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Soil Quality and Nutrient Management for Sustainable Food Production in Mulch Based Cropping Systems in Sub-Saharan Africa

Final Report of a Coordinated Research Project

Joint FAO/IAEA Programme
Nuclear Techniques in Food and Agriculture

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SOIL QUALITY AND NUTRIENT MANAGEMENT FOR SUSTAINABLE FOOD PRODUCTION IN MULCH BASED CROPPING SYSTEMS IN SUB-SAHARAN AFRICA

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FINAL REPORT OF A COORDINATED RESEARCH PROJECT

INTERNATIONAL ATOMIC ENERGY AGENCY
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Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
fax: +43 1 26007 22529
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
www.iaea.org/books

For further information on this publication, please contact:

Soil and Water Management and Crop Nutrition Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Email: Official.Mail@iaea.org

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FOREWORD

Retaining crop residue as soil mulch or soil cover is one of the highly beneficial practices of good soil management. Mulch enriches soil with essential plant nutrients and improves soil organic matter and soil biological activities, thus leading to increased soil fertility and improved soil structure and stability. Mulching also helps conserve and maintain moisture, protects soil from water erosion, helps maintain a more even soil temperature and reduces weed growth, thereby providing better growing environments for crop growth and enhanced crop productivity.

In 2012, the IAEA launched a coordinated research project entitled Soil Quality and Nutrient Management for Sustainable Food Production in Mulch-based Cropping Systems in Sub-Saharan Africa to investigate the effects of soil management and agronomic practices on soil fertility, ecosystem service efficiency and agricultural productivity in mulch based farming systems, and on climate change and variability in cropping or integrated crop–livestock systems in the moist and dry savannahs of sub-Saharan Africa. The goal was to improve the livelihoods of farmers in rural communities in a region dominated by a savannah ecosystem in its natural state. The project, which involved seven research contract holders (from Benin, Kenya, Madagascar, Mauritius, Mozambique, Pakistan and Zimbabwe), three technical contract holders (two from China and one from the Czech Republic) and four agreement holders (from Belgium, Kenya, New Zealand and the United States of America), was concluded in November 2016.

This publication presents data and reports collated from the project. Because of the selection of benchmark sites in diverse and representative environmental conditions, the results described provide a platform for extrapolating the recommended soil management practices to other agro-ecological regions of sub-Saharan Africa. The results are expected to help farmers in countries in sub-Saharan Africa with low crop yields to improve the productivity and profitability of their crops.

The IAEA officer responsible for this publication was M. Zaman of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture.

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SUMMARY

BACKGROUND

In mulch-based farming systems, it is important to adopt soil management practices that could potentially increase soil organic matter content (carbon sequestration) and maximise the efficiency of utilisation of soil nutrients (synthetic and organic fertilisers) and water storage for crop growth. Soil organic matter improves soil fertility, stabilises soil aggregates, increases soil water holding capacity to absorb and hold more water for crop growth and, more importantly, provides carbon as an energy source for the soil fauna and flora, which in turn enhances the soil's chemical and physical properties. The use of the stable isotopic techniques (C-13 and N-15) at enriched or natural abundance levels facilitate indepth analysis and understanding of the basic soil biological and physical processes, including soil carbon and nutrient cycling in mulch-based systems. The coordinated research project provides a platform for the extrapolation of the recommended soil management practices to all agro-ecological regions of SSA because of the selection of benchmark sites in diverse and representative environmental conditions.

OBJECTIVES

The objective of this coordinate research project (CRP) was to investigate the effects of soil management and agronomic practices in mulch-based farming systems on soil fertility, ecosystem service efficiency, agricultural productivity, and on climate change and variability in cropping or integrated crop-livestock systems in the moist and dry savannahs of SSA. The goal was to improve the livelihoods of low socio-economic farmers and rural communities in a region that is dominated by a savannah ecosystem in its natural state.

Specifically, the CRP aimed to resolve four key issues relating to soil quality and nutrient management for sustainable food production in mulch-based cropping systems in SSA:

- To improve soil fertility and soil health by promoting carbon sequestration through the replacement of exported nutrients (especially nitrogen (N), but also phosphorus (P) and sulphur (S) to a lesser extent) and by applying the principles of conservation agriculture;
- To increase productivity in integrated crop-livestock systems across different spatial scales in the moist and dry savannahs of SSA;
- To increase onfarm and area wide ecosystem service efficiency (e.g. nutrient, water, labour and energy use efficiency);
- To assess economic feasibility and conduct impact assessment of mulch-based farming systems in SSA.

STUDIES CARRIED OUT UNDER THIS CRP

Common experimental design and treatments

The common experimental design was a 2 × 2 × 2 factorial consisting of 8 combinations of treatments (T), replicated 3 or 4 times in randomised blocks, giving a total of 24 or 32 plots with 3 blocks (Fig 1). The main factor was tillage [No till (O) or conventional tillage (C)], with sub-plots of mulch (with or without M) and N fertiliser (with or without N). Mulch was applied at 30–50% coverage while N was commonly applied at 120 kg ha^{-1} (or 165 kg ha^{-1}, Pakistan) as urea or ammonium sulphate in single or split applications. The common crop was maize (*Zea mays* L.). Under dryland farming without irrigation or with irrigation it was possible to have either one (unimodal rainfall distribution) or two crops (bimodal) per year depending on location.

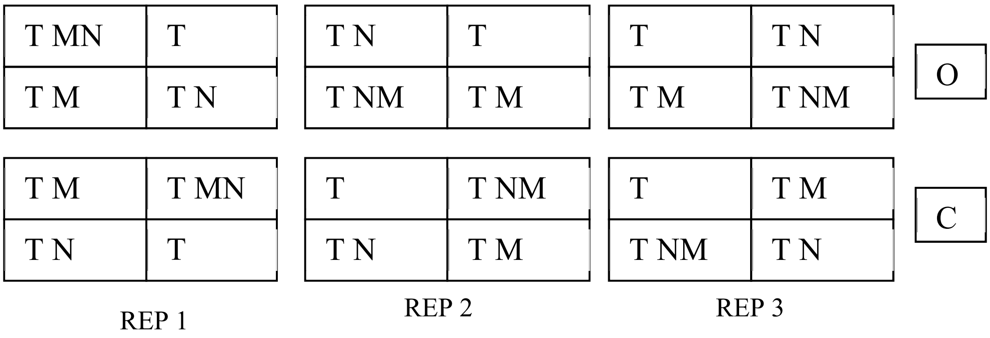

FIG. 1. Plot layout.

TABLE 1. EXPERIMENTAL DETAILS REPORTED BY THE CRP PARTICIPANTS

Country year rainfall distribution	Maize cv. N ha^{-1} plot size	Location	Soil type pH$_{H2O}$ Texture	Measurements
Benin 2015 (1 crop) Bimodal	AK 94 DMR ESR-Y 100 000 7 m × 5 m	Sékou 6°37'32.2" N 2°14'10.9" E	Rhodic ferralsol 5.9 Sandy loam	Plant height; N° of leaves; Collar diameter; Growth rate; Yield (dry matter; grain; economic; biological); Harvest index; Soil water status; N fertiliser use efficiency (agronomic, recovery, physiological)
Kenya 2013–2014 (4 crops) Bimodal	H516 7 m × 7 m	Kirege 0°20'07.0" S 37°36'46.0" E 1526 masl	Humic nitisol	Grain yield; Stover yield; Rainfall; Soil moisture (Diviner 2000) at 10 cm intervals to a depth of 80 cm
Madagascar 2014–2015 (2 crops) Unimodal	PANNAR-12 45 100 7 m × 7 m	Imerintsiatosika 18°58'59.8" S 47°17'27.6" E 1342 masl	Ferralsol 5.0	Grain yield, Stover (cob, husk, ear, straw) yield; N concentration of shoots and grain; N fertiliser efficiency (agronomic, recovery, physiological)
Mauritius	 50 000 7 m × 7 m	Réduit 20°13'52.9" S 57°29'22.6" E	Low humic latosol 4.1	Density (bulk, particle); Infiltration rate; Porosity; Microbiology (N fungi, bacteria); Respiration rate; Enzyme assays; Grain (yield, quality); Soil chemical data
Pakistan 2013–2015 (5 crops) Unimodal	EV-77 8 m × 8 m	Faisalabad 31°23' N 73°2' E 184 masl	Typic ustocrept 8.3 Loam	Yield (dry matter, grain); Soil organic C; Fertiliser (^{15}N) recovery and loss (mass balance) in 5th crop components and soil to 100 cm depth; Added nitrogen interaction
Zimbabwe		Domboshava 17°36'28.9" S 31°08'54.6" E	Haplic acrisol Sandy loam	Aggregate stability, soil texture, bulk density and soil organic C (depth intervals to 60 cm); Infiltration rate; Hydraulic conductivity

CRP ACHIEVEMENTS

Tillage

The experiments were not installed on long-term zero (or minimum) and conventional tillage plots. Therefore, it was not expected that the experiments would show significant differences between tillage treatments on the newly installed plots which were maintained only for a few years. For example, tillage treatments had no effect on dry matter or grain yield over 5 successive crops of maize grown under irrigation in N fertilised or unfertilised plots in Pakistan. Similarly, in Kenya tillage had only one significant effect on grain yield over 4 crops. However, reduced tillage was shown to benefit water stable aggregates in Zimbabwe in both mulched and unmulched plots. In Benin, conventional tillage was superior to no-till with respect to grain yield and growth parameters, but tillage *per se* did not affect water storage.

Nitrogen fertiliser

Dry matter and grain yield of maize responded significantly to N fertiliser addition in all experiments, which was an expected response on soils that had been cropped for many years and were low in total N. Generally, the response was greater for a split fertiliser application compared with a single application. N fertiliser efficiency was evaluated by several efficiency parameters (agronomic, physiological, apparent recovery) in Benin and Madagascar, and by using ^{15}N-labelled fertiliser, recovery in the 5th crop and soil was determined directly (and losses by mass balance) in Pakistan. In Madagascar the timing of N fertiliser addition was critical, with positive responses in dry matter and grain yields in 2014, but no response in 2015, where the apparent N recovery was very low due to the late application.

Mulch

The effect of mulch was quite variable. For example, in Pakistan, where mulch had no effect on dry matter or grain yields in unfertilised plots, the yields were reduced in fertilised plots, and N fertiliser recovery in the 5th crop was less in mulched plots where loss of fertiliser N (mass balance) increased while recovery in the soil increased. Thus, mulch may have increased immobilisation and denitrification due to greater C availability. In Kenya, mulch had no effect on grain or stover yields under conventional tillage across 4 crops (bimodal short and long rains over 2 years), while mulch reduced grain (but not stover) yields in 2 out of 4 crops under minimum tillage. The benefits of mulch were shown in Zimbabwe where significantly higher rates of hydraulic conductivity, corresponding to the steady state (final) infiltration were obtained (0.11–0.18 mm min^{-1}) when mulch was used compared to 0.07–0.10 mm min^{-1} obtained without mulch cover for both reduced and conventional tillage. These results show the importance of mulches in improving water infiltration with reduction in surface runoff and increased soil water seepage. Mulch had positive effects on growth parameters and grain yields in Benin, possibly due to greater water conservation. In addition, mulch had positive effects on N fertiliser use efficiency (agronomic, apparent recovery, physiological) under conventional tillage, but the differences were not consistent under reduced tillage.

CONCLUSIONS

Although the intention of the CRP was to focus on the Member States of SSA, it was subsequently expanded to countries of East Africa, the Indian Ocean and Asia. Application of synthetic N fertiliser in intensive cereal cropping systems is at the moment necessary to maintain yields worldwide. Application of mulch (i.e. retention of crop residues) and minimum or zero tillage are both core principles in conservation agriculture. However, reduced tillage practices are more suited to large scale mechanised agriculture in countries such as Brazil, Australia and North America. Such practices are not easily applied in subsistent smallholder agriculture where animal traction and traditional tillage practices are employed, like in countries of SSA. Several benefits may accrue from mulching but these will be governed by the availability and quality of the mulch. Poor soil fertility including acidity and nutrient deficiencies limit the amounts of mulch that can be produced by farmers, thus reducing their potential effectiveness. There are also competing demands for mulch (crop residues) that restrict availability, including animal feed, fuel for cooking and natural losses due to removal by wind, rain and insect (termite) activity. Large amounts of poor quality mulch (e.g. rice straw) may hinder planting operations and lead to the tieup (immobilisation) of available soil and fertiliser N and are therefore often burnt by farmers. Therefore, the adoption of mulch-based cropping and reduced tillage practices will depend on the socio-economic, edaphic and environmental conditions pertaining in each Member State.

EFFECTS OF TILLAGE AND RESIDUE RETENTION ON MAIZE (*ZEA MAYS* L.) YIELD AND SOIL WATER CONTENT OF HUMIC NITISOLS IN THE CENTRAL HIGHLANDS OF KENYA

E.W. NJOGU-MURITHI
Embu University College
Embu, Kenya

M.W. MUCHERU-MUNA
Kenyatta University
Nairobi, Kenya

F. NGETICH, D.N. MUGENDI
Embu University College
Embu, Kenya

J.N. MUGWE
Kenyatta University
Nairobi, Kenya

Abstract

To achieve sustainable agricultural production in Kenya, there is need to enhance the yields per unit of land while still conserving the soil resources. In the Central Highlands of Kenya, agriculture is rain fed and besides poor soil nutrient status, water is also a limiting factor to food production. There is therefore a need to address the poor soil nutrient status alongside soil water stresses, through appropriate tillage and crop residue management practices to increase crop productivity. Knowledge on the appropriate tillage and crop residue management for increased productivity is only partial in the region. As such, this research focused on addressing the knowledge gap by assessing the effects of tillage and mulching on maize (*Zea Mays* L.) yield and soil water content of Humic Nitisols in the central highlands of Kenya. Two mulch levels [removal (W) and retention (R) of crop residue] were applied randomly to plots measuring 7 m × 7 m under two tillage methods [conventional tillage (CT) and minimum tillage (MT)]. Special attention was given to the effects of these treatments to the maize yields and soil moisture content. There was significant treatment effect for grain yields under minimum tillage without residues (MTW), conventional tillage with residues (CTR) and minimum tillage with residues (MTR) treatments. For CTR, a significant ($P<0.0029$) increase in grain yield of 38% was recorded. There was significant ($P<0.017$) response to MTW in terms of grain yield and on average MTW yielded 87% higher than the control. In SR13 and LR14, significant ($P<0.007$ and $P<0.003$ respectively) grain response to MTR was observed. A significant yield increase in SR13 and 32% in LR14 was recorded in MTR plots compared to the control. A significant ($P<0.05$) treatment effect on soil moisture was observed within the top 10 cm depth, whereby the total amount of soil moisture stored within the 10-cm depth of the soil profile, was highest for MTR and MTW treatments. The results of the experiment show significant effects of MT and mulching on maize yields, soil moisture content of the Humic Nitisol in the Central Highlands of Kenya. Therefore, short-term implementation of MT and mulching under the soil and climate conditions prevailing in the Central Highlands of Kenya, enhances production in the already good seasons (high and well distributed rainfall) while maintaining a long-term prospect of stabilising yields and overcoming crop failure during poor rainfall seasons.

1. INTRODUCTION

To achieve sustainable agricultural production and food security in Kenya, there is need to enhance the yields per unit of land while still conserving the soil resources [1]. Besides poor soil nutrient status, water is also a limiting factor to food production under rain fed conditions, and thus water and nutrients alternate within a particular season as key factors limiting crop production [2]. The smallholder farmers who are mainly responsible for about 80% of agricultural production in Kenya, practice rain fed agriculture and are at risk of crop failure given the erratic nature of the rains [3]. In view of this, the farmers' ability to realise yields that would ensure household food security requires enhanced moisture storage in the soil profile. This can be achieved through tillage and crop residue management practices that ensure effective infiltration and retention of rainwater into the soil [4].

To achieve sustainable agricultural production and food security in Kenya, there is need to enhance the yields per unit of land while still conserving the soil resources [1]. Besides poor soil nutrient status, water is also a limiting factor to food production under rain fed conditions, and thus water and nutrients alternate within a particular season as key factors limiting crop production [2]. The smallholder farmers who are mainly responsible for about 80% of agricultural production in Kenya, practice rain fed agriculture and are at risk of crop failure given the erratic nature of the rains [3]. In view of this, the farmers' ability to realise yields that would ensure household food security requires enhanced moisture storage in the soil profile. This can be achieved through tillage and crop residue management practices that ensure effective infiltration and retention of rainwater into the soil [4].

Soil water conservation through tillage is a widely accepted approach for addressing the soil moisture constraint in rain-fed agriculture [5]. According to Martínez et al. [6] CT disturbs soil structure and may increase the risk of runoff and soil erosion. It is associated with crust and hardpan formation, soil, water and nutrients losses in the field, resulting in degraded soil with low organic matter and fragile physical structure, leading eventually to low crop yield [5, 7]. Consequently, in many areas of Kenya CT leads to a decline in crop yields and profitability [8]. Thus, other sustainable techniques like mulch-based no-till farming (with soil disturbance restricted to seed sowing) and conservation tillage involving some form of soil disturbance like strip-tillage, ripping and sub-soiling, ridging, and various locally-adapted reduced tillage practices are advocated [9]. According to Carter [10] excessive soil tillage is associated with soil degradation processes such as compaction, reduced soil aggregate stability and increased soil erosion, hence the trend towards reduced or MT and mulching.

No-tillage (NT) may have, under certain soil, climate and management conditions, potential advantages over CT [6]. Their potential in soil and water conservation is widely advocated, however, there is lack of a clear understanding of their effects on soil condition and crop yield for different soil, crop and climate condition [11]. Various soil types react differently to the same tillage method with respect to some selected soil properties, while the effects of tillage method on crop yield vary with the crop species [7].

Similarly, mulching is also reported as one of the agronomic practices important in conserving soil moisture, modifying the soil physical environment and increasing crop productivity [12]. However, to achieve sustainable crop production, efficient mulch management is necessary; therefore, appropriate site-specific methodology should be followed under different soil, crop and climate conditions [13].

Considering that the majority of smallholder farmers in the Central highlands of Kenya rely on rain-fed agriculture [14], solving the problem of low crop productivity requires that, besides poor soil nutrient status, low organic matter content and water deficit be addressed through selected approaches such as tillage and mulching. Thus, this research aimed at assessing the effects of the conventional versus zero tillage, and mulching on soil moisture conditions and crop yields under the agro-climatic conditions prevailing in the region.

2. MATERIAL AND METHODS

2.1. Site description

The study was conducted in Kirege Primary School (S 00°20’07.0”; E 037°36’46.0”), Chuka Division, in Tharaka-Nithi County, Kenya. The site lies at an altitude of 1526 m above sea level on the Eastern slopes of Mt. Kenya. It is characterised by an annual mean temperature of 20°C and a total annual rainfall of 900 to 1400 mm. The rainfall is bimodal with Long Rains (LR) from March to June and Short Rains (SR) from October to December [15]. It is a predominantly maize growing area with an average of one-acre farm size per household [14]. The predominant soil type in Chuka is Humic Nitisols which are very deep, well drained dark red to dark reddish-brown soils with moderate to high inherent fertility [15]. Agriculture in Chuka is characterised by smallholder mixed farming activities. The cash crops include bananas (*Musa paradisiaca*), coffee (*Coffea arabica*) and tea (*Camellia sinensis*) while food and horticultural crops are maize (*Zea mays*), beans (*Phaseouls vulgaris*), Irish potatoe (*Solanum tuberosum*), sweet potatoe (*Ipomoea batatas*), cabbage (*Brassica oleracea*), kale (*Brassica oleracea*), tomatoe (*Solanum lycopersicum*) and onion (*Allium cepa*). Nearly all farmers in the region practice dairy farming under zero and/or semi-zero grazing and the need for fodder is a main constraint [16]. The farmers in the region primarily rely on small scale rain-fed farming, which is mostly non-mechanised and involves minimal use of external inputs [17].

