988). Application of 30 and 90 kg N ha^{-1} gave similar maize yield in most seasons. This suggests that a smallholder farmer achieves no additional grain yield gain with 90 kg N ha^{-1} and they can therefore target 30 kg N ha^{-1} investment in mineral fertilizer. In a mulched NT system under semi-arid conditions, a study by Masvaya *et al*. (2017) showed that 40 kg N ha^{-1} gives the highest yield with above average seasonal rainfall. Under sub-humid conditions of Kenya, results from Kitonyo *et al*. (2018) showed that 80 and 120 kg N ha^{-1} give similar maize yield under 3 and 5 t ha^{-1} soil cover.

Conclusion

Increasing mulching levels reduced soil N uptake, reflected by chlorophyll content, in the maize plants particularly on the clay soil. Maize residue cover increased grain yield in eight out of 39 site-years across the seven experimental sites. Maize yield gains due to mulching were very limited even in low rainfall locations. Smallholder farmers can therefore apply relatively low levels of maize residue biomass, 2–4 t ha^{-1} or even less, in CA/NT-based cropping systems. Results of this study highlight that residue soil cover alone with maize stover is insufficient for a productive CA/NT system. The rotational component and increased N input through leguminous crops could be options to overcome N immobilization and increase productivity.

The effect of residue biomass soil cover on maize yields depends on the seasonal rainfall pattern. Lower maize yields at high residue biomass level, particularly on clay soil, suggests that soil N was immobilized. Smallholders practicing CA/NT need to invest in more mineral N fertilizer in seasons with high rainfall to offset soil N immobilization. Mineral N increased maize yield in the CA/NT systems in all seasons. Application of 30 and 90 kg N ha^{-1} can offset N immobilization and give similar maize yield benefit. Smallholders practicing CA/NT can therefore target investing in 30 kg N ha^{-1}.

The limited maize yield gain from maize residue biomass cover under CA/NT suggests smallholders may utilize parts of the crop residues more efficiently for livestock feeding during the feed shortage months of September–November on smallholder farms. Maize yield response to residue biomass soil cover could change if other crops (e.g. legumes and non-legumes) are included in the rotation with maize, or different types of mulching plant materials (e.g. leguminous rotational crops, leaves from leguminous shrubs or trees), and soil fertility management options (e.g. livestock manure) are used in CA/NT systems tested. For CA/NT systems, new strategies of providing soil cover should be explored and cover crops could be an attractive option because these crops can also improve soil fertility in the cropping system and provide livestock feed. Future studies are therefore needed to better understand soil N patterns in CA/NT systems under different soil types and rainfall regimes in southern Africa.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S174217051900005X.

Acknowledgement. This long-term study was financially supported by the International Fund for Agriculture Development (IFAD) through a long-term study on CA systems in southern Africa. We are grateful for this significant contribution. This study has been embedded into the CGIAR Research Program MAIZE, Flagship Sustainable intensification of smallholder farming systems. We acknowledge the CGIAR Fund Council, Australia (ACIAR), Irish Aid, European Union, International Fund for Agriculture Development (IFAD), Netherlands, New Zealand, Switzerland, UK, USAID and Thailand for funding to the CGIAR Research Program MAIZE. We thank numerous researchers and field workers from the four countries for their contribution to the study.

References

Andersson JA and D'Souza S (2014) From adoption claims to understanding farmers and contexts: a literature review of Conservation Agriculture (CA) adoption among smallholder farmers in Southern Africa. *Agriculture, Ecosystems & Environment* **187**, 116–132.

Barrios E, Kwesiga F, Buresh RJ and Sprent JI (1997) Light fraction soil organic matter and available nitrogen following trees and maize. *Soil Science Society of America Journal* **61**, 826–831.

Berg G and Smalla K (2009) Plant species and soil type cooperatively shape the structure and function of microbial communities in the rhizosphere. *FEMS Microbiology Ecology* **68**, 1–13.

Blackmer TM and Schepers JS (1996) Use of chlorophyll meter to monitor nitrogen status and schedule fertigation for corn. *Production Agriculture* **8**, 56–60.

Corbeels M, Sakyi RK, Kühne RF and Whitbread A (2014) *Meta-analysis of crop responses to conservation agriculture in sub-Saharan Africa* (CCAFS Report No. 12). Copenhagen: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Available at *www.ccafs.cgiar.org*.

Duncan AJ, Tarawali SA, Thorne PJ, Valbuena D, Descheemaeker K and Homann-Kee S (2013) Integrated crop/livestock systems – a key to sustainable intensification in Africa. *Tropical Grass* **1**, 202–206.

FAO (2002) Conservation agriculture: Case study in Latin America and Africa. 78 Rome: FAO Soils Bulletin.