2.2. Experimental design, treatments and field management

The field experiment began with clearing of the site and installation of water conservation structures during the LR 2012 season. The first season (SR 2012) was a homogenisation trial i.e. during this season a maize crop was planted without application of any treatment and zero application of external inputs. At the end of the homogenisation period, the experiment was laid out in a randomised completed block design (RCBD) replicated thrice. The plot size was 7 m × 7 m with a 1 m wide alley separating plots within a block and 2 m wide alley left between blocks. The treatments were: CTR; Conventional tillage without residue (CTW); MTR and MTW. The test crop was maize (*Z. mays*), H516 variety. The experiment was installed in the LR13 season and run until the SR14 season. In between are the SR13 and LR14 making a total of four seasons. The sowing dates were; LR13 was 22 March 2013; SR13 was 4 November 2013; LR14 was 18 March 2014 and SR14 was 20 October 2014.

For the CT treatment plots, ploughing was done by hand hoeing to a depth of about 0.15 m at the beginning of the season, and weeding was done using a hand hoe when required, to ensure clean fields as much as possible throughout the seasons. To minimise the weed problems in the MT plots, weed control was carried out during the off-season periods using herbicide (Glyphosate), and manual uprooting of weeds was done in the course of the season to minimise soil disturbance. For the residue retention treatments, maize stover from the previous cropping season was broadcast at rate of 3 t ha^{-1}. Three maize seeds per hill were planted, with a spacing of 0.75 m between and 0.25 m within the rows, and were thinned out to 2 per hill two weeks after emergence. Inorganic fertilisers [Nitrogen, phosphorus and potassium fertiliser (NPK)

23:23:0 and triple superphosphate (TSP)] were applied during planting at a rate of 120 kg N ha^{-1} and 90 kg P ha^{-1}. Pests were controlled when necessary following conventional best practices.

2.3. Data collection

2.3.1. Rainfall data

Daily rainfall amounts were determined using a tipping bucket, data logging rain gauge, Hobo, model; RG3-M (manufactured by Onset Computer Corporation Company) with a 0.2 mm resolution installed within the field trial site. The data logger was launched at the beginning of the season and read out at the end of each season, although frequent checks were done to monitor its functionality. Besides the data logging rain gauge, a backup manual rain gauge was mounted nearby. Once read out, the data were exported using HOBOware Pro Version 3.2.2. and further processed in MS Excel. Daily rainfall was calculated by multiplying the number of tips per day (09:00 h) by 0.2 mm tipping bucket resolution of the rain gauge.

2.3.2. Yield data

After harvest, grain and stover (above-ground biomass minus grain) yields were determined from a net plot and converted to a per hectare basis. To achieve this, the following parameters were determined during and after harvesting at the end of each season: Net plot stand count per plot; Number of cobs per net plot; Fresh weight of all cobs with grains (kg) from the net plot; Dry weight of all the cobs with grains (kg) from the net plot; Dry weight of the grains (kg) after shelling; weight of dry cobs after shelling; Fresh weight of stover from the net plot; Fresh weight of randomly sampled stover from the net plot; Dry weight of the sampled stover after oven drying at 65°C until constant weight. Based on this information, per unit area grain and biomass weight were calculated. The grain yield was converted to a per hectare basis after standardising at 12.5% moisture content, while the stover dry weight was calculated on the basis of fresh weight adjusted for the moisture content and converted to a per hectare basis.

2.3.3. Soil moisture measurements

To facilitate continuous non-destructive soil moisture monitoring throughout the study period a Polyvinyl chloride (PVC) access tube was installed in the middle of each plot. To achieve this, access channels for soil moisture measurement were established manually by drilling through the soil with an auger and installing PVC tubes (180 cm long and 7.5 cm diameter) with a watertight lid at the bottom. Precautions to avoid air gaps in the space between the channels and the PVC tubes were taken by carefully refilling the area with soil for tight contact. To prevent entry of surface runoff to the PVC tubes, 20 cm of the tubes was projected above the soil surface. Soil moisture content per plot was measured between planting and harvest of the maize crop using Diviner 2000 once a week from the long rains of 2014. The portable probe was inserted into the PVC access tube to measure soil moisture content at regular intervals of 10 cm through the soil profile down to a maximum of 80 cm depth.

2.4. Data analysis

Soil moisture content and maize yield data were subjected to an analysis of variance (ANOVA) using the mixed Model in SAS 9.3. In the analysis of soil moisture, ANOVA was carried out separately for 10 cm up to 80 cm depth of the soil profile. Differences between treatment means were examined using the least significant difference (LSD) at the 5% level of probability.

3. RESULTS AND DISCUSSION

3.1. Seasonal rainfall

The four consecutive cropping seasons LR13, SR13, LR14, and SR14 were characterised by different rainfall patterns, with higher rainfall occurring in the short rainy seasons (on average 635 mm ± 12) compared to the long rainy seasons (on average 455 mm ± 9). Generally, distribution was erratic with each season having a wet period and a single within season drought spell (Fig 1).

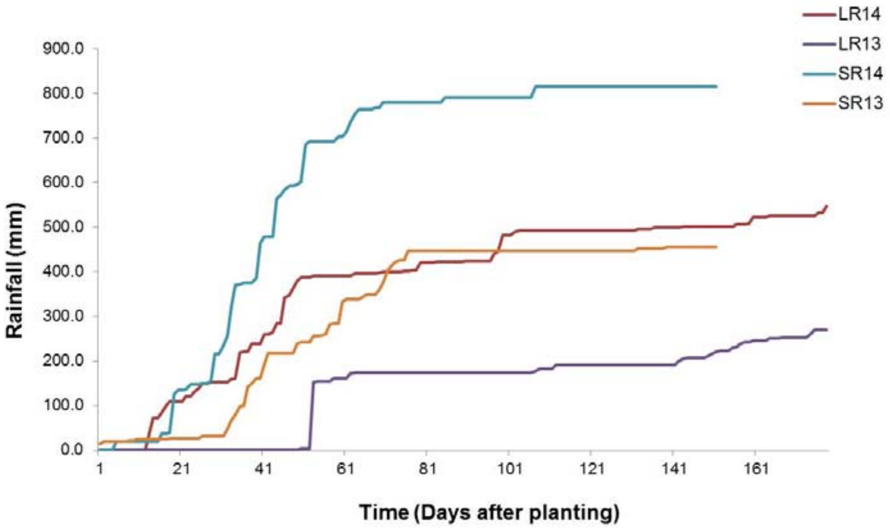

FIG. 1. Cummulative rainfall at Kirege as observed for 4 consecutive seasons. 'Long rains' (LR) from March to June and 'short rains' (SR) from October to December.

The LR13 started with a severe dry period followed by heavy rains toward the end of April before a mid season dry spell, lasting for about a month. In contrast, SR13 started well but ended with a severe and prolonged drought. In LR14 and SR14 much of the rain was received in the first two months after which there was a prolonged drought period. This unfortunately coincided with the vegetative stage of the hybrid 516 maize varieties grown at the site.

Rainfall being one of the climatic variables is the most important because of its two extreme effects as a limiting resource, such as in the case of droughts and as an agent of catastrophe, such as in the case of floods. However, in Sub-Saharan Africa (SSA) the effects of its deficiency rather than excess are most commonly experienced, manifesting in the form of crop failures due to deficit in soil moisture caused by dry spells [18].

The sub-humid zone of Central Kenya experiences extreme climate events whereby even in seasons when high rainfall is received, consecutive rainfall events are intersperced by a long dry period [19], and explains the kind of rainfall pattern observed during this study. Though both LR and SR were characterised by different rainfall patterns, a period of dry weather was common. An intra-seasonal dry spell of 28 days was experienced during SR14 and LR14, respectively, whereas during SR13 and LR13 drought periods of 35 and 43 days were experienced.

According to Araya and Stroosnijder [20], meteorological drought spells are important causes of low yield in many drought prone environments and in this study the lowest yields were recorded during SR13 and LR13 seasons. Twomlow et al. [21] observed that distribution and reliability of rainfall are often more important than total rainfall and the results of this study agree with this observation because despite having cumulatively less rainfall during the long rains, the harvest was better due to the good distribution of the rainfall in comparison to the short rains.

3.2. Maize yields

The variable rainfall led to large differences in the grain and stover yields between the seasons therefore showing a significant seasonal effect. Grain and stover yields varied from 0.6 to 5.5 t ha^{-1} and from 3.1 to 8.9 t ha^{-1}, respectively (Table 1).

TABLE 1. MAIZE YIELD (T HA^{-1}) RESPONSE TO TILLAGE AND MULCHING IN KIREGE, KENYA DURING LONG RAINS 2013 (LR13), SHORT RAINS 2013 (SR13), LONG RAINS 2014 (LR14) AND SHORT RAINS 2014 (SR14)

	LR13		LR14		SR13		SR14	
Treatment	Grain	Stover	Grain	Stover	Grain	Stover	Grain	Stover
CTR	2.6^{a}	5.9^{a}	4.7^{ab}	7.6^{a}	1.1^{ab}	6.6^{a}	2.4^{abc}	3.9^{a}
CTW	1.6^{a}	4.9^{ab}	5.3^{ab}	6.5^{a}	0.6^{b}	6.1^{a}	2.6^{abc}	6.2^{a}
Control	0.9^{a}	3.1^{b}	3.4^{c}	4.4^{b}	0.7^{b}	7.3^{a}	1.8^{c}	3.9^{a}
MTR	2.4^{a}	4.1^{ab}	4.5^{b}	6.2^{ab}	1.5^{a}	8.9^{a}	1.9^{bc}	4.3^{a}
MTW	1.9^{a}	5.2^{ab}	5.5^{a}	6.9^{a}	1.7^{a}	7.8^{a}	2.8^{a}	3.9^{a}
LSD	1.69	2.19	0.89	1.85	0.62	5.24	0.15	2.89
Probability	0.269	0.05	0.0029	0.0031	0.0076	0.78	0.039	0.373

Note: Same superscript letters in the same column denote no significant difference between treatments. In this and subsequent Tables, CTR = Conventional tillage with residue; CTW = Conventional tillage without residue; MTR = Minimum tillage with residue; MTW = Minimum tillage without residue.)

The lowest grain (0.6 t ha^{-1}) and stover (3.1 t ha^{-1}) yields were observed in the SR13 and LR13 seasons, respectively. There were also notable differences between grain and stover yields such that within each season stover yields were generally higher than the grain yields. However, significant difference in stover yield was recorded only in LR13 under CTR and LR14 under CTR, CTW and MTW. In LR13 stover yields showed a significant ($P<0.05$) response to CTR which had the highest stover yield (5.9 t ha^{-1}) with 90% more stover being harvested from the CTR plots in comparison to the control. In LR14 the percentage increase in stover yield was 72, 48 and 57% for CTR, CTW and MTW, respectively when compared to the control.

There were significant treatment effects for grain yields whereby MTW, CTR and MTR treatments yielded better than the control. In the case of CTR, a significant ($P<0.0029$) increase in grain yield at 38% was recorded in LR14. Significant response to MTW in terms of grain yield was observed for three consecutive seasons (SR13, LR14 and SR14 at $P<0.008$, $P<0.003$, P<0.04, respectively) such that on average MTW yielded 87% higher than the control. In SR13 and LR14 significant (P<0.0076 and P<0.0029, respectively) grain response to MTR was observed. A yield increase by 114% in SR13 and 32% in LR14 was recorded in MTR plots compared to the control.

Low yields (especially grain yields which are very low compared to the potential 6 t ha^{-1} in the area) are attributed to poor rainfall distribution in SR seasons, whereby much of the rainfall was received early in the season and later followed by a prolonged drought period which coincided with the crops' vegetative growth thus compromising the yielding capacity of the crop [22]. These results agree with studies by Mucheru-Muna et al. [23]. Balarios and Edmaedes [24] reported that drought stress occurs with different intensity at any plant development stage from germination to physiological maturity, while flowering is the most critical stage in maize drought stress.

Overall, the highest percentage increase in stover yields of 90% was recorded in CTR in LR13. This is attributable to residue retained as opposed to the CTW and MTW treatments. Mulching has been appreciated as a suitable agronomic practice for enhancing the soil moisture and consequently crop yield. However, just as in the study by Mupangwa et al. [25], this study recorded higher stover yields in comparison to grain yield, indicating that the soil moisture conserved was just enough to positively impact stover production but was inadequate for conversion of accumulated biomass into grain.

Although the yield in SR13 was way below the potential yield of 6 t ha^{-1} in the area, 114% increase in yield compared to the control is an indication of the positive response to MT and mulching considering that the rainfall in that season was poorly distributed. In this case, the yield benefits of MT and mulching as soil moisture conservation approaches were realised given that the grain development stage of the maize crop coincided with a dry spell. Much of the soil water accumulated early in the season was effectively utilised in the conversion of biomass to grain later in the season when there was a dry spell. Coinciding with this, was the finding of Mpangwa et al. [25] who observed an improvement in maize yield under a mulching treatment despite the poor rainfall distribution in one of the seasons during their study, while Bescansa et al. [26] pointed out that such a result could also be due to better soil water retention resulting from changes in the pore-size caused by MT and mulching.

Evidently, there is substantial difference between conservation agriculture-based treatments (MT and mulching) and the conventional practices, with MT and mulching yielding higher results. This observation is in agreement with that of Thierfelder et al. [27] who also observed higher yields in MT plots with mulching compared to the CT. Despite the variable yield differences between CT and MT during these initial years of the experiment, the trends were positive towards MT in the long-term, which agreed with the previous study [27].

3.3. Soil moisture

3.3.1. Soil moisture during the wet period

Average soil moisture content varied under different treatments at 0–80 cm depths (Figs 2 a–c). However, a significant ($P<0.05$) treatment effect was only observed within the top 10 cm depth. In the LR14, cumulatively about 391 mm of rain fell in the first six weeks of the season (Fig 2 d) and soil moisture content increased simultaneously in all treatments, at all the three depths during this period. After the sixth week, soil water content declined for all the treatments (Figs 2 a, c). Thereafter, the general trend at the three depths was soil moisture content fluctuating as influenced by the rainfall until the end of the wet period on 10 June 2014. In the top 10 cm soil depth, MTW had the highest water content while CTR had the lowest water contents. At 20 cm and 30 cm depths, soil moisture content was the highest under CTW by the end of the wet period (Figs 2 a–c).

In short rains 2014, a higher rainfall amount was experienced (Fig 2 d) and the magnitude of soil moisture build up increased, but the trends were similar to those observed in LR14. Soil moisture fluctuated concurrently in all treatments reaching the highest peak on 5 December at the end of the wet period in that season and following trends similar to those in LR14 (Figs 2 a–c). A significant ($P<0.05$) treatment effect was only observed within the top 10 cm depth by the end of the wet period, and in comparison, to the control, there was more moisture in the soil profile under MTR and MTW than under CT within the top 10 cm depth. At 20 cm depth, both MTW and CTW had greater soil moisture content while at 30 cm depth, soil moisture content was highest under CTW and lowest in MTW compared to the control.

3.3.2. Soil moisture during the dry period

Both seasons had a distinct within season dry period. The LR14 commenced after 10 June 2014 (Fig 2 d). Soil moisture in the profile reduced simultaneously in all treatments although the reduction occurred earlier and at a faster rate in the case of CTW and MTW treatments compared to those that received mulch (Figs 2 a–c). In the SR14, the dry period started after 9 December 2014 and soil moisture reduction in the soil profile was faster under CT treatments. Within the top 10 cm depth in both seasons, soil moisture under MT treatments was consistently higher compared to the CT treatments.

3.3.3. Soil moisture at the end of the season

At the end of the LR14 season and relative to the control, the soil water content was greater by 9% under MTR, 6% under MTW, 4% under CTR and 3% under CTW, while at the end of the SR14 season and in comparison, to the control, soil moisture was more by 10% under MTR, 7% under MTW, 3% under CTW and less by 3% under CTR.

Each season was characterised by a period of water accumulation (wet period) and a period of water depletion (dry period) in the soil profile. With reference to the rainfall pattern during the two experimental seasons, much of the rain was received in the first half of the season while for the rest of the season, periods of dry spells dominated (Fig 2). During the water accumulation period early in the seasons, soil water content increased due to the influence of rainfall and larger values of soil moisture content were recorded in MTW and CTW treatments following rainfall events within the top 20 cm depth (Fig 2).

There was better rainfall capture without than with mulching following rainfall events. According to Bescansa et al. [26] higher soil moisture content cannot solely be associated with mulching, while Moraru and Rusu [28] observed that penetration of the rainwater and consequent increase of the water storage in the soil profile is influenced by the amount and intensity of rainfall in addition to the soil qualities that are closely interdependent and influenced by tillage system like hydro-physical properties, soil texture and compaction.

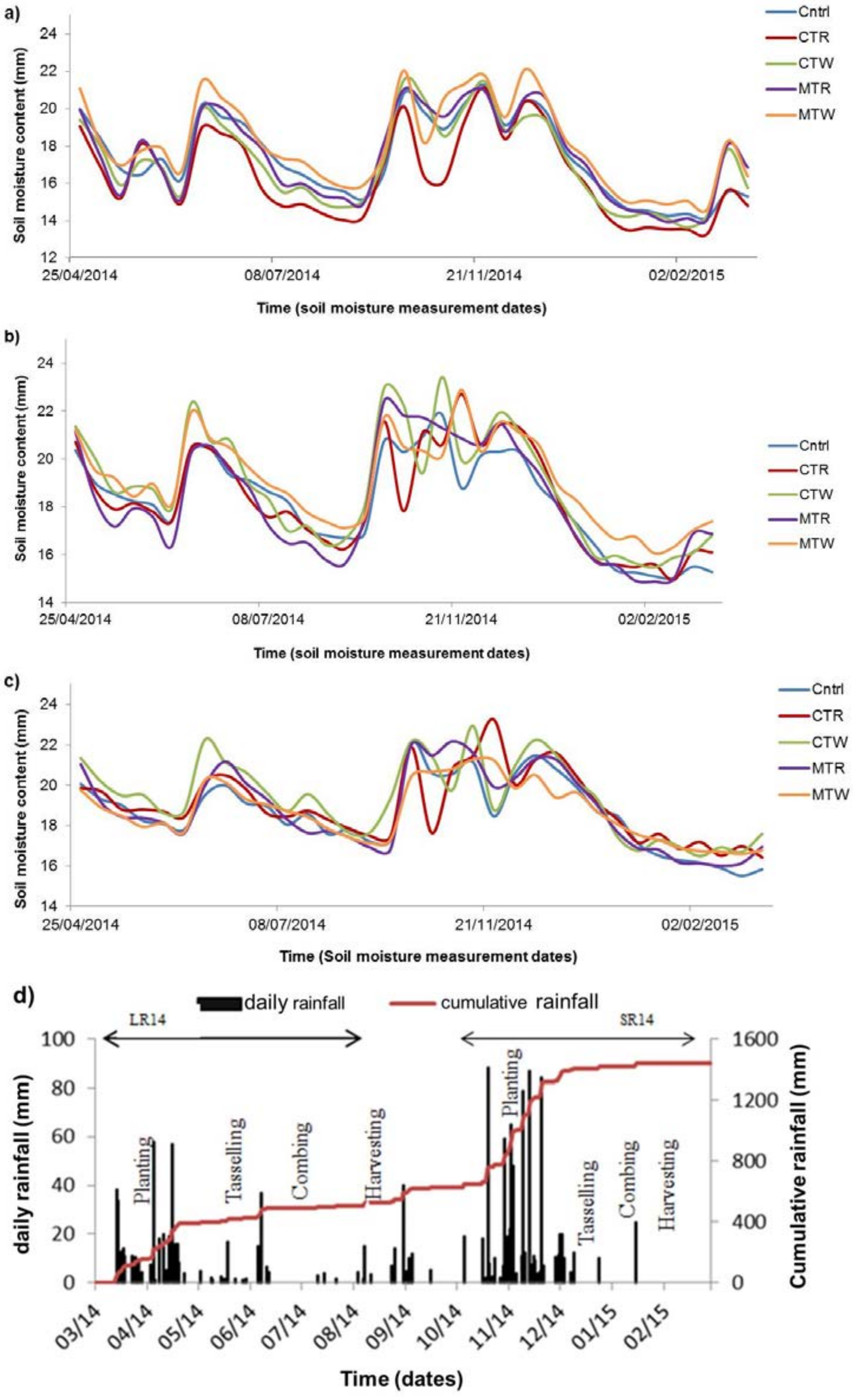

FIG. 2. Soil moisture content changes under different treatments in 0–30 cm soil profile, (a) 10 cm depth; (b) 20 cm depth; (c) 30 cm depth during the LR14 and SR14 seasons in Kirege and (d) Rainfall distribution and cumulative rainfall between planting and harvesting during the LR14 and SR14 seasons.

However, as the season progressed and especially after the wet period, total soil moisture changes were characterised by gradual decline in all the treatments but the decline was faster without than with mulch and in CT than in MT. According to Acharya et al. [13], mulching reduces evaporation from the soil surface by retarding the intensity of the radiation and wind velocity on the mulched surface. This explains why soil moisture decline was faster in unmulched than in mulched treatments.

Because of the improved aggregate stability and improved soil structure under MT, a higher proportion of mesopores is achieved. MT results in greater plant available water of the soil as opposed to CT where the mechanical inversion of the soil during tillage creates macropores and increases soil porosity. As such, CT enhanced faster decline of soil moisture in the top soil during the dry period.

One of the reasons for faster decline in soil moisture under MTW in comparison to MTR, was continuous withdrawal of water by the developing crop and by the end of the growth period, the soil had been dried at least affecting the top 15 cm profile [26]. Furthermore, maize yields were highest under the same MTW indicating that the soil moisture conserved was available to the crop for accumulation of biomass that was later converted into grain.

The soil moisture content, within the top 10 cm depth of the soil profile, was highest for MTR and MTW treatments by the end of the experiment. Since there was no significant difference in terms of soil water content at the end of the season between these two treatments, it is an indication of a greater tillage effect than mulching effect on soil water content in the short-term. According to Giller et al. [29], for the characteristic soils widespread throughout SSA, the beneficial effects of mulching may not sufficiently offset the negative effects of MT especially during the initial years of MT. Additionally, Rockstrom et al. [2] after a study in semi-arid and sub-humid locations in East and Southern Africa, concluded that MT resulted to increased water productivity, even with little or no crop residue mulch.

Though the treatments effect on soil moisture content may not be clear in the short-term, there was an indication of a positive response to MTR or MTW over time [30]. Thus, in the short-term tillage had a greater effect on soil water status than crop residue [26].

4. CONCLUSION

The results of the 2 years (four seasons) experiment show significant impacts of MT and mulching on maize yields and soil moisture content of a Humic Nitisol in the Central Highlands of Kenya. Indications are that the effects of tillage and mulching become pronounced in the long-term irrespective of the rainfall received. As such, we conclude that short-term implementation of MT and mulching under the soil and climate conditions prevailing in Central Highlands of Kenya, enhances production in the good seasons (high and well distributed rainfall) while maintaining a long-term prospect of stabilising yields and overcoming crop failure during poor rainfall seasons.

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SHORT-TERM EFFECTS OF TILLAGE AND RESIDUE CONSERVATION ON DRY MATTER YIELD AND FATE OF ^{15}N-UREA APPLIED TO IRRIGATED MAIZE TO MAIZE ROTATION UNDER SUBTROPICAL CONDITIONS

W. ISHAQUE, M.A. RIAZ, Z.H. HASHMI
Nuclear Institute for Agriculture & Biology
Faisalabad, Pakistan

F. MALIK
Pakistan Institute of Nuclear Sciences & Technology
Islamabad, Pakistan

T. MAHMOOD
Nuclear Institute for Agriculture & Biology
Faisalabad, Pakistan

Abstract

A field study was conducted under a subtropical arid climate to compare short-term effects of different tillage [conventional tillage (CT) *versus* zero tillage (ZT)] and residue conservation [mulch (M) *versus* non-mulch] regimes on productivity of irrigated maize grown for five consecutive seasons during 2.5 years. The fate of fertiliser N applied to the 5th maize crop was also investigated using the ^{15}N tracer technique. The highest soil organic carbon (SOC) was recorded in the ZT treatment receiving mulch showing 26–35% and 19–44% higher values in fertilised and unfertilised treatments, respectively; with higher increases corresponding to CT compared to ZT treatments. Averaged across five cropping seasons, tillage or mulch had no effect on total biomass and grain yields in the unfertilised plots. In the fertilised plots also, while tillage had no effect on total biomass and grain yields, mulching significantly reduced the total biomass (12–14% reduction) as well as the grain yield both under CT and ZT. The highest grain yield was recorded under ZT without mulch. Recovery of fertiliser N in soil ranged from 28–39% of the applied N with the lowest recorded in the ZT treatment without mulch. The fertiliser N recovery in the plant was highest in ZT without mulch; the treatment showed 40% fertiliser N use efficiency (above-ground components) that was almost 30% higher than other treatments. Irrespective of the mulch treatments, total fertiliser N recovery in the soil-plant system and the fertiliser N loss were not affected by tillage regimes. However, mulch application to ZT reduced the total fertiliser N recovery in the plant by 9% and the fertiliser N loss increased by 18%. Results of this short-term study suggested that compared to other tillage/mulch regimes, ZT without mulch produced similar or higher grain yield, showed highest fertiliser N use efficiency and caused similar or lower fertiliser N loss in continuous maize cropping under subtropical conditions prevailing in the Central Punjab, Pakistan.

1. INTRODUCTION

Agriculture has been traditionally relying on tillage for seedbed preparation and weed control. However, CT practices and removal/burning of crop residues not only affect the productivity of agricultural systems but also contribute to environmental degradation. Major negative effects associated with CT include stagnant or reduced crop yields, decline in soil structure, losses of soil organic C and N pools as CO_2, CH_4 and N_2O, and increased production costs and environmental pollution caused by fossil fuel combustion [1, 4]. Conservation tillage practices including reduced/minimum tillage and ZT have been introduced as alternate technologies for sustainable agriculture and to mitigate environmental problems associated with

CT [3]. Transition from CT to conservation tillage began more than 50 years ago with the development of herbicides, and since then ZT has been adopted by farmers worldwide on about 95 mha [5]. However, adoption of ZT farming has been mostly accomplished in mechanised medium- and large-sized farms, whereas it is practiced on a very limited scale on small land holdings [5]. Leading countries practicing ZT farming include the United States (20.3 mha, Brazil (13.5 mha), Argentina (9.25 mha), Australia (8.64 mha) and Canada (4.01 mha) [6, 7].

While CT practices bury or remove up to 90% of crop residues, ZT farming relies on retention of more than 90% of the residue as surface mulch to control soil erosion, runoff, evaporation and weed growth [3, 8]. However, ZT or no-tillage is generally defined as planting crops in unprepared soil with at least 30% mulch cover [9] and with this moderate residue application rate, ZT systems may perform better than higher application rates [10]. The most visible effect of ZT is the protection of soil resource against erosion, a major factor in developing sustainable agricultural production systems [9, 11, 12].

The impact of ZT on accumulation of SOC is generally more noticeable in long-term than short-term studies conducted under temperate and tropical climates. In most cases, however, SOC in NT systems is concentrated in the soil surface rather than the whole soil profile as observed under CT. In a 9-year study under subtropical, hot and humid climate, the ZT system with high residue inputs accumulated more SOC in the 0–30 cm soil layer as compared to CT [13]. After 25 years of tillage in an experiment under a temperate climate in Canada, SOC storage was higher under ZT than CT but the effect was restricted to the upper 0–5 cm soil layer [14]. In another long-term study comparing ZT and CT on 11 sites in the eastern United States, higher SOC under NT was observed but only within 0–10 cm depth [15]. After 5 years under minimum tillage in conjunction with residue mulch under subtropical conditions, soil quality improved in the surface layer as compared to other tillage regimes [16]. Besides, ZT compared to CT is well documented to increase the stratification ratio (SR) of SOC (the SOC in the 0–5 cm divided by that in 5–10, 10–20 and 20–40 cm). As compared to total organic C, SR is regarded as a more reliable predictor of soil quality independent of soil type and climatic regimes [17–19]. Considering C accumulation by ZT farming, the latter has the potential to mitigate greenhouse gas emissions. Conversion of all croplands to ZT may lead to C sequestration equivalent to 1 Pg C year^{-1} [20] or 0.1–1.0 t C ha^{-1} year^{-1} [21]. However, ZT compared to CT may lead to higher N_2O emission signifying the need of improved N management to realise the full benefit of C sequestration for mitigating global warming [22, 23].

Variable effects of tillage and residue mulching have been reported on crop yields in short-term as well as long-term studies. In a short-term study comparing ZT and CT under a subtropical climate, ZT combined with surface residue mulch and high N application rate produced higher maize forage yield [24]. In a 2-year study, ZT combined with application of 4 t ha^{-1} of rice straw mulch (either removed after 20 days, or retained for the whole wheat growing period) conserved soil moisture, suppressed weed growth, promoted root development thus improved wheat grain yield [25]. However, in another short-term study under a subtropical climate, no significant effect of tillage or mulch was observed on maize yield [26]. In a long-term study comparing ZT with complete or partial removal of residue yields in ZT without residue were reduced, whereas ZT with partial residue retention gave yields equivalent to ZT with full residue retention [27]. Although maize forage yield was not affected by the tillage treatments in a sandy soil, it was reduced under ZT compared to CT in heavier textured soil due to restricted root development [28]. Corn and soybean yields in US were typically higher under ZT than under CT on moderate- to well drained soils [29]. Increased yields under ZT farming have also been found in low rainfall areas [30].

Although long-term ZT combined with crop residue mulch is well documented to improve soil quality and crop productivity, the magnitude and pattern of tillage-induced changes are soil and site specific. While ZT farming has been relatively well understood and employed on a large scale in temperate regions, relatively little knowledge exists on performance of ZT technology in tropical and subtropical regions. In these regions, fast turnover of SOC due to the warm climate and the traditional practice of removing crop residues from fields have caused loss of soil fertility, thus leading to poor crop productivity. The present study was conducted to elucidate effects of tillage (ZT vs. CT) and crop residue management (mulch vs. non-mulch) practices on crop yield and fate of fertiliser N under irrigated maize grown in the Central Punjab, Pakistan.

2. MATERIALS AND METHODS

2.1. Study site

Field experiments were conducted at the Nuclear Institute for Agriculture and Biology (NIAB), Faisalabad (31°23' N, 73° 2' E; 184 m above mean sea level), Pakistan. The area has a subtropical arid climate characterised by large seasonal fluctuations in temperature and precipitation. Mean monthly winter and summer temperatures range from 5–15°C and 21–48°C, respectively. January is the coldest month with a mean minimum temperature of 5°C whereas May and June are the hottest months with mean maximum temperatures of 39.4 and 41.1°C, respectively. Mean annual rainfall is about 360 mm of which about two third is received during July and August in the form of high intensity monsoon downpours. The annual excess of pan-evaporation over rainfall is around 1600 mm, the greatest rainfall deficit occurring during the months of May (203 mm) and June (314 mm). The soil (Typic Ustocrept, Hafizabad series) is a deep, well drained loam developed in mixed calcareous medium-textured alluvium derived from the Himalayas [31]. Some physicochemical properties of the soil profile (measured at the start of the study) are given in Table 1.

2.2. Experiments

Eight treatments including two tillages (CT and ZT), mulch (with and without mulch) and N fertiliser (fertilised and unfertilised) regimes were laid in a split plot design (3 replicates) with tillage kept in the main plot, whereas mulch and N treatments were randomised in 24 subplots each measuring 8 m × 8 m. Continuous maize to maize cropping sequence was followed with spring maize grown during February-May and fall maize during July-November.

TABLE 1. PHYSICAL AND CHEMICAL CHARACTERISTICS OF THE SOIL AT THE STUDY SITE

Depth	Clay	Silt	Organic C	Total N	Saturation	ρb	$EC_{1:1}$	$pH_{1:1}$	θ_{FC}	θ_{PWP}
(cm)	(%)					(g cm^{-3})	(dSm^{1})		(m^3 m^{-3})	
0–15	27	32	0.48	0.09	48	1.48	0.48	8.25	0.29	0.11
15–35	24	37	0.30	0.08	47	1.40	0.35	7.96	0.28	0.10
35–55	20	35	0.21	0.05	46	1.39	0.41	8.08	0.23	0.11
55–75	20	34	0.15	0.01	46	1.43	0.46	8.19	0.27	0.11
75–100	20	34	0.01	0	45	1.55	0.5	8.13	0.27	0.10

Crop (*Zea mays* L. cv. EV-77) was planted with row to row and plant to plant distances of 75 and 20 cm, respectively. Phosphorus (P_2O_5) as triple superphosphate and potassium (K_2O) as potassium sulfate were applied at 100 kg ha^{-1} each at land preparation before sowing. Nitrogen as urea was applied at 165 kg ha^{-1} in three equal splits; at land preparation before sowing, 15–25 days after sowing and at the tasseling stage. In treatments receiving mulch, 30% coverage of the soil surface (4.8 t ha^{-1}) was calculated on the basis of biomass equivalent of the crop during the first harvest. In CT + M treatment, mulch was applied at the soil surface after tillage. For non-mulched plots, crop residues from the previous crop were completely removed. At crop maturity, four subsamples (1 m^2 each) were taken from each replicate plot and pooled to determine total above-ground biomass and grain yields.

2.3. ^{15}N-balance

^{15}N microplots (0.9 m × 1.5 m × 120 cm high; surface area, 1.35 m^2) were made from iron sheet and inserted to a depth of 1 m within the main plot. There were two plant rows with a row to row distance of 75 cm; each row was 37.5 cm apart from the boundary. With a plant to plant distance of 15 cm, there were 6 plants in each row (12 per microplot); terminal plants in each row were 7.5 cm away from boundary. ^{15}N-labelled urea (10.27 atom% ^{15}N) was applied at 165 kg N ha^{-1} in 3 split applications; [73 kg N ha^{-1} at land preparation before sowing (12 July 2015); 46 kg N ha^{-1} 60 days after sowing (10 September 2015; with irrigation water) and 80 days after sowing on 1 October 2015 with irrigation water].

The crop was harvested at maturity and all above-ground components separated, oven dried and weighed. Before grinding, portions of different aboveground components (stem, leaf, leaf sheath, cob sheath, cob trash, etc) were weighed in corresponding ratios and pooled to make a 50 g stover sample. Soil from each microplot was excavated in 0–15, 15–30, 30–45, 45–60, 60–80 and 80–100 cm increments, air dried and sieved to collect roots. Roots from all depths were pooled. Total N of plant and soil samples was determined by the standard Kjeldahl method [32] and samples prepared for ^{15}N analysis [33]. The Rittenberg method was used to convert ammonium to N_2 and the ^{15}N content was measured on a VG Isogas mass spectrometer fitted with a double inlet system. Added nitrogen interaction (ANI) was calculated by the difference between the soil N uptake by the unfertilised plants and the soil N uptake by the fertilised plants. The percent N derived from fertiliser (*%Ndff*) was calculated according to following equation:

$$\%Ndff = \frac{atom\ \%\ ^{15}N\ excess\ of\ sample}{atom\ \%\ ^{15}N\ excess\ of\ fertiliser} \times 100 \tag{1}$$

Data were subjected to analysis of variance followed by LSD Statistix 8.1 software. All values are reported as means of three replicates.

3. RESULTS

3.1. Effects on soil organic C after 5 maize crops

Individual effects of fertiliser N and tillage on SOC were confined to the upper 15 cm soil layer, whereas those of mulching were observed up to 30 cm depth (data not shown). Averaged across tillage and mulch treatments, application of fertiliser N significantly increased SOC content (13% increase; $P<0.05$) but only in the upper 15 cm soil layer. Averaged across mulch and N treatments, ZT compared to CT caused significantly higher SOC (30% increase; $P<0.05$) in the upper 15 cm soil layer, whereas mulching caused 17% and 11% higher SOC in the 0–15 and 15–30 cm soil layers, respectively ($P<0.05$). Regarding interactive effects in the unfertilised soil, tillage or mulch had no effect on SOC except that mulch application to NT significantly increased SOC in the upper 15 cm layer as compared to CTR or CTW (23–31% increase; $P<0.05$) (Table 2). In treatments receiving N fertiliser, tillage had no effect on SOC in the absence of mulch but significantly reduced SOC in the presence of mulch (46% reduction; $P<0.05$) (Table 2). Comparing all treatments, the highest SOC was recorded in the ZT treatment receiving N fertiliser and mulch; the treatment showed 26–35% higher SOC in fertilised and 19–44% higher in unfertilised treatments ($P<0.05$); higher increases corresponded to CT compared to ZT in both fertilised and unfertilised treatments.

TABLE 2. EFFECTS OF TILLAGE, MULCH AND NITROGEN FERTILISER ON TOTAL ORGANIC CARBON (TOC) OF SOIL AFTER FIVE MAIZE GROWING SEASONS

Treatment[a]		TOC ($t\ ha^{-1}$)[b]			
		0–15 cm	15–30 cm	30–50 cm	0–50 cm
Fertilised	ZT	14.2 bc	11.5 bc	10.7 ns	36.5 bc
	ZT + M	19.1 a	12.8 ab	10.9 ns	42.8 a
	CT	12.4 cd	11.6 bc	10.4 ns	34.4 cd
	CT + M	13.1 bcd	13.3 a	10.0 ns	36.4 bc
Unfertilised	ZT	13.7 bcd	11.4 bc	10.1 ns	35.1 cd
	ZT + M	15.5 b	11.9 abc	11.3 ns	38.7 b
	CT	10.7 d	11.0 c	10.5 ns	32.3 d
	CT + M	12.0 cd	12.3 abc	10.7 ns	35.0 cd
LSD	$P<0.05$	3.0	1.6	1.2	3.1
	$P<0.01$	4.2	2.2	1.7	4.2

Note: Values are means of 3 replicates; data in a column followed by different letters are significantly different by Duncan's multiple range test ($P<0.05$). In this and subsequent Tables, ZT = Zero till; CT = Conventional till; M = Mulched.

3.2. Total biomass and grain yields

Regarding individual treatment effects, N application significantly increased the total biomass yield (57% increase; $P<0.05$) and the grain yield (148% increase; $P<0.05$) (Tables 3 and 4). While tillage had no effect on the total biomass and grain yields, mulch significantly reduced the total biomass yield (13% reduction; $P<0.05$) but had no effect on the grain yield (Tables 3 and 4). Averaged across five cropping seasons, tillage or mulch had no effect on total biomass and grain yields in the unfertilised plots (Tables 3 and 4). In fertilised plots also, while tillage had no effect on total biomass and grain yields, mulching significantly reduced the total biomass (12–14% reduction; $P<0.05$) (Table 3) as well as the grain yield (15–17% reduction; $P<0.05$) both under CT and ZT (Table 4). In the fertilised plots, the grain harvest index [(HI); averaged across five cropping seasons] ranged from 0.43–0.46 and was not affected by tillage or mulch treatments. However, in unfertilised treatments the HI (0.25–0.32) was much lower than the fertilised and was higher (0.32) in mulched compared to non-mulched (0.25–0.28) treatments.