FAO (2015) Conservation Agriculture. Available at http://www.fao.org/ag/ca/index.html

Gentile R, Vanlauwe B, Van Kessel C and Six J (2009) Managing N availability and losses by combining fertilizer N with different quality residues in Kenya. *Agriculture, Ecosystems & Environment* **131**, 308–314.

Giller KE, Cadisch G, Ehaliotis C, Adams E, Sakala W and Mafongoya PL (1997) Building soil nitrogen capital in Africa. In Buresh JR, Sanchez PA and Calhoun F (eds), *Replenishing Soil Fertility in Africa*. Madison, Wisconsin, USA: Soil Science Society of America Special Publication No 51, pp. 151–192.

Giller KE, Witter E, Corbeels M and Tittonell P (2009) Conservation agriculture and smallholder farming in Africa: the heretic's view. *Field Crops Research* **114**, 23–34.

Girvan MS, Bullimore J, Pretty JN, Osborne AM and Ball AS (2003) Soil type is the primary determinant of the composition of the total and active bacterial communities in arable soils. *Applied and Environmental Microbiology* **69**, 1800–1809.

Habig J and Swanepoel C (2015) Effects of conservation agriculture and fertilization on soil microbial diversity and activity. *Environments* **2**, 358–384.

Hadas A, Kautsky L, Goek M and Kara EE (2004) Rates of decomposition of plant residues and available nitrogen in soil, related to residue composition through simulation of carbon and nitrogen turnover. *Soil Biology & Biochemistry* **36**, 255–266.

Hlatywayo R, Mhlanga B, Mazarura U, Mupangwa W and Thierfelder C (2016) Response of maize (Zea mays L.) secondary growth parameters to conservation agriculture and conventional tillage systems in Zimbabwe. *Agricultural Science* **8**, 112–126.

Homann Kee-Tui S, Bandason E, Maute F, Nkomboni D, Mpofu N, Tanganyika J, Van Rooyen AF, Gondwe T, Dias P, Ncube S, Moyo S, Hendricks S and Nisrane F (2013) Optimizing livelihood and environmental benefits from crop residues in smallholder crop-livestock systems in Southern Africa: Crop residue uses and trade- offs, exploring options for sustainable intensification with stakeholders. International Crops Research Institute for Semi-Arid Tropics (ICRISAT), Patancheru, AP, India, 60 pp.

Jaleta M, Kassie M and Erenstein O (2015) Determinants of maize stover utilization as feed, fuel and soil amendment in mixed crop-livestock systems, Ethiopia. *Agricultural Systems* **134**, 17–23.

Jat ML, Gathala MK, Saharawat YS, Tetarwal JP, Gupta R and Yadvinder S (2013) Double no-till and permanent raised beds in maize–wheat rotation of north-western Indo- Gangetic plains of India: effects on crop yields, water productivity, profitability and soil physical properties. *Field Crops Research* **149**, 291–299.

Jayne TS, Mather D and Mghenyi E (2010) Principal challenges confronting smallholder agriculture in Sub-Saharan Africa. *World Development* **38**, 1384–1398.

Kassam A, Friedrich T, Shaxson F and Pretty J (2009) The spread of conservation agriculture: justification, sustainability and uptake. *International Journal of Agricultural Sustainability* **7**, 292–320.

Kitonyo OM, Sadras VO, Zhou Y and Debton MD (2018) Nitrogen fertilization modifies maize yield response to tillage and stubble in a sub-humid tropical environment. *Field Crops Research* **223**, 113–124.

Kumwenda JDT, Saka AR, Snap SS, Ganunga RP and Benson T (1998) Effects of organic legume residues and inorganic fertilizer nitrogen on maize yield in Malawi. In Waddington S, Murwira HK, Kumwenda JDT, Hikwa D and Tagwira F (eds), *Soil Fertility Research for Maize Based Farming Systems in Malawi and Zimbabwe*. Proceedings of the Soil Fertility Research Results and Planning Workshop. 7–11 July 1997, Mutare, Zimbabwe: Africa University, pp. 165–171.

Lal R (2015) Sequestering carbon and increasing productivity by conservation agriculture. *Journal of Soil and Water Conservation* **70**, 55–62.

Lemaire G, Charrier X and Hebert Y (1996) Nitrogen uptake capacities of maize and sorghum crops in different nitrogen and water supply conditions. *Agron* **16**, 231–246.

Liu K and Wiatrak P (2011) Corn (*Zea mays* L.) plant characteristics and grain yield response to N fertilization programs in no-till system. *American Journal of Agricultural and Biological Sciences* **6**, 279–286.