TABLE 3. EFFECTS OF TILLAGE, MULCH AND NITROGEN APPLICATION ON TOTAL BIOMASS YIELD OF MAIZE

Treatment		Biomass yield (t ha^{-1})^{a}					
		Fall-2013	Spring-2014	Fall-2014	Spring-2015	Fall-2015	Mean
Fertilised	ZT	17.7 a	15.1 a	18.0 a	13.1 a	14.5 a	15.7 a
	ZT + M	13.7 bc	12.1 bc	15.5 bc	12.5 ab	13.8 ab	13.5 bc
	CT	16.4 a	13.4 b	17.0 ab	12.0 bc	12.9 b	14.3 ab
	CT + M	14.5 b	12.4 bc	13.8 c	11.2 c	11.4 c	12.6 c
Unfertilised	ZT	12.3 c	11.9 c	10.1 d	5.1 e	10.8 c	10.0 d
	ZT + M	8.7 d	9.9 d	8.2 e	8.6 d	9.3 d	8.9 de
	CT	13.3 bc	9.8 de	9.4 de	5.8 e	6.8 e	9.0 de
	CT + M	9.0 d	8.6 e	7.7 e	5.1 e	8.3 d	7.7 e
LSD $P<0.05$		1.8	1.3	1.8	1.2	1.0	1.5
LSD $P<0.01$		2.5	1.8	2.5	1.6	1.4	2.0

Note: Values are means of 3 replicates; data in a column followed by different letters are significantly different by Duncan's multiple range test ($P<0.05$).

Considering the grain yield data of fertilised treatments over five cropping seasons, ZT compared to CT either had no effect, or produced higher grain yield; this was observed both with and without mulch (Table 4). Mulching significantly reduced the grain yield under ZT (all cropping seasons; 7–32% reduction; $P<0.05$) as well as under CT (4 of 5 seasons; 7–25% reduction; $P<0.05$). However, while the negative effect of mulch generally increased under CT with time (i.e. 13% reduction during the first cropping season compared to 20% reduction during the fifth), the negative effect decreased under ZT (32% reduction during the first cropping season compared to 7% reduction during the fifth).

3.3. Fate of ^{15}N Fertiliser under 5th maize crop (fall 2015)

TABLE 4. EFFECTS OF TILLAGE, MULCH AND NITROGEN APPLICATION ON MAIZE GRAIN YIELD

Treatment		Grain yield (t ha^{-1})					
		Fall-2013	Spring-2014	Fall-2014	Spring-2015	Fall-2015	Mean
Fertilised	ZT	7.9 a	6.6 a	8.1 a	5.8 a	7.0 a	7.1 a
	ZT + M	5.4 d	5.8 b	6.5 b	5.2 b	6.5 b	5.9 c
	CT	7.2 b	6.0 a	7.7 a	5.4 ab	6.4 b	6.5 b
	CT + M	6.3 c	5.0 c	5.8 b	5.0 b	5.1 c	5.5 c
Unfertilised	ZT	3.2 e	2.9 d	2.4 c	1.4 cd	3.2 d	2.6 de
	ZT + M	3.4 e	2.8 de	2.7 c	2.0 c	2.7 e	2.7 d
	CT	3.1 e	2.4 ef	2.1 c	1.2 d	1.9 f	2.2 e
	CT + M	3.3 e	2.2 f	2.5 c	1.3 cd	2.4 e	2.4 de
LSD $P<0.05$		0.7	0.5	0.8	0.6	0.4	0.6
LSD $P<0.01$		1.0	0.7	1.1	0.9	0.6	0.7

Note: Values are means of 3 replicates; data in a column followed by different letters are significantly different by Duncan's multiple range test ($P<0.05$).

Recovery of fertiliser N up to 100 cm working depth ranged from 28–39% of the applied with lowest recorded in the ZT treatment without mulch (Table 5). While mulching significantly increased the fertiliser N recovery in soil under ZT (21% increase; $P<0.05$), it had no effect under CT. However, under both mulched and non-mulched treatments, fertiliser N recovery in soil was lower under ZT compared to CT, the effect was more pronounced in the non-mulched (27% reduction) compared to mulched treatments (9% reduction). Of the residual fertiliser N in soil, most (43–57%) was recovered in the upper 15 cm layer; the recovery was significantly higher under mulched treatments both under ZT (36% increase; $P<0.05$) and CT (15% increase; $P<0.05$).

TABLE 5. FERTILISER N RECOVERY IN DIFFERENT SOIL LAYERS AS AFFECTED BY TILLAGE AND MULCH TREATMENTS

Treatment	Recovery at cm depth interval (% of applied)[a]						
	0–15	15–30	30–45	45–60	60–80	80–100	0–100
ZT	12.9 c	4.5 bc	3.1 b	2.7 b	2.7 b	2.3 b	28.2 b
	(21.4)	(7.4)	(5.1)	(4.4)	(4.4)	(3.8)	(46.5)
ZT + M	20.1 a	4.2 c	3.2 b	3.0 ab	2.4 b	2.6 a	35.5 a
	(33.2)	(6.9)	(5.3)	(5.0)	(4.0)	(4.3)	(58.7)
CT	17.0 b	7.8 a	5.9 a	3.4 a	2.5 b	2.2 b	38.7 a
	(28.1)	(12.8)	(9.7)	(5.4)	(4.2)	(3.5)	(63.7)
CT + M	20.1 a	5.1 b	3.7 b	2.6 b	4.6 a	2.7 a	38.8 a
	(33.2)	(8.3)	(6.1)	(4.3)	(7.6)	(4.4)	(63.9)
LSD $P<0.05$	2.4	0.6	1.0	0.5	1.2	0.2	3.6
$P<0.01$	3.5	0.8	1.5	0.7	1.8	0.3	5.4

Note: Values are means of 3 replicates; data in a column followed by different letters are significantly different by Duncan's multiple range test ($P<0.05$); data in parentheses are kg N ha^{-1}.

The overall fertiliser N recovery in plant as well as in different plant components was highest in ZT without mulch (Table 6; $P<0.01$); this treatment showed the fertiliser N use efficiency (above-ground components) of 40%, which was almost 30% higher than other treatments which did not differ with respect to fertiliser N recovery.

TABLE 6. FERTILISER N RECOVERY IN DIFFERENT PLANT COMPONENTS AS AFFECTED BY TILLAGE AND MULCH TREATMENTS

Treatment	Recovery (% of the applied)[a]				
	Grain	Straw	Total aboveground	Root	Weed
ZT	24.2 a[b]	15.9 a	40.0 a	1.8 a	0.2 a
	(39.9)	(26.2)	(66.0)	(2.9)	(0.30)
ZT + M	16.5 b	11.1 b	27.6 b	0.8 c	0.1 b
	(27.2)	(18.3)	(45.5)	(1.2)	(0.09)
CT	17.0 b	11.2 b	28.2 b	0.9 b	0.0 b
	(28.0)	(18.5)	(46.5)	(1.5)	(0.07)
CT + M	17.0 b	11.1 b	28.1 b	0.7 c	0.0 b
	(28.0)	(18.3)	(46.3)	(1.1)	(0.06)
LSD $P<0.05$	1.5	1.7	1.1	0.2	0.1
$P<0.01$	2.2	2.5	1.7	0.2	0.1

Note: Values are means of 3 replicates; data in a column followed by different letters are significantly different by Duncan's multiple range test ($P<0.05$); data in parentheses are kg N ha^{-1}.

Total fertiliser N recovery (soil + plant) and fertiliser N loss were not affected by tillage treatments both with or without mulch (Table 7). However, as observed for fertiliser N recovery in plant, mulching with ZT significantly reduced the total fertiliser N recovery by 9% and increased the fertiliser N that was not accounted for by 18% ($P<0.01$) (Table 7).

TABLE 7. ^{15}N BALANCE UNDER MAIZE AS AFFECTED BY TILLAGE AND MULCH TREATMENTS

Treatment		Recovery (% of the applied) [a]			
		Plant	Soil	Total	Unaccounted for
ZT		42.0 a (69.2)	28.2 c (46.6)	70.3 a (115.8)	29.7 b (49.0)
ZT + M		28.4 b (46.8)	35.5 b (58.5)	63.9 b (105.4)	36.1 a (59.6)
CT		29.1 b (48.1)	38.7 ab (63.8)	67.8 ab (111.9)	32.2 ab (53.1)
CT + M		28.8 b (47.5)	38.8 a (64.0)	67.6 ab (111.5)	32.4 ab (53.5)
LSD	$P<0.05$	1.2	3.3	5.4	5.4
	$P<0.01$	1.7	4.7	7.8	7.8

Note: Values are means of 3 replicates; data within a column followed by different letters are significantly different by Duncan's multiple range test ($P<0.05$); Data in parentheses are kg ha^{-1}.

Availability from the unfertilised native soil N pool ranged from 66–113 kg N ha^{-1} (Table 8) and a substantial increase was recorded due to fertiliser N application (130–151 kg N ha^{-1}). In the absence of mulch, ZT compared to CT showed higher soil N availability in unfertilised (42% increase) as well as in the fertilised treatments (12% increase). In the presence of mulch, however, while soil N availability was not affected by tillage in fertilised treatments, it was significantly higher under ZT compared to CT (20% increase; $P<0.01$) in unfertilised soil. Mulch significantly reduced the soil N availability only under NT in both unfertilised (23% reduction; $P<0.01$) and fertilised (14% reduction; $P<0.01$). A positive ANI (38–69 kg N ha^{-1}) was recorded under all treatments (Table 8); it was significantly higher in CT compared to NT (36–43% increase; $P<0.01$) without showing any effect of mulch under both tillage regimes.

TABLE 8. PLANT N DERIVED FROM SOIL (NDFS) AND ADDED N INTERACTION (ANI) AS AFFECTED BY TILLAGE AND MULCH TREATMENTS

Treatment		Ndfs (kg ha^{-1})		ANI
		Fertilised	Unfertilised	(kg ha^{-1})
ZT		151a^{a}	113a	38 b
ZT + M		130 b	86 b	44 b
CT		133b	66c	67 a
CT + M		138 b	69 c	69 a
LSD	$P<0.05$	11	6	9
	$P<0.01$	15	8	13

Note: Values are means of 3 replicates; data within a column followed by different letters are significantly different by Duncan's multiple range test ($P<0.05$).

4. DISCUSSION

In the present study, ZT treatment with mulch application showed highest SOC in the surface layer of both fertilised and unfertilised soils. As compared to CT, ZT is well known to increase SOC storage in the surface layer under temperate climate [14, 34]. Although ZT may not always store more SOC than CT in the whole soil profile [15, 35], the present short-term study indicated significantly higher SOC also in the 0–50 cm profile under ZT compared to CT. Besides, while tillage treatments in the absence of mulch did not influence SOC in the upper 0–15 cm layer, maize grain yield and fertiliser/soil N uptake were higher under ZT compared to CT, indicating improved crop growth conditions under ZT. However, findings of this short-term study may not apply to long-term effects of tillage regimes on soil quality parameters. Besides, continuous ZT farming is known to cause stratification of SOC with highest accumulation in the surface soil layer; this increases the SR and thus soil quality [17, 19]. Therefore, it is worth investigating SR under different tillage/residue management regimes under climatic conditions prevailing in this region.

While tillage and residue management practices are known to have little or no effects on grain yield under different environmental conditions [26, 36, 39], maize grain yield under our experimental conditions was either not affected by tillage regime, or was significantly higher under ZT compared to CT, though this was observed in the absence of mulch. Our results are also contrary to a study conducted under similar (subtropical) climate in the Indian Punjab [16] where ZT without mulch showed lower yields than CT. Although yields reported by Ghuman and Sur [16] became higher under ZT compared to CT after 2 years, this was only when mulch was applied to ZT. In our study, it was the ZT treatment without mulch that showed the highest grain yield during the 5th cropping season and this coincided well with the highest fertiliser and soil N recoveries in the plant. On the other hand, mulch application to NT significantly reduced the grain yield and this was associated with reduced fertiliser and soil N recovery in the plant and increased fertiliser N loss. Lower grain yield under CT (both with and without mulch) were also associated with increased fertiliser N loss and reduced fertiliser/soil N recovery in the plant. The soil environment in the study area is indeed very conducive to ammonia volatilisation and denitrification losses, and as high as 39–42% of the applied N may be lost from summer crops grown under CT [40, 41].

Regarding fertiliser N dynamics, the present results are in contrast with some earlier reports in which type of soil tillage did not influence the fate of fertiliser N and the N availability to crops [42, 45]. In the present study, the lowest fertiliser N recovery in soil, as observed under ZT without mulch, is attributable to increased recovery by the plant. However, a substantial (21%) increase in the fertiliser N recovery in soil was recorded due to mulching in the ZT treatment that showed lower recovery by the plant but increased N loss. While increased N recovery in soil due to mulching of ZT is attributable to increased microbial immobilisation caused by higher availability of C [46], mulch is known to increase NH_3 volatilisation loss from fertiliser N broadcast onto crop residues [47] as well as denitrification loss due to higher C availability [36]. However, in the present study, such effects of mulch on the dynamics of fertiliser or soil N were not observed under CT.

As observed for fertiliser N uptake, the availability of soil N to the maize crop was also highest under ZT without mulch. While tillage as such might have increased microbial immobilisation of soil N (as observed for increased fertiliser N recovery in soil under CT), the lower soil N availability in mulched than non-mulched treatments under ZT might be due to increased immobilisation as well as the loss of N mineralised from the native soil pool; a similar effect of mulching was also observed for recovery of fertiliser N in plant and soil under ZT. A positive ANI may indicate a real net mineralisation of soil N as the result of fertiliser N application, and much higher ANI values under CT than under ZT may be attributable to increased aeration caused by tillage, thus leading to higher turnover of the soil organic N pool.

5. CONCLUSIONS

Results of the present short-term study revealed highest maize grain yield and crop N uptake from fertiliser as well as native soil N pools under ZT without retention of crop residues as surface mulch. Obviously, fertiliser N as well as N mineralised from the native soil N pool were more protected from losses/immobilisation under the ZT treatment without mulch as compared to all other treatments. However, residue retention is critical for ZT farming, and it can take time (e.g. 5 years before the benefits are observed. In the present study though mulch application significantly reduced the grain yield both under ZT (all 5 cropping seasons) and CT (4 of 5 cropping seasons), negative effect of mulch under ZT was much less during later cropping seasons (4th and 5th crop; 7–10% yield reduction) as compared to earlier seasons (12–32% yield reduction). Consequently, at least regarding maize grain yield, long-term effects of applying mulch to ZT might be different than the short-term effect observed in the present study. However, we envisage that long-term application of mulch to ZT may lead to reduced N availability to crops due to increased immobilisation and loss of fertiliser N in irrigated cropland under the warm climates prevailing in the tropics and subtropics. To improve fertiliser N use efficiency under ZT, placement of N fertiliser below the C enriched zone can be a better alternative to the conventional broadcast method and to achieve this, some soil disturbance may be inevitable under ZT. Therefore, it is worth continuing this study with modification in fertiliser N application method to explore long-term effects of different tillage/mulch regimes on crop productivity and soil conservation.

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EFFECT OF TILLAGE, MULCHING AND N FERTILISER ON SOIL WATER CONTENT AND MAIZE NITROGEN USE EFFICIENCY (NUE) INDICES IN DEGRADED FERRALSOL “TERRE DE BARRE” OF SOUTHERN BENIN

P. HOUNGNANDAN, F. KOUELO ALLADASSI, T.M. AKPLO,
A. HOUNTONGNINOU
Faculté des Sciences Agronomiques, Université d’Abomey-Calavi Cotonou, Bénin

Abstract

The objective of this study was to evaluate the effect of tillage and mulching on soil water ststus and nitrogen fertiliser use efficiency in a maize cropping system. An experiment was carried out at Sekou village in southern Benin on a degraded ferralsol. The experiment consisted of two tillage systems i.e. no tillage and conventional tillage (Tillage), two levels of mulching i.e. no mulch and mulch (50% of soil cover) and two rates of nitrogen fertiliser (0 and 180 kg ha^{-1}) installed in a randomised complete block design of eight treatments and four replications. Tillage did not affect soil water status, but mulching conserved over 12% of soil moisture (14.4% or 0.14 g g^{-1}). The highest physiological efficiency was achieved with the contribution of mulch and direct sowing. In fact, 1 kg of nitrogen exported by maize plants into tillage and mulch plots generated 34.5 ± 4.0 kg and 39.6 ± 3.4 kg of grain, respectively. The nitrogen input on tillage or direct seeding and mulching, reached the best agronomic and physiological efficiencies with higher nitrogen recovery rate. However, the supply of nitrogen through direct seeding with mulch further improved the efficiency of nitrogen use. Therefore, one kg of urea exported by grain through direct seeding combined with mulch induced the best maize grain yield (40.9 ± 12.2 kg). It was more efficient to apply nitrogen on no-tillage combined with mulch in the degraded ferralsol.

1. INTRODUCTION

Food security is challenged by an increasing global population, climate change and finite resources. With the exponential growth in the human population and decreasing access to arable lands, food demand and environmental deterioration are becoming the biggest global issues [1, 2]. Specifically, the high population density in southern Benin is a serious problem not only for the state but very damaging to the environment. Soil degradation is mainly due to poor agricultural practices. The traditional fallow system cannot maintain the level of soil fertility due to the population pressure for more intensive cropping. Innovation in farming practices would be the solution for sustainable conservation agriculture. Deforestation, soil exposure to climatic stress and poor agricultural practices are the real factors of land degradation.

Cropping systems with permanent soil cover, which have been developed in recent years in Benin, do not involve conventional tillage. The soil remains covered throughout the year by crop residues or cover crops. These systems seem potentially well suited to limit runoff and soil erosion, improve nitrogen use by crops and soil moisture, among other benefits [3]. In Sub-Saharan Africa (SSA) soils, major nutrients are in very small quantities which require the use of nitrogen, phosphate and potassium fertilisation to improve the yield of maize [4]. Nitrogen and phosphorus are the major nutrients that limit crop yields on ferralsols “terre de barre” in southern Benin [5]. Generally, maize absorbs up to 43% of its nitrogen needs during the first 50 days after sowing, and at 40 days of emergence, the absorption rate reached 4 kg ha^{-1} day^{-1} [6]. Igué et al. [7] estimate that the recommendations of mineral fertilisers in Benin are mostly outdated, too general and do not take into account the severe land degradation, which causes their inefficiency and, consequently, falling crop yields.

Maize production is thus subject to many constraints and requires adequate fertilisation of the soil for better nutrition of the crop [8]. No use or unbalanced use, inadequate or excessive fertiliser is one of the major causes of low yields obtained in most African countries [9]. The inefficiency in the use of nutrients like nitrogen in fertilisers contributes to the depletion of financial resources, increased production costs and potential environmental risks [10, 11]. This involves improving the efficiency of absorption and determining the efficiency of nutrient use by crops, and hence the need to identify efficiencies [12]. The efficiency of utilisation of nutrients by a plant is an important concept for the evaluation of production systems in general, and can be significantly affected by fertiliser management practices [11, 13]. Malcolm [14] defined efficiency as output per unit of fertiliser applied or recovery of the applied fertiliser.

This study aims to evaluate the effect of tillage, mulching and nitrogen on nitrogen use efficiency (NUE) by maize and soil moisture status on a degraded ferralsol in Southern Benin. Thus, basic data on the effects of mulching on NUE and soil water conservation which are not yet available for the growing maize in the region will be provided.

2. MATERIALS AND METHODS

2.1. Experimental site

The experiment was conducted in Sekou village, district of Allada between parallels 06° 37' 32.2" North latitude and 02° 14'10.9" East longitude with 90.8 m altitude. The site is under the influence of a subequatorial climate with two rainy seasons. The average annual rainfall is 1000 mm, an average annual temperature of 28°C and a potential evapotranspiration of 1543 mm year^{-1} [16]. The study area is dominated by red lateritic soils developed on sedimentary materials, classified as ferralsols and locally called "Terre de barre". At 20 cm of depth the soil has a sandy clay texture, and is very poor in soil organic carbon (4.4 g kg^{-1}), total nitrogen (0.21 g kg^{-1}), available phosphorus (27.7 mg kg^{-1}) and slightly acid (pH 5.9).

2.2. Materials

Maize cultivar AK 94 DMR ESR-Y is a composite and medium early variety with yellow seeds. It has a growing cycle of 90 days and a potential yield of 3.5 to 4 t ha^{-1}. Maize residue from the previous season mixed with some wasteland residues were used as mulch. The coverage rate of the soil mulch was 30%. Potassium and phosphorus were applied as basal fertiliser at 30 kg K_2O ha^{-1} and 50 kg P_2O_5 ha^{-1}, respectively. Nitrogen was applied in the form of urea on the 20th and 40th day after sowing (DAS) at 120 kg N ha^{-1}. Experimental plots were weeding twice, first at 21 DAS and a second at 45 DAS.

2.3. Experimental design

This experimental design was a factorial arranged in Randomised Complete Blocks. Three factors with two terms each were studied: Tillage (plowing and no tillage), mulching (30% mulch and no mulch) and nitrogen (0 and 120 kg N ha^{-1}). Nitrogen is important here not only for the development of the crop but because it promotes the decomposition of the mulch. There were 8 treatments and 4 replications. Each experimental unit has an area of 35 m^2 (7 m × 5 m). Planting lines were arranged along the lengths of the experimental units. Thus, each experimental unit contained 14 lines of 10 plants each (the distance between the planting hole was between 50 cm and 50 cm line), a total of 140 plants per plot. The distance between two experimental units was one 1 m and between the two blocks was 2 m. The combination of factors and conditions are presented in Table 1.

TABLE 1. TREATMENT FACTORIAL COMBINATIONS

Tillage	Mulching	Nitrogen (kg ha^{-1})	Treatments
None	None	0	T1
		120	T2
	30%	0	T3
		120	T4
Tillage	None	0	T5
		120	T6
	30%	0	T7
		120	T8

2.4. Data collected

2.4.1. Soil water

Soil water concentration (W_d) at time t to a depth of 20 cm was determined from soil samples. These soil samples were taken in plots without mulch and mulch plots using an auger every 7 days until 90 DAS before sunrise. The sampling method "zig zag" of Mathieu and Pieltain [16] was used to obtain representative composite soil samples. The fresh weight of the samples was determined on site using an electronic balance and the dry weight determined in the labouratory after drying in the air a few days and then at 65°C in an oven for 72 hours. The weight of soil moisture was determined by the following formula proposed by Saïdou et al. [17]: $W_d = (FW - DW) \times 100 / DW$ with W_d = Gravimetric (dry) soil water concentration; FW = fresh weight of soil and DW = dry weight of soil.

2.4.2. Nitrogen fertiliser efficiency

On a surface area of 5.6 m^2, the maize plants were cut at ground level. The cobs were harvested and husked. Straw, husks and cobs were weighed (total fresh weight) and sampled (sample fresh weight). The samples were dried in an oven for 72 hours at 70°C. Dry weight of samples (straw and husks) was obtained. The oven dried cobs without husks were shelled. Dry weights of grain samples were obtained. Nitrogen concentration of different yield components was determined by the Kjeldahl method. These data were used to determine yield and N uptake of grains and aboveground biomass. Several indices of nitrogen fertiliser use efficiency were calculated [18, 19]:

$$Agronomic\ efficiency\ of\ applied\ N\ (kg\ kg^{-1}): AE_N = (Y_N - Y_0)\ /\ F_N \quad (2)$$

$$Apparent\ recovery\ of\ applied\ N\ (kg\ kg^{-1}): RE_N = (U_N - U_0)\ /\ F_N \quad (3)$$

$$Physiological\ efficiency\ of\ applied\ N\ (kg\ kg^{-1}): PE_N = (Y_N - Y_0)\ /\ (U_N - U_0) \quad (4)$$

where

F_N = amount of (fertiliser) N applied (kg ha^{-1})

Y_N = crop yield (kg ha^{-1}) with applied N

Y_0 = crop yield (kg ha^{-1}) in a control treatment with no N

U_N = total plant N in aboveground biomass at maturity (kg ha^{-1}) in a plot that received N

U_0 = the total N in aboveground biomass at maturity (kg ha^{-1}) in a plot that received no N

2.5. Data analysis

SAS version 9.2 was used for the analysis of variance of data. Differences among treatment means were compared by least significant difference at *P*<0.05.

3. RESULTS

3.1. Soil water status

Tillage has no significant effect on soil water status (Table 2). However, the soil water status was slightly higher on the tillage cf. no tillage (Fig 1). These results are similar to those obtained for mulching (Table 2 and Fig 2). This non-significant difference between treatments was due to abundant rainfall before and during the first two months of the trial. The low rainfall during the last month of the trial shows a clear difference in the mulch (Fig 2).

The Pearson correlation test shows significant correlations between rainfall and soil water status for the different treatments: no tillage (r = 0.812**; *P* value of 0.004); tillage (r = 0.783**; *P* value of 0.007); no mulch (r = 0.745*; *P* value of 0.013) and mulch (r = 0.814**; *P* value of 0.004). The combined effect of tillage and mulching generated the same results and showed that the mulch treatment conserved slightly more soil moisture (Fig 3).

TABLE 2. COMPARISON TEST (T-STUDENT) OF TWO INDEPENDENT SAMPLES OF SOIL WATER CONTENT

Parameters	No tillage	Tillage	No mulch	Mulch
Mean	9.1 ± 2.2	10.0 ± 2.4	9.4 ± 2.4	10.7 ± 2.2
T value	−0.866		−1.275	
P-value (α 0.05)	0.398		0.219	
Difference	Not significant		Not significant	

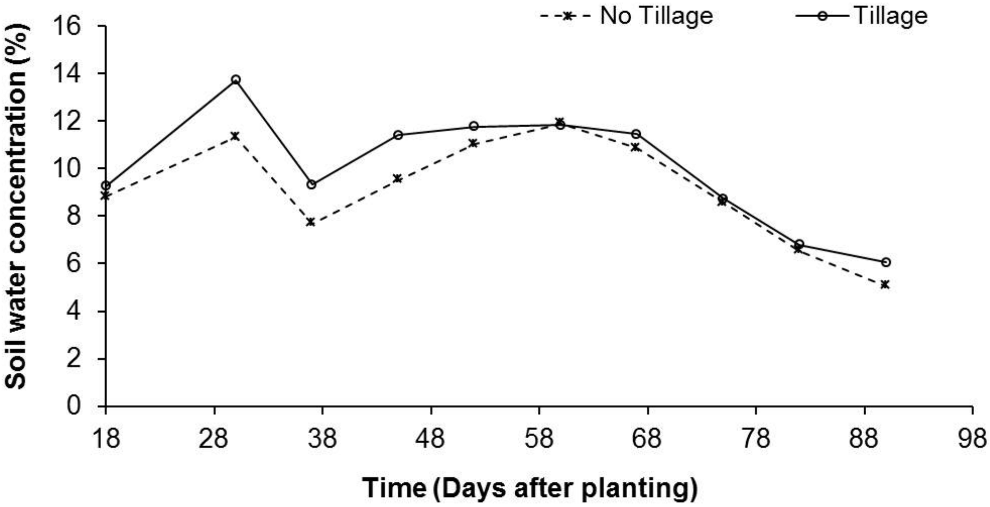

FIG. 1. Tillage effect on soil water distribution in maize cropping.

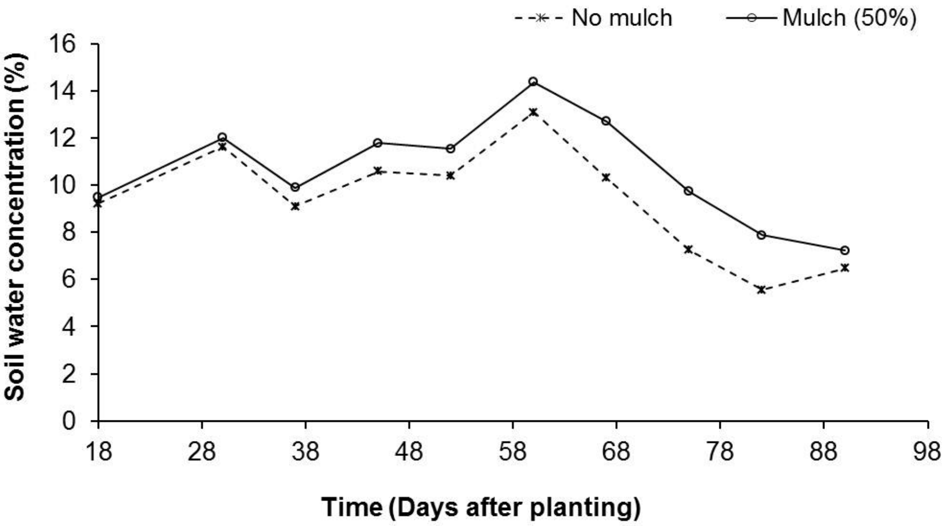

FIG. 2. Mulching effect on soil water distribution in maize cropping.

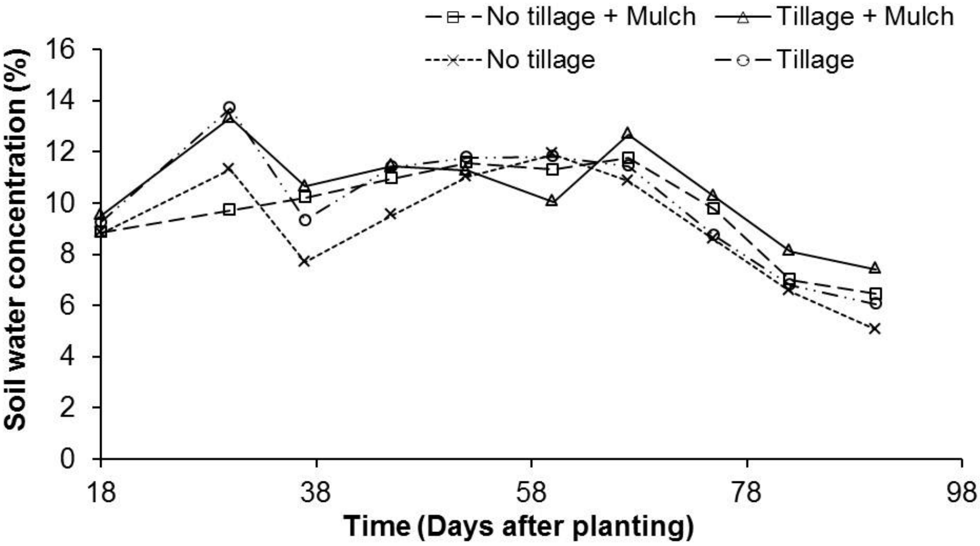

FIG. 3. Combined effect of tillage and mulching on soil water distribution in maize cropping.

3.2. Nitrogen fertiliser efficiency

Mulching significantly (*P*<0.05) influenced the efficiency of nitrogen fertiliser (AE_N , PE_N , RE_N). Tillage also had a very highly significant (*P*<0.001) effect only on PE_N (Table 3). The highest N fertiliser efficiencies were obtained on tillage versus no tillage and on mulch versus no mulch. In fact, for one kg of N exported in maize grain, no-tillage and mulch provided 34.5 and 39.6 kg of maize, respectively (Table 4). It appears that it is more efficient to apply nitrogen fertiliser in direct sowing (no-till) or mulching treatments. The combined effect of tillage and mulching significantly affected the AE_N and PE_N (Table 3). For apparent N fertiliser recovery, the difference between treatments was not significant. Tillage combined with mulch generated the higher AE_N and RE_N. However, the higher PE_N was obtained for no-tillage combined with mulch (Table 5). Therefore, for one kg N exported in maize grain, tillage combined with mulch provided 25.4 kg of grain.

TABLE 3. P-VALUE OF ANOVA OF TILLAGE AND MULCHING ON NITROGEN FERTILISER EFFICIENCY

Factors	df[a]	P-value		
		AE_N	PE_N	RE_N
Tillage	1	0.063ns	<0.001***	0.6***
Mulching	1	<0.001***	0.006**	<0.001***
Tillage*Mulching	1	0.004**	0.023*	0.153ns[b]

[a] df: degree of freedom; [b]ns: not significant at *P*>0.05; * Significant at *P*<0.05; ** Significant at *P*<0.01 *** Significant at *P*<0.001

TABLE 4. EFFECT OF TILLAGE AND MULCHING ON NITROGEN FERTILISER EFFICIENCY

Factors	Modalities	N fertiliser efficiency		
		AE_N	PE_N	RE_N
Tillage	No tillage	17.8 ± 2.4a	39.6 ± 3.4a	45.8 ± 8.9a
	Tillage	12.8 ± 5.0	16.6 ± 4.6b	42.2 ± 13.3a
Mulching	No mulch	6.9 ± 2.6b	21.6 ± 6.6b	16.9 ± 3.8b
	Mulch	23.7 ± 2.3a	34.5 ± 4.0	71.1 ± 5.7a
Mean		15.3	28.1	44.0

Note: Means followed by the same letters in the same column are not significantly different (*P*>0.05).

TABLE 5. COMBINED EFFECT OF TILLAGE AND MULCHING ON NITROGEN FERTILISER EFFICIENCY

Tillage	Mulching	N fertiliser efficiency		
		AE_N	PE_N	RE_N
No tillage	No mulch	13.6 ± 1.5b	38.3 ± 8.1a	23.8 ± 11.8b
	Mulch	21.9 ± 7.6a	40.9 ± 12.2a	67.8 ± 6.0a
Tillage	No mulch	0.2 ± 0.02c	5.0 ± 0.04b	10.0 ± 0.8b
	Mulch	25.4 ± 5.9a	28.2 ± 5.8a	74.4 ± 23.4a
Mean		15.3	28.1	44.0

Note: Means followed by the same letters in the same column are not significantly different (*P*>0.05).

4. DISCUSSION

4.1. Soil water status

The distribution of soil water under no-tillage and tillage followed the same trend, which was consistent with the results of Tamia et al. [20] that soil water content does not vary significantly in very porous ferralsols between tillage and no-tillage treatments. The difference between soil water content with and without mulch depends on the measurement period (at the beginning and during the last two months of the rainy season). Indeed, the non-significant influence of mulch on soil water content at the beginning of the season can be due, according to Kessler [21], insufficient rainfall or competition between the young crop plants and weeds for the use of water and nutrients. According to this author, this competition for water also depends on the type of mulch which according to its volume can seriously influence the underlying soil water content. In this case, Zomboudré et al. [22] reported that the competition for water usually occurs early in the season, when part of the rain and even light is intercepted by the mulch.

The amount of water that reaches the soil under mulch may be insufficient since young weeds and mulch may absorb the water [23]. The increase in soil water under mulch compared to plots without mulch during the last two months of the rainy season (from days 67 to 82 after sowing) can be explained by the fact that as the season progresses, the mulch plots tend to be wetter than unmulched plots because of the shading and cover effects of mulch [23]. This coverage effect of mulch conserves the moisture in the soil, reducing evaporation of water and protecting it against dryness [24]. Higher soil water content was observed in the surface layer in the mulching treatment, which was probably due to lower surface runoff and evaporation because there was no change in surface soil porosity [25, 26]. Our results corroborate those obtained in the Democratic Republic of Congo by Bolakonga et al. [27] who found soil moisture significantly higher in mulched compared to unmulched plots in a ferralsol. The soil water content in the mulching treatment was higher than that of a bare plot at the time of sowing; after one month, however, these soil water contents were similar [28, 29]. Collectively, these results indicate that the soil water content in the mulching treatment was higher than in the non-mulching treatment at the time of sowing.

4.2. Nitrogen fertiliser efficiency

The results of this study revealed that no tillage combined with mulch generally had the highest efficiencies of nitrogen applied to maize grain. So, in the no tillage plots covered by mulch nitrogen losses by leaching are lessened due to a reduction in mineralisation. Bollinger et al. [30] concluded that no tillage plots with mulch had higher concentrations and increased availability of phosphorus, nitrogen, calcium, magnesium and potassium than tillage plots. This in turn promotes the mobilisation of a sufficient amount of nitrogen to produce grain. Our results are consistent with global data collected by Ladha et al. [31]. The various efficiency values obtained with tillage/no tillage with mulch were well within the range of data of Fixen et al. [13], with the exception of the value of PE_N for tillage combined with mulch. Tchimbakala et al. [32] asserted that the greater the physiological efficiency of nutrients, the number of molecules needed to produce a unit of dry matter is less. Furthermore, the values of RE_N were larger than those of PE_N. This is explained by the fact that the numbers of grains per ear are set at physiological maturity, which creates a remobilisation of nitrogen from leaves and stem to grain, while the distribution of nitrogen in the plant is proportional to the respective demand of the organs for their formation.

5. CONCLUSION

It appears from this study that the contribution of mulch with or without tillage had a positive influence on the soil water status. Direct seeding and tillage had a similar influence on the soil water content. This is explained by the very porous structure and very little variation in direct seeding and tillage of the soil in the experimental site. In view of these results, it is interesting to recommend to farmer tillage-mulching cropping system for conservation of water in the soil in order to improve water use by the crop. For the evaluation of nitrogen fertiliser efficiency on the degraded ferralsols in southern Benin, the main results showed that tillage, mulching and nitrogen had a positive influence on the N fertiliser efficiency indicators for exported maize grain. Nevertheless, the contribution of direct seeding combined with mulch and nitrogen is more efficient than tillage with mulch. Agricultural extension policies must therefore advocate applying N fertiliser with direct seeding and mulch to significantly increase maize production on the degraded ferralsols of southern Benin.

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EFFECT OF TILLAGE AND MULCHING ON SOIL HYDRAULIC CONDUCTIVITY, BULK DENSITY AND AGGREGATION OF A HAPLIC ACRISOL UNDER MAIZE (*ZEA MAYS* L.) IN SEMI-ARID ZIMBABWE

E. CHIKWARI, A. MANYANGA, L. MHAKA, C. MUKUNGURUTSE, T. CHIPANGURA, N. NYAPWERE
Chemistry and Soil Research Institute
Harare, Zimbabwe

F. MAPANDA
University of Zimbabwe
Harare, Zimbabwe

J. GOTOSA
Bindura University of Science Education
Harare, Zimbabwe

Abstract

In a study that has run since the 2012 and 2013 cropping season, reduced tillage (RT) and conventional tillage (CT) were compared with and without mulching. Nitrogen fertilisation (+) or no nitrogen fertilisation (−) was the sole agronomic variable that was tested along with tillage-mulch interactions. Tillage is historically a factor that addresses soil physical properties while mulching is seen to influence the extent tillage has on both physical and chemical dynamics. Measurements on infiltration rates, bulk density (Bρ) and aggregate stability showed the significance of RT on soil conditioning since these portray the potential of soil to receive, retain and distribute water without implications on soil and nutrient loss. Significantly higher rates of hydraulic conductivity, corresponding to the steady state (final) infiltration were obtained (0.11–0.18 mm min^{-1}) when mulch was used compared to 0.07–0.10 mm min^{-1} obtained without mulch cover for both reduced and conventional tillage. These results show the importance of mulches in improving water infiltration with reduction in surface runoff and increased soil water seepage. Bulk density ranges showed the benefits from RT with values of 1.58–1.64 kg m^{-3} compared to CT (1.65–1.69 kg m^{-3}). The influence of mulching was evident and the following orders were noted: +Mulch +N < −Mulch +N < −Mulch –N < +Mulch RN, corresponding to the following ranges of BD; 1.58–1.77, 1.58–1.87, 1.60–1.83 and 1.64–1.87 kg m^{-3} for RT and +Mulch +N < Mulch −N < − Mulch +N < −Mulch −N, corresponding to the following ranges of BD; 1.66–1.76, 1.69–1.83, 1.65–1.86 kg m^{-3} for CT, respectively. Stratification ratios (SR) were used to determine the effect of management on organic carbon buildup. Reduced tillage with mulching built up more SOC with a mean SR of 2.12. The lowest SR (1.44) was obtained for conventional tillage without residues (CTW). Soil aggregate stability was found to correlate positively with soil organic C. Water stable aggregate values of 67–85% were obtained under RT with mulch while for CT under mulch values ranged from 55 to 68%.