Mapfumo P, Mtambanengwe F and Vanlauwe B (2007) Organic matter quality and management effects on enrichment of soil organic matter fractions in contrasting soils in Zimbabwe. *Plant and Soil* **296**, 137–150.

Martinsen V, Shitumbanuma V, Mulder J, Ritz C and Cornelissen G (2017) Effects of hand hoe tilled conservation farming on soil quality and carbon stocks under on-farm conditions in Zambia. *Agriculture, Ecosystems & Environment* **241**, 168–178.

Masvaya EN, Nyamangara J, Descheemaeker K and Giller KE (2017) Is maize-cowpea intercropping a viable option for smallholder farms in the risky environments of semi-arid Southern Africa? *Field Crops Research* **209**, 73–87.

Matusso JM, Mugwe J and Mucheru-Muna M (2015) Effects of different maize (*Zea mays* L.) soybean (Glycine max (L.) Merrill) intercropping patterns on soil mineral-N, N-uptake and soil properties. *African Journal of. Agricultural Research* **9**, 42–55.

Mazvimavi K and Twomlow S (2009) Socioeconomic and institutional factors influencing adoption of conservation agriculture by vulnerable households in Zimbabwe. *Agricultural Systems* **101**, 20–29.

Mhlanga B (2015) Evaluation of the effects of relay cropping and rotation on supplementary biomass production and its retention in maize-based systems under conservation agriculture in Zimbabwe. Department of Crop Science, University of Zimbabwe.

Mloza-Banda HR, Makwiza CN and Mloza-Banda ML (2016) Soil properties after conversion to conservation agriculture from ridge tillage in southern Malawi. *Journal of Arid Environments* **127**, 7–16.

Muchabi J, Lungu OI and Mweetwa AM (2014) Conservation agriculture in Zambia: effects on selected soil properties and biological nitrogen fixation in soybeans (*Glycine max* (l.) Merr). *Sustainable Agriculture Research* **3**, 28–36.

Muchow RC (1988) Effect of nitrogen supply on the comparative productivity of maize and Sorghum in a semi-arid tropical environment I. Leaf growth and leaf nitrogen. *Field Crops Research* **18**, 1–16.

Muchow RC and Davis R (1988) Effect of N supply on the comparative productivity of maize and sorghum in a semi-arid tropical environment II. Radiation interception and biomass accumulation. *Field Crops Research* **18**, 17–30.

Mupangwa W and Thierfelder C (2014) Intensification of conservation agriculture systems for increased livestock feed and maize production in Zimbabwe. *International Journal of Agricultural Sustainability* **12**, 425–439.

Mupangwa W, Twomlow S and Walker S (2012) Reduced tillage, mulching and rotational effects on maize (*Zea mays* L.), cowpea (*Vigna unguiculata* (Walp) L.) and sorghum (*Sorghum bicolor* L. (Moench)) yields under semi-arid conditions. *Field Crops Research* **132**, 139–148.

Mupangwa W, Twomlow S, Walker S and Hove L (2007) Effect of minimum tillage and mulching on maize (*Zea mays* L.) yield and water content of clayey and sandy soils. *Physics and Chemistry of the Earth* **32**, 1127–1134.

Mupangwa W, Nyagumbo I and Mutsamba E (2016*a*) Effect of different mulching materials on maize growth and yield in conservation agriculture systems of sub-humid Zimbabwe. *AIMS Agriculture and Food* **1**, 239–253.

Mupangwa W, Mutenje M, Thierfelder C and Nyagumbo I (2016*b*) Are conservation agriculture (CA) systems productive and profitable options for smallholder farmers in different agro- ecoregions of Zimbabwe? *Renewable Agriculture and Food Systems* **32**, 87–103.

Ngwira AR, Thierfelder C and Lambert DM (2012) Conservation agriculture systems for Malawian smallholder farmers: long-term effects on crop productivity, profitability and soil quality. *Renewable Agriculture and Food Systems* **28**, 350–363.

Nyagumbo I, Munamati M, Mutsamba EF, Thierfelder C, Cumbane A and Dias D (2015) The effects of tillage, mulching and termite control strategies on termite activity and maize yield under conservation agriculture in Mozambique. *Crop Protection* **78**, 54–62.

Nyamangara J, Masvaya EN, Tirivavi R and Nyengerai K (2013) Effect of hand-hoe based conservation agriculture on soil fertility and maize yield in selected smallholder areas in Zimbabwe. *Soil & Tillage Research* **126**, 19–25.

Nyamangara J, Marondedze A, Masvaya EN, Mawodza T, Nyawasha R, Nyengerai K, Tirivavi R, Nyamugafata P and Wuta M (2014) Influence of basin-based conservation agriculture on selected soil quality parameters under smallholder farming in Zimbabwe. *Soil Use and Management* **30**, 550–559.