1. INTRODUCTION

Smallholder farming in the semi-arid tropics is challenged by poor soil fertility, water availability and climatic variability and change. The global climate change problems have worsened Zimbabwe's problems of decreased crop production as a result of soil moisture and fertility constraints [1, 2]. The impacts of climate change in the form of higher surface temperatures, floods, erratic rainfall events and mid-season droughts have the potential to reduce regional production of key staple crops such as maize and millet [3]. Average yields of rain-fed agriculture in semi-arid parts of Zimbabwe oscillate around 1 t ha^{-1} for the major cereal crops (maize, millet and sorghum) and this is below the 3 to 5 t ha^{-1} that can be produced if water availability is enhanced [4, 5] showing the yield gap compared to that possible with adaptation measures being employed. To close the yield gap, water and soil productivity of rain-fed agriculture have to increase. There is therefore a need to undertake research to assess the success of different soil and water management strategies in a range of socio-environmental situations.

Technologies that increase soil water and nutrient use efficiency should be promoted and adopted. Basic technologies that optimise soil water and nutrient use include soil surface management, water harvesting, soil amendment and cropping strategies. These need to be explored at the farm scale, promoted and adopted with research undertaken to assess their effectiveness in increasing agricultural productivity and sustainable livelihoods of rural smallholders. Conservation agriculture aims to conserve, improve and make more efficient use of natural resources through integrated management of available soil, water and biological resources combined with external inputs. Conservation agricultural practices provide more favorable soil conditions for sustainable crop production and soil organic carbon sequestration [6]. Conservation agriculture is premised on the three principles of reduced or no soil disturbance, provision of soil cover through live or dead mulch and the use of crop rotations which also seek to conserve the soil, water and nutrients in cropping systems. It thus provides a feasible option for redressing declining crop productivity in Zimbabwe's smallholder sector and has been demonstrated to improve water productivity in Eastern and Southern Africa [7] while its advantages with respect to reducing soil degradation have been well documented [8].

Among other factors, the retention of crop residues as soil cover remains a major bottleneck to adoption of conservation agriculture by farmers in Zimbabwe [9, 10]. Surface mulch increases soil water storage by reducing evaporation from the surface, improving infiltration and soil water retention, decreasing Bρ and facilitating condensation of soil water at night due to temperature reversals [11]. A study by Chakraborty et al. [12] showed that there was more than 60% depletion in soil surface moisture with bare soil (no mulch) against less than 50% of the same with mulch. Rainwater productivity was found to improve in conservation farming with water productivity gains of 4500–6500 m^3 rainwater per tonne of maize grain yield in the lower yield range of <2.5 t ha^{-1} [12]. An exponential relationship of improvement in water productivity when improving agricultural water management in low yielding farming systems has been confirmed from several experiments [13]. The foregoing study evaluated the benefits of conservation agriculture in terms of soil water infiltration, soil structural improvement and aggregation as key facets for improving soil productivity.

Intensive tillage increases soil degradation and erosion, reducing soil productivity and organic carbon [14]. On the other side, RT practices can increase surface SOC [15]. The dynamics of SOM are markedly influenced by tillage and residue management [16]. Soil aggregates are the arrangement of soil particles of different sizes joined by organic and inorganic materials [17] and their stability can be used as an index of soil structure [18]. Soil aggregates improve soil organic carbon stabilisation from microbial action [19]. The adoption of no tillage enhances physical stabilisation of SOC as influenced by improved soil aggregation [20]. This, therefore, increases SOC residence time [21]. The amount of water stable aggregates and organic carbon increases with the number of years under no tillage [22]. Mohanty et al. [23] noted increases in the proportion of macro aggregates (>0.25 mm) in no-till systems while the proportion of micro aggregates (0.053–0.25 mm) was lower in the same systems compared to conventional practices. The degradation of macro aggregates in conventional systems resulted from intensive physical disturbance which exposes SOC to mineralisation [24]. RT with residue retention was found to increase SOC contents compared to CT in the top 0–10 cm layer [23]. Under no tillage, lower Bρ is related to more aggregation and higher litter content at the soil surface whereas loss of finer particles by water erosion and low SOM contents result in less aggregation and higher Bρ in conventional tillage systems [25, 26]. Most of the studies have not compared no tillage with conventional tillage where both practices received mulch cover. This study therefore looked at the effect of adding a mulch cover after CT.

2. METHODOLOGY

2.1. Study site

The experiment was conducted at Domboshava Training Centre, Zimbabwe, located 17°36’289” South, 31°08’546” East. This site receives moderately high rainfall between 750–1000 mm in a normal season. Soils are medium textured sandy loam to sandy clay and according to FAO/UNESCO [27] are classified as Haplic Acrisols.

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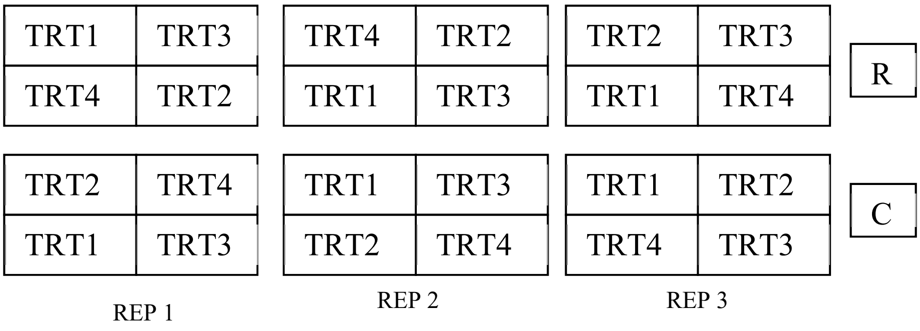
2.2. Experimental design and plot layout

A Randomised Complete Block (RCB) experimental design was employed in the study. The following treatments were tested under two tillage systems, Conventional Tillage (CT) and Reduced Tillage (RT): (1) Mulch with nitrogen fertiliser addition (+Mulch +N), (2) Mulch without N fertiliser addition (+Mulch −N), (3) No mulch but nitrogen fertiliser added (−Mulch +N) and (4) No mulch and no nitrogen fertiliser added (−Mulch −N). The treatments were replicated three times with maize as the test crop (Fig 1).



TRT1	TRT3	TRT4	TRT2	TRT2	TRT3	
TRT4	TRT2	TRT1	TRT3	TRT1	TRT4	R
TRT2	TRT4	TRT1	TRT3	TRT1	TRT2	
TRT1	TRT3	TRT2	TRT4	TRT4	TRT3	C
REP 1		REP 2		REP 3		

FIG. 1. Plot layout in a randomised complete block design.

2.3. Infiltration rates

Infiltration tests were conducted on the two tillage practices, CT and RT for each of the four agricultural practices. Infiltration tests were carried out using double ring infiltrometers. The rings measured 56 cm and 32 cm diameter for the outer and inner rings, respectively. The rings were inserted 6 cm into the soil using a rubber-lid hammer combination. Water was added to both the outer and inner rings to the same level and the fall in water level recorded at stipulated time intervals for the duration of more than 2 hours. Water in the outer ring ensured that there was no lateral water movement from the inner ring. Constant refilling of water and appropriate recordings were made to show the time interval (Δt, min), cumulative time (t, min), depth of water infiltrometer (mm), and water intake (Δf, mm). Infiltration rates (V, mm min^{-1}) were computed from the water intake and time interval as:

$$V = \Delta f \,/\, \Delta t \tag{5}$$

2.4. Soil sampling and analysis

A motorised auger was used to take samples in thin sections of 0–2, 2–4, 4–6, 6–8, 8–10, 10–15, 15–20, 20–30, 30–45, 45–60 cm. The samples were placed in clearly labelled plastic sample bags. The soils were airdried before passing each sample through a 2 mm sieve. These samples were for analysis of particle size distribution and texture, organic carbon and aggregate stability. Soil samples were also taken for Bρ determination using soil corers. The depth ranges for Bρ were 0–10, 10–20, 20–30, 30–40, 40–50 and 50–60 cm.

2.5. Soil texture

The hydrometer method was used for particle size distribution analysis. Samples were first air dried and then dispersed in calgon using an electric stirrer. Particle size distribution was determined by sedimentation of samples in 1000 ml measuring cylinders followed by hydrometer readings to determine silt + clay and clay. The soil sample was then air dried and sieved to determine the coarse, medium and fine sand fractions. The final texture was computed using the pedprogram software (pedological program).

2.6. Bulk density

Soil cores were taken from six soil depths (0–10, 10–20, 20–30, 30–40, 40–50 and 50–60 cm). The soil core sampler used to take undisturbed soil cores was of an auger type pushed with a rubber hammer. The cores used measured 51 mm × 50 mm and gave a volume (v) of ca. 100 cm^3. The gravimetric method was used to determine weight (Wt) of soil oven dried at 105°C. Bulk density (Bρ) was then computed using the formula:

$$B\rho = Wt \,/\, v \tag{6}$$

The use of the auger type of soil core sampler, pushed into the soil in the manner adopted in this study was reported to give values of Bρ, 0.04 kg m^{-3} lower than the actual [28].

2.7. Organic carbon

Organic carbon in soil was completely oxidised by heating with a solution of potassium dichromate and sulphuric acid. The excess dichromate was then determined colorimetrically using a Cecil UV-VIS Spectrophotometer.

2.8. Aggregate stability

The wet aggregate stability was determined on the principle that unstable aggregates will break more easily than stable aggregates when immersed in water. To determine the stability, 8 sieves were each filled with 4 g of soil aggregates which passed through 1–2 mm sieves. The 8 sieves were placed in a can filled with water, which was moved up and down for 5–10 minutes. Unstable aggregates fell apart and passed through the sieves and were collected in the water-filled cans underneath the sieves. The cans were then removed and replaced by another set of sodium hydroxide filled cans and the process was repeated. The two sets of cans were then oven dried. After drying, the weight of stable and unstable aggregates was determined. Dividing the weight of stable aggregates by the total aggregate weight expressed as a percentage gave an index for the aggregate stability.

3. REULTS and discussion

3.1. Soil texture and clay content

Soil texture and clay content at intervals down to 60 cm depth are shown in Table 1. Clay content increased with soil depth, while texture changed from loamy sand in the surface soil to sandy clay loam in the subsoil. There were no consistent differences between the clay contents in RT vs. CT across the depth intervals.

3.2. Soil organic carbon

Soil organic C contents over intervals to a depth of 60 cm are given in Table 2. Soil organic carbon showed a wide variation of the treatments in the top 10 cm (Fig 2). With increasing depth, this variation diminished. It is hypothesised that the degree of stratification of soil organic carbon with soil depth, expressed as a ratio, could indicate soil quality or soil ecosystem functioning, because surface organic carbon is essential to erosion control, water infiltration and conservation of nutrients [29]. In this study stratification was based on the 0–5 cm soil layer relative to the 30–60 cm subsoil depth interval.

$$Stratification\ ratio\ = \frac{Average\ SOC\ (0-5\ cm)}{Average\ SOC\ (30-60\ cm)}\ (SR) \tag{7}$$

SR for the 8 treatments is shown in Table 3. Stratification ratios allow different management options to be compared on the same assessment scale because of an internal normalisation procedure that accounts for inherent soil differences. Franzluebbers [30] reported that greater stratification of SOC with the adoption of conservation tillage under inherently low soil organic matter conditions (coarse, light textured soils or warmer climatic regimes) suggests that the standing stock of SOC alone is a poor indicator of soil quality. High SR of SOC could be good indicators of dynamic soil quality, independent of soil type and climatic regimes, because ratios greater than 2 would be uncommon under degraded conditions [30].

TABLE 1. SOIL TEXTURE AND CLAY CONTENT FOR FOUR AGRICULTURAL PRACTICES UNDER REDUCED (RT) AND CONVENTIONAL (CT) TILLAGE

Agricultural practice	Soil depth (cm)	Soil texture		Clay content (%)	
		RT	CT	RT	CT
(i) Mulch + nitrogen fertiliser	0–2	c LS	c LS	6.00 ± 1.73	7.00 ± 1.00
	2–4			7.67 ± 2.08	7.67 ± 1.15
	4–6			8.00 ± 2.00	8.00 ± 2.00
	6–8			6.33 ± 2.31	10.33 ± 1.15
	8–10			6.33 ± 1.15	10.00 ± 1.00
	10–15	c SaL	m SaL	13.00 ± 7.81	15.33 ± 5.86
	15–20	m SaCL		18.67 ± 6.66	20.67 ± 6.51
	20–30	c SaCL	c SaCL	22.67 ± 6.51	24.67 ± 5.51
	30–45			24.00 ± 5.29	26.00 ± 2.65
	45–60	m SaCL		22.33 ± 2.31	24.33 ± 4.93
(ii) Mulch without nitrogen fertiliser	0–2	c LS	c LS	7.00 ± 2.65	9.33 ± 2.52
	2–4			5.67 ± 0.58	9.67 ± 1.53
	4–6			7.67 ± 2.52	8.33 ± 1.53
	6–8			8.33 ± 1.53	8.00 ± 1.73
	8–10	c SaL		10.00 ± 1.00	8.00 ± 1.73
	10–15		m SaL	9.33 ± 1.15	11.67 ± 4.04
	15–20	m SaL	m SaCL	14.00 ± 4.36	20.00 ± 6.24
	20–30	c SaL	c SaCL	18.67 ± 7.64	24.67 ± 10.12
	30–45	c SaCL		21.00 ± 2.65	25.67 ± 4.04
	45–60			21.67 ± 2.08	25.67 ± 2.52
(iii) No mulch + nitrogen fertiliser	0–2	c LS	c LS	6.33 ± 1.15	6.00 ± 1.73
	2–4			6.33 ± 1.15	6.33 ± 1.53
	4–6			6.67 ± 1.53	6.33 ± 1.15
	6–8			8.33 ± 0.58	7.00 ± 2.00
	8–10			8.67 ± 3.08	7.67 ± 0.58
	10–15		c SaL	9.00 ± 2.65	9.67 ± 0.58
	15–20			12.00 ± 3.46	11.00 ± 3.61
	20–30	c SaL		14.33 ± 7.57	15.00 ± 6.56
	30–45	c SaCL	c SaCL	19.33 ± 2.08	21.00 ± 1.00
	45–60		m SaCL	22.00 ± 2.65	20.33 ± 2.89
(iv) No mulch without nitrogen fertiliser	0–2	c LS	c LS	9.67 ± 3.06	6.67 ± 0.58
	2–4		c SaL	8.67 ± 1.15	9.00 ± 1.00
	4–6		c LS	9.33 ± 0.58	9.00 ± 1.00
	6–8			9.67 ± 2.31	9.67 ± 1.15
	8–10		c SaL	9.33 ± 2.08	10.33 ± 1.53
	10–15	m SaL		11.00 ± 1.00	11.33 ± 0.58
	15–20		m SaL	17.33 ± 4.04	15.00 ± 5.29
	20–30	c SaL		17.67 ± 2.52	16.33 ± 5.13
	30–45	c SaCL	c SaCL	23.67 ± 0.58	22.00 ± 5.20
	45–60			26.00 ± 1.00	25.00 ± 1.00

Note: Texture: m, medium grained, c, coarse grained; textural classes: LS = Loamy sand, SaL = Sandy loam, SaCL = Sandy clay loam. Values are means ± standard errors of means (n = 3).

TABLE 2. SOIL ORGANIC C AND WATER STABLE AGGREGATE (WSA) PROPORTION UNDER REDUCED (RT) AND CONVENTIONAL (CT) TILLAGE

Agricultural practice	Soil depth (cm)	Organic C (%)		WSA (%)	
		RT	CT	RT	CT
(i) Mulch + nitrogen fertiliser	0–2	2.2 ± 0.5 aA	1.4 ± 0.2 aA	86 ± 6 aA	55 ± 6 aA
	2–4	2.0 ± 0.4 aA	1.4 ± 0.2 aA	74 ± 6 aA	59 ± 10 aA
	4–6	1.6 ± 0.3 aB	1.5 ± 0.3 aA	70 ± 14 aB	61 ± 20aA
	6–8	1.2 ± 0.4 aC	1.5 ± 0.4 aA	68 ± 5 aC	66 ± 21 aA
	8–10	1.2 ± 0.4 aC	1.4 ± 0.5 aA	63 ± 16 aB	68 ± 17 aB
	10–15	1.2 ± 0.3 aC	1.1 ± 0.4 aAB	57 ± 8 aA	63 ± 24 aAB
	15–20	1.1 ± 0.2 aC	1.2 ± 0.2 aAB	67 ± 19 aB	64 ± 19 aAB
	20–30	1.0 ± 0.3 aC	0.9 ± 0.3 aB	67 ± 6 aB	65 ± 18 aAB
	30–45	0.9 ± 0.1 aC	0.9 ± 0.2 aB	48 ± 16 aA	66 ± 14 aAB
	45–60	0.9 ± 0.5 aC	0.8 ± 0.3 aB	57 ± 8 aA	58 ± 13 aAB
(ii) Mulch without nitrogen fertiliser	0–2	1.6 ± 0.45bA	1.7 ± 0.8 bA	75 ± 11 bA	49 ± 6 aA
	2–4	1.6 ± 0.7 bA	1.7 ± 0.8 bA	84 ± 8 bA	65 ± 6 bB
	4–6	1.3 ± 0.8 bAB	1.7 ± 0.7 aA	62 ± 24 bB	60 ± 6 aAB
	6–8	1.2 ± 0.7 aB	1.8 ± 0.6 bA	45 ± 28 bC	79 ± 6 bC
	8–10	1.4 ± 0.5 aAB	1.6 ± 0.5 abA	74 ± 7 bA	61 ± 10 aB
	10–15	1.1 ± 0.5 aB	1.4 ± 0.9 aA	65 ± 22 bA	67 ± 21 aBC
	15–20	1.2 ± 0.6 aB	1.2 ± 0.5 aAB	54 ± 23 bC	65 ± 7 aB
	20–30	1.0 ± 0.4 bB	0.9 ± 0.4 aAB	43 ± 1 bD	58 ± 12 aAB
	30–45	0.9 ± 1.5 bB	1.0 ± 0.4 aB	50 ± 4 aCD	54 ± 18 bA
	45–60	0.8 ± 0.6 aB	0.8 ± 0.5 aB	60 ±12 aC	57 ± 14 aAB
(iii) No mulch + nitrogen fertiliser	0–2	1.6 ± 0.2 bA	1.6 ± 0.4 abA	71 ± 6 bA	57 ± 6 aA
	2–4	1.4 ± 0.4 bAB	1.6 ± 0.4 bA	61 ± 6 bA	73 ± 7 bB
	4–6	1.6 ± 0.7 abA	1.5 ± 0.3 aA	68 ± 6 aB	72 ± 17 bB
	6–8	1.5 ± 0.6 bA	1.3 ± 0.2 aA	70 ±15 aA	64 ± 6 aAB
	8–10	1.3 ± 0.4 aAB	1.3 ± 0.1 aA	71 ± 4 aA	69 ± 11 aB
	10–15	1.0 ± 0.3 aB	1.2 ± 0.2 abA	73 ± 27 cA	74 ± 4 bB
	15–20	0.9 ± 0.3 abB	1.0 ± 0.4 aAB	59 ± 12 bB	59 ± 27 aA
	20–30	0.7 ± 0.0 bB	0.8 ± 0.2 aB	78 ± 19 cA	39 ± 6 bC
	30–45	0.6 ± 0.4 cB	1.1 ± 0.2 aAB	70 ± 10 bA	46 ± 7 cC
	45–60	0.4 ± 0.1 bB	1.1 ± 0.9 bAB	68 ± 8 bB	52 ± 3 aA
(iv) No mulch without nitrogen fertiliser	0–2	1.1 ± 0.6 cA	1.6 ± 0.5 abA	69 ± 17 cA	76 ± 5 bA
	2–4	1.0 ± 0.2 cA	1.8 ± 0.8 bA	77 ± 10 bA	83 ± 5 cA
	4–6	1.3 ± 0.2 bA	2.1 ± 1.1 bA	64 ± 3 aA	79 ± 12 bA
	6–8	1.1 ± 0.3 aA	1.8 ± 0.8 bA	49 ± 18 bB	70 ± 10 aA
	8–10	1.3 ± 0.6 aA	1.6 ± 0.6 abA	57 ± 13 cB	69 ± 20 aA
	10–15	1.2 ± 0.2 aAB	1.2 ± 0.4 aAB	77 ± 19 cA	65 ± 23 aAB
	15–20	1.0 ± 0.3 aAB	1.4 ± 0.7 abAB	71 ± 7 aA	57 ± 33 aB
	20–30	0.9 ± 0.3 abB	1.1 ± 0.6 abB	83 ± 14 cAC	78 ± 8 cA
	30–45	0.8 ± 0.1 acB	1.1 ± 0.8 aB	59 ± 9 cB	65 ± 29 aAB
	45–60	0.8 ± 0.3 aB	1.0 ± 0.8 abB	80 ± 11 cA	38 ± 24 bC

Note: In this and subsequent Tables, Texture: m = medium grained, c = coarse grained; textural classes: LS = Loamy sand, SaL = Sandy loam, SaCL = Sandy clay loam. Values are means ± standard errors of means (n = 3). Letters in lower case compare values across treatments while letters in upper case compare values for the different depths in the same treatment.

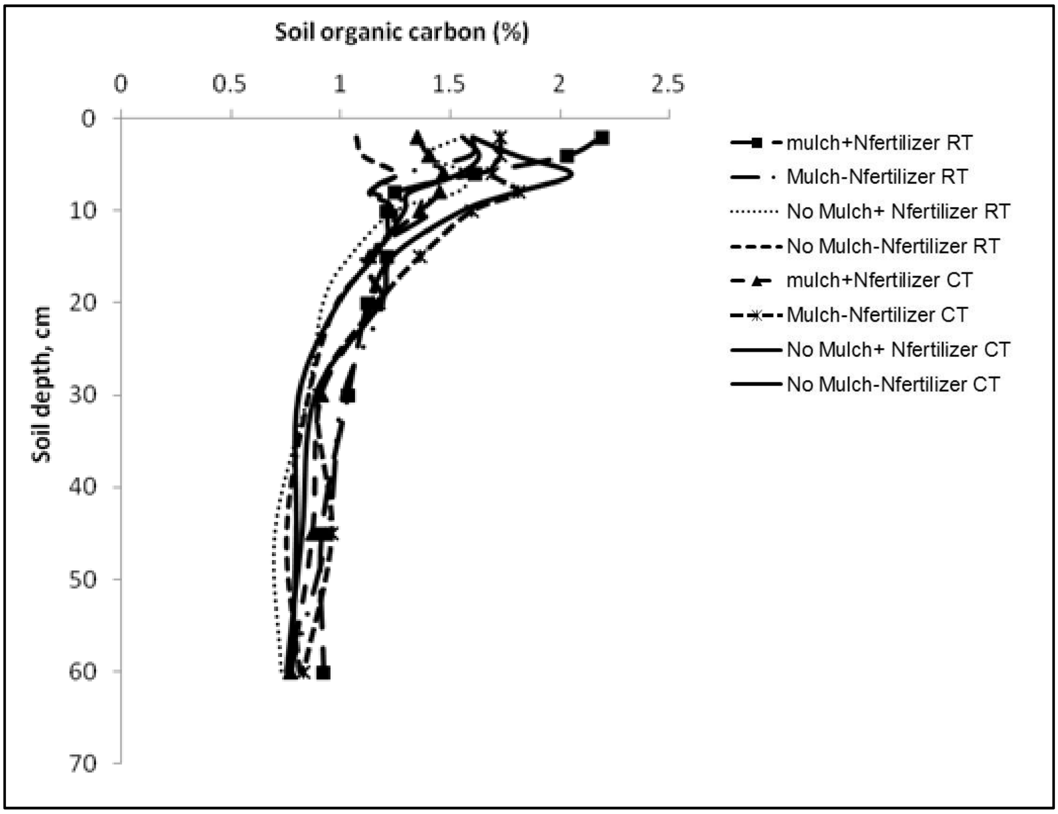


FIG. 2. Soil organic carbon profiles under different tillage and agricultural practices.

The highest SR obtained in this current study was 2.12 obtained with RT under mulching where no nitrogen fertiliser was added. The lowest SR (1.44) was obtained in the treatment that received conventional tillage and lacked mulch. The results tend to agree with the findings from Sà and Lal [31] who obtained SR for SOC in the range 1.12 to 1.51 for conventional tillage compared with 1.64 to 2.61 for long-term under no tillage. In this study conventional tillage however had a mulch cover which could be a reason for higher SRs. In similar work by Diaz-Zorita and Grove [29], conservation tillage was found to promote the occurrence of SOC-SR in ranges greater than 2 while conventional tillage with mouldboard plough always resulted in SOC-SR lower than 2.

TABLE 3. SOIL ORGANIC CARBON % (0–5, 30–60 CM) AND STRATIFICATION RATIOS (SR) OF DIFFERENT SOIL MANAGEMENT OPTIONS

Tillage	Agricultural practice	0–5 cm	30–60 cm	SR
CT	+Mulch +N	1.41	0.82	1.72
	+Mulch −N	1.72	0.90	1.92
	−Mulch +N	1.58	1.10	1.44
	–Mulch −N	1.82	1.04	1.75
RT	+Mulch +N	1.94	0.92	2.12
	+Mulch −N	1.49	0.86	1.74
	−Mulch +N	1.51	0.52	2.90
	−Mulch −N	1.14	0.78	1.46

3.2. Soil aggregate stability

The percentage of water stable aggregates (WSA) with soil depth is given in Table 2. There was improved soil aggregation on RT in combination with mulches. Values of WSA ranged from 67–85% for the soils that were mulched under RT while a lower range of 55–68% was obtained under conventional tillage with residues (CTR) (Table 2). The results show the effect of physical disturbance through ploughing which degrades soil macro aggregates. Improved aggregation was noted in the top 10 cm owing to higher amounts of soil organic carbon in the top soil layers. A positive correlation (R^2= 0.56) was also obtained for soil organic carbon and WSA across the whole range of values (Fig 3).

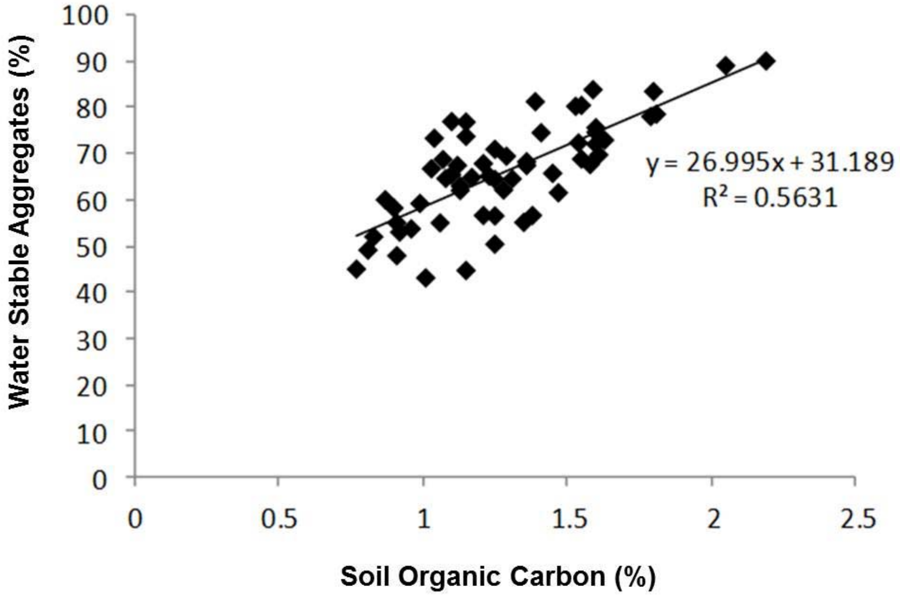


FIG. 3. Relationship between soil organic carbon and proportion of water stable aggregates (WSA) for the Haplic Acrisol.

3.3. Water infiltration and hydraulic conductivity

The use of mulches under both reduced and conventional tillage showed that soil surfaces are conditioned to allow higher rates of water infiltration. Significantly higher rates of hydraulic conductivity, corresponding to the steady state (final) infiltration were obtained (0.11–0.18 mm min^{-1}) compared to 0.07–0.10 mm min^{-1} obtained without mulch cover under both reduced and conventional tillage (Fig 4 and Table 4). Initial infiltration rates were significantly higher as well in the practices with mulch cover (1.67–1.93 mm min^{-1}) compared to the unmulched treatments where infiltration rates ranged from 0.80 to 1.20 mm min^{-1}. These results show the importance of mulches in improving water infiltration with reduction in surface runoff and increased soil water seepage. There was no significant difference in maximum and minimum infiltration rates at $P<0.05$ in the different treatments, although the mulched and unfertilised treatment under RT significantly differed from the rest.

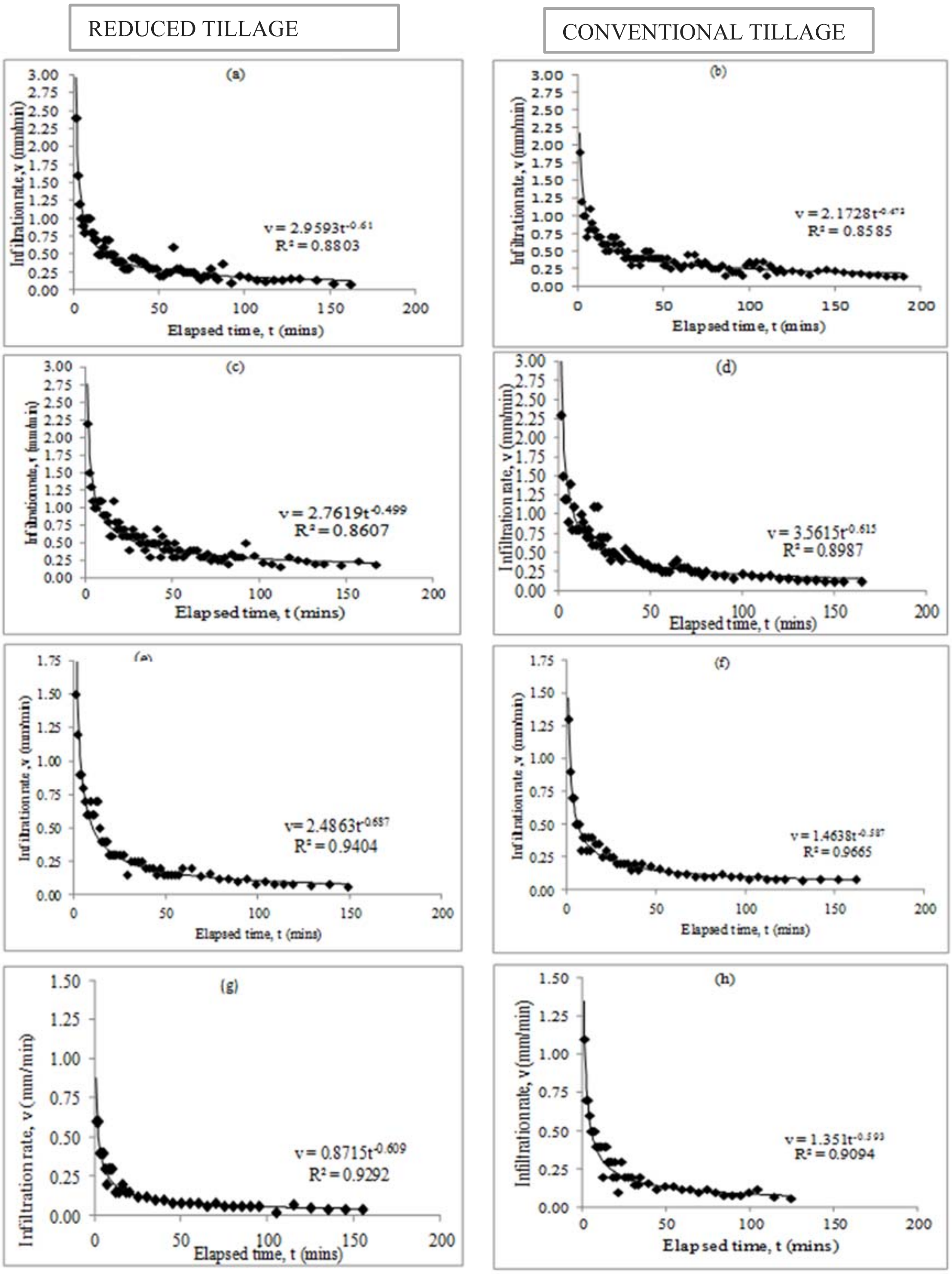


FIG. 4. Change of infiltration rate with time for (a, b) mulch with nitrogen fertilisation, (c, d) mulch without nitrogen fertilisation, (e, f) no mulch but with nitrogen fertilisation and (g, h) no mulch and no nitrogen fertilisation.

TABLE 4. WATER INFILTRATION RATES AND HYDRAULIC CONDUCTIVITY (MM MIN^{-1}) FOR DIFFERENT AGRICULTURAL PRACTICES AT THE DOMBOSHAVA SITE

Mean infiltration parameters	+Mulch +N		+Mulch −N		−Mulch +N		−Mulch −N	
	RT	CT	RT	CT	RT	CT	RT	CT
a) Initial infiltration rate	1.73a	1.93A	1.93a	1.67A	0.93b	1.20B	0.80b	1.20B
b) Maximum steady state infiltration rate	0.16a	0.14A	0.24b	0.17A	0.14a	0.15A	0.11a	0.20B
c) Minimum steady state infiltration rate	0.07a	0.08A	0.13b	0.09A	0.07a	0.06A	0.04a	0.11A
d) Hydraulic conductivity	0.11a	0.11A	0.18b	0.13A	0.10a	0.10A	0.07c	0.15B

Note: In this and subsequent Tables, RT = Reduced Tillage, CT = Conventional Tillage; Values with the same letter within a row are not significantly different at $P \leq 0.05$; Lower case compares treatments under RT while upper case compares treatments under CT.

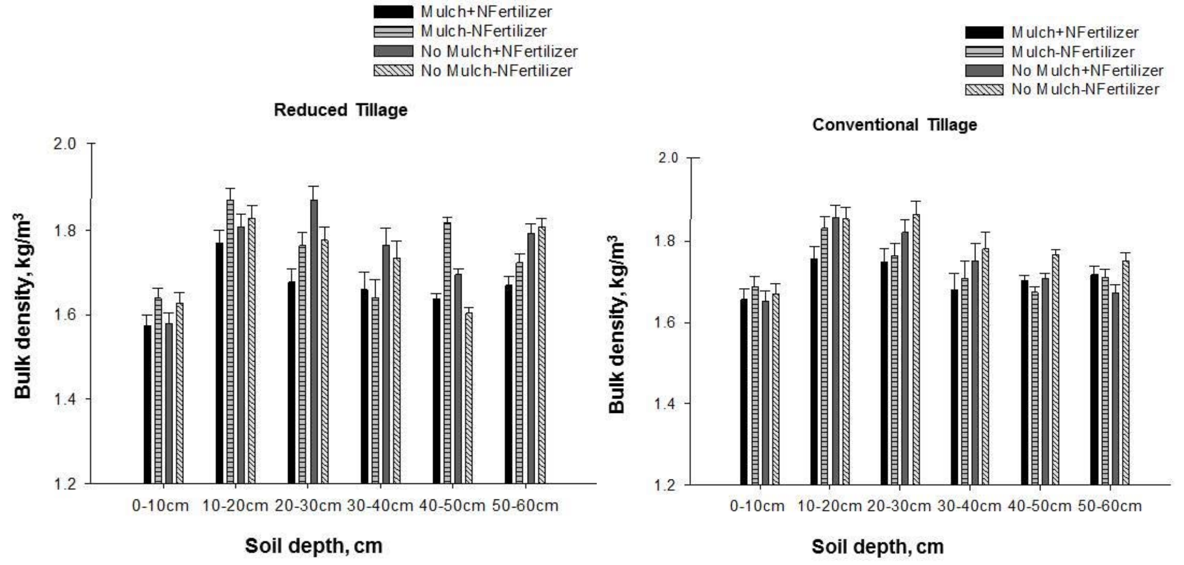


FIG. 5. Variation of bulk density (Bρ) (mean ± se) with mulching or no mulching with or without nitrogen fertilisation under reduced and conventional tillage. Bars represent standard error (se) of means, $p<0.05$.

Significant differences were noted between RT and CT in the top 0–10 cm soil depth ($P<0.05$). Much lower Bρ values were obtained with RT than CT. The range for RT was 1.58–1.64 kg m^{-3} while that for CT was 1.65–1.69 kg m^{-3}. Bρ also differed significantly ($p<0.05$) among the various treatments within the same tillage regime. The following order was noted: +Mulch +N < −Mulch +N < +Mulch –N < −Mulch −N, which corresponded to the following ranges, 1.58–1.77, 1.58–1.87, 1.60–1.83 and 1.64–1.87 kg m^{-3}, respectively. In the CT plots, treatments significantly differed at $p<0.05$ and there was a strong dependency on soil depth ($p<0.001$). The following order was noted: +Mulch +N < +Mulch −N < −Mulch +N < −Mulch −N, which corresponded to the following ranges; 1.66–1.76, 1.69–1.83, 1.65–1.86 and 1.67–1.87 kg m^{-3}, respectively. The 0–10 cm and 30–40 cm depths had lower values for the mulched and fertilised plots, 1.66 and 1.68 kg m^{-3}, respectively. The same trend was observed for the same depth ranges (0–10 and 30–40 cm) in the plots that received mulch but not fertilised and unmulched plots.

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THE IMPACT OF CROPPING SYSTEM AND NUTRIENT USE EFFICIENCY FOR MAIZE ON A FERRALSOL IN THE MADAGASCAR HIGHLANDS

M. RABENARIVO, L. RABEHARISOA
Université d'Antananarivo
Antananarivo, Madagascar

Abstract

The objective of this study was to evaluate the effect of tillage, N fertiliser and mulch application on nitrogen use efficiency in a maize cropping system under weathered acidic soil of Highland of Madagascar. Field experiments were carried out at Itasy region (Middle West of Madagascar) Imerintsiatosika village on degraded ferralsol. The experiments consisted of two tillage systems i.e. no tillage and conventional tillage, two levels of mulching i.e. no mulch and mulch (30% of soil cover) and two rates of nitrogen fertiliser (0 and 120 kg ha^{-1}) using randomised complete block design with eight treatments and four replications. The four results showed that applying mulch on its own or with chemical fertiliser and conservation tillage had no significant effect on the maize crop yield; however maize yield was significantly increased when urea fertiliser was applied at 120 kg N ha^{-1} without mulch.

1. INTRODUCTION

In the context of low fertility of soil and low crop productivity in the Malagasy Highlands, traditional agricultural practices of smallholders need to be improved. In this project, agro-ecological practices through mulch-based cropping systems were studied and compared with conventional agricultural practices. Agriculture is the main economic activity in Madagascar, with 70% of the population belonging to family run farms. The development of upland soils called “tanety” is the main priority of Malagasy farmers. The tanety soil is acid and has a low fertility. Soil acidity and low fertility are the two major factors limiting crop production in the highland areas of Madagascar. Soil acidity has a major effect on plant nutrient physiological processes [1, 2], like the toxicity of aluminium (Al^{3+}) and hydrogen (H^+) and deficiency of major nutrients. The acidity, low fertility and nutrient depletion of soil constitute major constraints of crop production in Madagascar. To avoid Al^{3+} toxicity and to improve the availability of major nutrients, the acid soils have to be corrected by addition of agricultural lime to a pH value that is favorable for crop production [3]. The objectives of this study were to: (i) evaluate the effect of three years of N fertiliser application, residue retention and tillage in continuous maize cropping on grain yield, and (ii) examine and quantify nitrogen fertiliser efficiency.