Nyamapfene K (1991) *Soils of Zimbabwe*. Harare, Zimbabwe: Nehanda Publishers (Pvt) Ltd.

Palm C, Blanco-Canqui H, Declerck F, Gatere L and Grace P (2014) Conservation agriculture and ecosystem services: an overview. *Agriculture, Ecosystems & Environment* **187**, 87–105.

Pandey RK, Maranville JW and Chetima MM (2000) Deficit irrigation and nitrogen effects on maize in a Sahelian environment II. Shoot growth, nitrogen uptake and water extraction. *Agricultural Water Management* **46**, 15–27.

Payne R, Murray D, Harding S, Baird D, Soutar D and Lane P (2002) *GenStat for Windows*, 6th Edn. Jordan Hill Road, Oxford, UK: VSN International, Wilkson House.

Pittelkow CM, Liang X, Linquist BA, Van Groenigen KJ, Lee J, Lundy ME, Van Gestel N, Six J, Venterea RT and Van Kessel C (2014) Productivity limits and potentials of the principles of conservation agriculture. Res letter. *Nature* **517**, 365–368.

Pittelkow CM, Linquist BA, Lundy ME, Liang X, van Groenigen KJ, Lee J, van Gestel N, Six J, Venterea RT and van Kessel C (2015) When does no-till yield more? A global meta-analysis. *Field Crops Research* **183**, 156–168.

R Core Team (2017) *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing. Available at http://www.R-project.org/.

Rusinamhodzi L, Corbeels M, van Wijk MT, Rufino MC, Nyamangara J and Giller KE (2011) A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. *Agronomy for Sustainable Development* **31**, 657–673.

Rusinamhodzi L, Corbeels M, Zingore S, Nyamangara J and Giller KE (2013) Pushing the envelope? Maize production intensification and the role of cattle manure in recovery of degraded soils in smallholder farming areas of Zimbabwe. *Field Crops Research* **147**, 40–53.

Sakala WD, Cadisch G and Giller KE (2000) Interactions between residues of maize and pigeon pea and mineral N fertilizers during decomposition and N mineralization. *Soil Biology & Biochemistry* **32**, 679–688.

Thierfelder C and Wall PC (2010) Rotations in conservation agriculture systems of Zambia: effects on soil quality and water relations. *Experimental Agriculture* **46**, 309–325.

Thierfelder C, Mutenje M, Mujeyi A and Mupangwa W (2014) Where is the limit? Lessons learned from long term conservation agriculture research in zimuto communal area, Zimbabwe. *Food Security* **7**, 15–31.

Thierfelder C, Rusinamhodzi L, Ngwira AR, Mupangwa W, Nyagumbo I, Kassie GT and Cairns JE (2015) Conservation agriculture in Southern Africa: advances in knowledge. *Renewable Agriculture and Food Systems* **30**, 328–348.

Twomlow SJ, Steyn JT and Du Preez CC (2006) Dryland farming in Southern Africa. Chapter 19. In Petersen GA, Unger WP, Payne WA (eds), *Dryland Agriculture*, 2nd Edn. Agronomy Monograph No. 23. Madison, Wisconsin: American Society of Agronomy, pp. 769–836.

Valbuena D, Erenstein O, Homann-Kee Tui S, Abdoulaye T, Claessens L, Duncan AJ, Gérard B, Rufino MC, Teufel N, van Rooyen A and van Wijk MT (2012) Conservation agriculture in mixed crop–livestock systems: scoping crop residue trade-offs in Sub-Saharan Africa and South Asia. *Field Crops Research* **132**, 175–184.

Verhulst N, Govaerts B, Verachtert E, Castellanos-Navarrete A, Mezzalama M, Wall PC, Chocobar A, Deckers J and Sayre KD (2010) Conservation agriculture, improving soil quality for sustainable production systems. In Lal R and Stewart BA (eds), *Advances in Soil Science: Food Security and Soil Quality*. Boca Raton, FL, USA: CRC Press, pp. 137–208.

Wall PC, Thierfelder C, Ngwira A, Govaerts B, Nyagumbo I and Baudron F (2013) Conservation agriculture in eastern and Southern Africa. In Jat RA, Sahrawat KL and Kassam AH (eds), *Conservation Agriculture: Global Prospects and Challenges*. Wallingford Oxfordshire OX10 8DE, UK: CABI, pp. 263–292.

Wood CW, Reeves DW and Himelrick DG (1993) Relationships between chlorophyll meter readings and leaf chlorophyll concentration, N status and crop yield : a review. *Proceedings of the Agronomy Society of New Zealand* **23**, 1–9.