2. MATERIALS AND METHODS

2.1. Experimental site

The study was carried out in the Itasy region (Middle West of Madagascar) at Imerintsiatosika, located 30 km from the capital, Antananarivo, with South longitude of S 18°58’59.8’’and East latitude of E 47°17’27.6’’ at 1342 m of altitude.

The study site is on the top of sloping landscape position. The climate is tropical with two distinct seasons: rainy and warm from December to April; dry and cold from May to November with an annual average rainfall of 1200 mm. The maximum temperature ranges between 22 to 28°C and 10 to 17°C for the minimum.

The soil is an Oxisols according the American classification [4], a Ferralsol according the FAO classification and a Sol Ferrallitiques Dessaturés according the French classification.

2.2. Design of the experiment

Before the study, the field was in fallow dominated by a dense cover of herbaceous savannah vegetation and *Aristida* spp. The experimental design had three replicate blocks, which contained eight treatments with a control. Each block was divided in eight plots of 49 m^2 (7 m × 7 m). The plots were completely randomised. The plants spacing was 40 × 50 cm. A single plot contained 6 rows of maize.

2.3. Liming and fertilisation

Lime was added to each plot because the soil pH was strongly acid at the beginning of the experiment. After manual tillage (0.30 m of depth) dolomitic limestone was broadcast manually at 3000 kg ha^{-1} (0.3 kg m^{-2}) on 6 December 2013, two weeks before sowing, with the exception of the four control plots.

Every year since 2012, all of the plots were fertilised uniformly with phosphorus as Triple Superphosphate (TSP) containing 46% of P at the rate of 20 kg ha^{-1} and with potassium as KCl containing 50% of K at the rate of 60 kg ha^{-1}. All of the fertilisation with TSP and KCl were applied at planting. The TSP and KCl was banded at 5 cm near the maize seed.

2.4. Treatments

Eight treatments were installed including the combination of nitrogen level, type of tillage and plant residue management. Nitrogen level consisted of two rates: zero 0 N = 0 kg N ha^{-1} and a high rate of N 120 kg^{-1} N ha^{-1} as urea. The nitrogen dose was split: one-third (40 kg N ha^{-1}) for the first application at planting and the remaining two-third of N (80 kg N ha^{-1}) for the second application at 30 to 45 days after planting. Urea was banded at 5 cm from the seed or plant. Two types of tillage were used, tilled and no-till. There were two types of residues management; residues removed and 30% of residues retained in the plot as mulch.

2.5. Soil sampling and analyses

Samples were taken at three depth intervals, 0–5, 5–15 and 15–30 cm. A composite sample was obtained from each plot with a mixture of three samples. Soil sampling was carried out before and at the end of each growing season. Two reference plots were also sampled. The soil samples were air dried and sieved through a 2 mm sieve.

The soil pH was measured using a glass electrode in the supernatant suspension of 1:2.5 soil to water ratio using distillated water (10 g of dry soil in 25 ml water). To determine the pH_{KCl}, 1.86 g of KCl was added for each soil suspension. Organic carbon content was determined using the Walkley-Black method. Available P was determined by the resin method.

2.6. Soil properties

Before the establishment of the experiment, the initial soil properties were analysed. The physical and chemical characteristics of the soil are reported in Table 1. The soil was clay in texture, medium in organic carbon and available P and low in total nitrogen. The pH in the 0–5 cm layer was very strongly acid.

TABLE 1. SOIL PHYSICAL AND CHEMICAL PROPERTIES BEFORE THE EXPERIMENT IN 2012

pH_{H20}	Organic C ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Olsen P ($mg\ kg^{-1}$)	Clay ($g\ kg^{-1}$)
5.0	17.5	1.12	41.47	422

2.7. Crops

In January 2012, soybean (*Glycine max*) variety FT10 was planted on the plots. Maize (*Zea mays*), PANNAR-12 hybrid variety, was seeded on 7 December 2013 (2014 crop) and 4 December 2014 and 2015 crop), at a density of 45,100 plants ha^{-1}.

Maize was hand harvested at grain maturity. Yield was determined from three sub-plots (3 replicates of 1 × 2 m) per plot of 49 m^2. In each sub-plot, six maize plants were harvested. The outside 2 rows at the end of each plot were not harvested to avoid negative border effect. Whole plant samples were separated into ear, cob, husk, kernels, stem and leaf. These plant samples were dried at 65°C for one week. After drying, the plant samples were weighed to determine dry matter, and then finely ground for total N analysis using an automated wet chemistry and continuous flow analyser (SAN^{++} SA3000/5000 Scalar Analytical, Breda, The Netherlands).

2.8. Statistical analysis

The t-test was used for the comparison of means and analysis of variance (ANOVA) for the significance of treatments using the R 2.10 version of software.

3. RESULTS AND DISCUSSION

3.1. Maize grain yield

3.1.1. 2014 growing season

The ANOVA showed that the mulch application (i.e. the maize residues left on the soil surface) didn't affect maize yield; no significant differences were found between with and without mulch. The interaction of maize residues and tillage system also did not show significant differences (data not shown), and mulch application, tillage system and their interaction did not significantly influence maize yield. However, a different level of Nitrogen, phosphorus and potassium fertiliser (NPK) application showed a significative difference ($p<0.01$) and a highly significant difference ($p<0.001$) on maize yield. The interaction effect between mulch and NPK applications showed a non-significant difference for maize yield.

Yield of maize husk ranged from 0.2 t ha^{-1} in the control (0 C) to a maximum of 0.6 t ha^{-1} in C + 120 kg N (Table 2). The cob ranged from 0.1 to 0.7 t ha^{-1}. The grain yield ranged from 0.3 to 2.5 t ha^{-1}. Shoot yield had a minimum of 1.4 t ha^{-1} to a maximum of 7.3 t ha^{-1}. In general, all maize yields at 120 kg N were higher compared with no fertiliser (Table 2). Total aboveground maize dry matter ranged from 9.7 ± 2.8 to 11.2 ± 1.8 t ha^{-1} for the treatment with N fertiliser and from 6.2 ± 0.2 to 7.8 ± 1.6 t ha^{-1} in the treatment without fertiliser.

TABLE 2. MEAN YIELDS (T HA^{-1}) OF GRAIN AND DRY MATTER OF MAIZE IN THE 2014 SEASON

Treatment	0 C + 120 N	C + 120 N	0 C + 0 N	C + 0 N	0 C	C
Wet						
Cob + Husk	2.2 ± 0.5ab	2.7 ± 0.5a	2.0 ± 0.5abc	1.7 ± 0.4bc	1.0 ± 0.4c	1.3 ± 0.3bc
Grain	3.1 ± 0.9ab	3.3 ± 0.9a	2.0 ± 0.3bc	2.1 ± 0.3bc	0.6 ± 0.1c	0.4 ± 0.4c
Ear	5.3 ± 1.2ab	6.1 ± 1.4a	4.0 ± 0.3bc	3.8 ± 0.4bcd	1.6 ± 0.2d	1.7 ± 0.7cd
Shoot	10.0 ± 2.1a	11.1 ± 1.5a	6.9 ± 0.8b	6.4 ± 0.9b	1.6 ± 0.2c	2.6 ± 2.0c
Shoot + Ear	15.3 ± 3.2a	17.1 ± 1.8a	10.9 ± 1.0b	10.2 ± 1.1b	3.2 ± 0.5c	4.3 ± 2.7c
Dry						
Husk	0.6 ± 0.1a	0.6 ± 0.1a	0.5 ± 0.2ab	0.6 ± 0.2ab	0.2 ± 0.1b	0.3 ± 0.2ab
Cob	0.6 ± 0.1ab	0.7 ± 0.1a	0.4 ± 0.1cd	0.4 ± 0.1bc	0.1 ± 0.0e	0.2 ± 0.1de
Cob + Husk	1.2 ± 0.3ab	1.4 ± 0.1a	0.9 ± 0.2bc	1.0 ± 0.3abc	0.3 ± 0.1d	0.5 ± 0.3cd
Grain	2.2 ± 0.6ab	2.5 ± 0.7a	1.5 ± 0.2bc	1.5 ± 0.3bc	0.4 ± 0.1c	0.3 ± 0.3c
Ear	3.4 ± 0.8ab	3.9 ± 0.8a	2.5 ± 0.1b	2.5 ± 0.5b	0.8 ± 0.2c	0.8 ± 0.6c
Shoot	6.3 ± 2.3ab	7.3 ± 2.0a	5.4 ± 1.5abc	3.6 ± 0.5bc	1.4 ± 0.5c	2.1 ± 1.3bc
Shoot + Ear	9.7 ± 2.8ab	11.2 ± 1.8a	7.8 ± 1.6bc	6.2 ± 0.2c	2.2 ± 0.3d	2.9 ± 1.8d

Note: Means ± standard deviation; Data followed by the same letter within a column were not significantly different

3.1.2. 2015 growing season

The ANOVA test showed that the use of mulch didn’t affect yield. The comparison between with and without mulch did not show a significant difference (*P* value > 0.5); it is explained by the low quantity of the mulch left in the plot (one third of plant biomass production). The treatment tillage *vs* no till didn’t have a significant effect because this was the first year of the no till practice. However, the use of NPK fertiliser had a significant positive effect on the yield of corn.

Husk weight of maize ranged from 0.2 to 0.7 t ha^{-1} in dry matter (Table 3). For the cob weight, the value varied from 0.1 to 0.6 t ha^{-1} in dry matter. The shoot weight was 1.0 to 4.0 t ha^{-1}, and the grain yield ranged from 0.1 to 2.5 t ha^{-1} dry matter. The NPK fertiliser showed significant differences; the treatments with NPK (0 C + 120 kg N, C + 120 kg N) promoted significant increases in the yields of the different parts of the maize plants. Maize biomass and grain yield were positively affected by NPK fertiliser, but not by tillage system and residue application, because of the low quantities of maize residues used and the first year of the no tillage system. As in 2014, the 120 NPK treatment had the highest total dry matter of husk, cob, grain and shoot. The urea fertilisation did not produce significant difference in grain.

There were highly significant effects for the treatment using 120 kg N and PK. The production of total aboveground (shoot + ear) maize dry matter is presented in Table 3. For the treatments using N, the total aboveground biomass ranged from 7.7 ± 1.8 to 7.1 ± 1.1 t dry matter ha^{-1}. For the treatment without N, this total aboveground maize dry matter varied between 6.2 ± 0.9 to 6.1 ± 0.8 t dry matter ha^{-1}.

TABLE 3. MEAN YIELDS (T HA^{-1}) OF GRAIN AND DRY MATTER OF MAIZE IN THE 2015 SEASON

Treatmentnt	0 C + 120 N	C + 120 N	0 C + 0 N	C + 0 N	0 C	C
Wet						
Husk	0.8 ± 0.1a	0.8 ± 0.2a	0.6 ± 0.1b	0.7 ± 0.1b	0.4 ± 0.3c	0.3 ± 0.2c
Cob	1.1 ± 0.2a	1.0 ± 0.2ab	0.8 ± 0.2b	0.8 ± 0.1b	0.3 ± 0.4c	0.2 ± 0.2c
Cob + Husk	1.9 ± 0.3a	1.8 ± 0.4a	1.4 ± 0.2b	1.4 ± 0.1b	0.7 ± 0.7c	0.5 ± 0.4c
Grain	3.1 ± 1.0a	2.7 ± 0.6a	2.6 ± 0.5a	2.6 ± 0.5a	0.3 ± 0.3b	0.2 ± 0.3b
Ear	5.7 ± 1.4a	5.2 ± 1.0a	4.6 ± 0.7a	4.6 ± 0.7a	1.4 ± 1.3b	1.1 ± 0.8b
Shoot	4.4 ± 0.9a	4.0 ± 0.6ab	3.2 ± 0.4bc	3.1 ± 0.4c	1.4 ± 0.6d	1.5 ± 1.2d
Shoot + Ear	10.0 ± 2.2a	9.1 ± 1.6a	7.7 ± 1.1a	7.6 ± 0.8a	2.8 ± 1.8b	2.5 ± 2.1b
Dry						
Husk	0.6 ± 0.1a	0.7 ± 0.1a	0.6 ± 0.1ab	0.5 ± 0.1ab	0.3 ± 0.2bc	0.2 ± 0.2c
Cob	0.6 ± 0.1a	0.5 ± 0.1a	0.5 ± 0.1a	0.5 ± 0.1a	0.1 ± 0.2b	0.1 ± 0.1b
Cob + Husk	1.2 ± 0.2a	1.2 ± 0.2a	1.1 ± 0.2a	1.0 ± 0.1a	0.4 ± 0.4b	0.3 ± 0.2b
Grain	2.5 ± 0.8a	2.2 ± 0.5a	2.2 ± 0.4a	2.2 ± 0.5a	0.2 ± 0.4b	0.1 ± 0.5b
Ear	3.7 ± 1.0a	3.4 ± 0.6a	3.3 ± 0.6a	3.3 ± 0.6a	0.6 ± 0.6b	0.4 ± 0.4b
Shoot	4.0 ± 0.8a	3.6 ± 0.5a	2.9 ± 0.4b	2.8 ± 0.4b	1.1 ± 0.4c	1.0 ± 0.7c
Shoot + Ear	7.7 ± 1.8a	7.1 ± 1.1a	6.2 ± 0.9a	6.1 ± 0.8a	1.7 ± 0.9b	1.5 ± 1.1b

Note: Means ± standard deviation; data followed by the same letter within a column were not significantly different

3.2. N concentration of maize plants

The N concentration in maize by treatments is shown in Table 4 and the ANOVA test in Table 5. The ANOVA test showed that the plant N concentration in different parts of whole maize plants were significantly different (*P* value < 0.001) between the treatments for the growing seasons 2014 and 2015. In general, the control treatment had significantly higher values of N concentration in the different maize parts; this higher N concentration for the control was due to the partition and accumulation of N through a low quantity of maize biomass and grain. The N concentration for the 2014 maize grain was significantly higher than for the 2015 maize grain caused by the later urea application in 2015 (1.5 month after sowing). N concentrations in the 2014 grain and shoot for the treatments with urea (C + 120 kg N, 0 C + 120 kg N) were higher than treatments without urea (C + 0 N, 0 C + 0 N), reflecting an impact of urea fertiliser. For the treatments without fertiliser N application (0 C + N and C + 0 N), the lower N concentrations in grain and straw were due to the low N availability in the soil.

As previously noted, N concentrations of the maize plant for the treatments with urea were higher than treatments without urea, reflecting the late date of urea application. The N concentration in the maize plants didn't have significant difference for the treatment with or without urea. Grain and husk increased significantly but not for the straw and cob. Straw N concentrations were less than 5.9 g kg^{-1} in all treatments except for the control treatments. Nitrogen was concentrated in the grain, cob and straw, particularly in the treatment with urea fertiliser. The maize fertilised with 120 kg N had higher N concentrations among all treatments especially the control treatments for the 2 years. Relative to the control (0 C and C), N concentration was significantly higher than the other treatments.

The range value of N concentration in grain in 2014 was 14.0 ± 0.8 to 18.0 ± 0.3 g kg^{-1}; in straw (stalk and leaf) the range of values was from 3.1 ± 0.6 to 11.8 ± 1.0 g kg^{-1}. The value for N concentration in 2015 grain ranged from 10.7 ± 0.6 to 19.8 ± 0.3 g kg^{-1}. For the straw (stalk and leaf) N concentration was 6.1 ± 0.6 to 9.9 ± 1.0 g kg^{-1}. For the cob, N concentration values varied widely from 6.6 ± 0.7 to 29.9 ± 18.5 g kg^{-1}. The N concentration for husk ranged from 6.4 ± 0.3 to 8.0 ± 1.2 g kg^{-1}. In ascending order of importance, N concentration values of maize are husk, straw, cob and grain (Table 4).

In 2015, the treatment using 120 kg N did not have a significant effect on N concentratiion compared to the control treatment (0 N) for all maize biomass and grain. It was probably due to the late application of two-third (80 kg N) of the second dose of urea fertiliser, because the 2nd date was at 45 days after the first application (40 kg N). It did not correspond to a maximum or optimum of plant N assimilation. In general, the N concentration for husk was the lowest followed for stem, cob and grain both in 2014 and 2015. Greater N accumulation occurred in grain compared to the other maize plant parts like stem, husk and cob. For the years 2014 and 2015, total N concentration increased as fertiliser N increased. In 2014 straw and grain N concentration was significantly influenced by urea fertiliser application. However, in 2015, the application of 120 kg N compared to no N fertiliser did not significantly modify the N concentration of maize plant parts.

TABLE 4. EFFECT OF MULCH AND NPK APPLICATION ON N CONCENTRATION (G KG^{-1}) IN MAIZE (BIOMASS AND GRAIN) AT HARVEST FOR ALL TREATMENTS IN YEARS 2014 AND 2015

Year	Treatments	Husk	Straw (leaf + stem)	Cob	Grain
2014	0 C + 120 N	-	5.7 ± 0.4c	-	16.7 ± 0.3a
	C + 120 N		5.9 ± 0.7c		16.1 ± 1.3a
	0 C + 0 N		3.2 ± 0.6d		14.0 ± 0.8b
	C + 0 N		3.1 ± 0.6d		14.5 ± 1.5b
	0 C		8.9 ± 0.7b		18.0 ± 0.3a
	C		11.8 ± 1.0a		15.9 ± 2.6ab
2015	0 C + 120 N	3.6 ± 0.4b	6.1 ± 0.6d	6.6 ± 0.7c	12.6 ± 0.4b
	C + 120 N	4.0 ± 0.7b	7.2 ± 0.7c	7.5 ± 0.9c	12.3 ± 0.5b
	0 C + 0 N	3.4 ± 0.3b	6.5 ± 0.5d	6.5 ± 1.4c	11.0 ± 0.9b
	C + 0 N	3.4 ± 0.3b	6.1 ± 0.5d	7.6 ± 1.2c	10.7 ± 0.6b
	0 C	7.5 ± 1.7a	9.9 ± 1.0a	19.6 ± 10.9b	19.8 ± 0.3a
	C	8.0 ± 1.2a	8.6 ± 0.1b	29.9 ± 18.5a	18.7 ± 6.4a

Note: Means ± standard deviation; data within the same column in the same year followed by the same letter were not significantly different; 0 C and C: no treatment with NPK.

TABLE 5. P-VALUE OF N CONCENTRATION

Year	Variable	P-value
2014	grain	0.00108 **
	Straw (stem+ leaf)	1.04e-13 ***
	Cob	na
	Husk	na
2015	grain	1.83e-07 ***
	Straw (stem + leaf)	2.19e-07 ***
	Cob	2.45e-05 ***
	Husk	6.49e-09 ***

na: not applicable; ** Significant at p<0.01; *** Significant at p<0.001

3.3. N fertiliser use efficiency for maize

Nutrient use efficiency measures the capacity of the plant to respond to N fertiliser application. Different nutrient use efficiency parameters were utilised to estimate the impact of the tillage system and mulch on the fertiliser N efficiency of the crop [5, 7]. All data were used to evaluate the Nitrogen Use Efficiency (NUE), which is the quantity and percentage of N fertiliser recovered in maize yield and N uptake. The NUE was used to evaluate the impact of fertilisation on maize plant dry matter or grain. The Nitrogen Use Efficiency components are: Agronomic efficiency (AE), Recovery efficiency (RE) and Physiological efficiency (PE).

3.3.1. *Definitions*

Recovery efficiency is expressed as a percentage. RE was defined by the equation:

$$RE\ (\%)\ =\ (Total\ plant\ N\ uptake\ with\ fertiliser\\ -\ total\ plant\ N\ uptake\ without\ fertiliser)\ \times\ 100\\ /\ level\ of\ fertiliser\ application \tag{8}$$

The physiological efficiency is the plant's ability to transform a quantity of fertiliser N into plant N. PE is the total grain yield produced per unit of N absorbed. i.e.

$$PE\ (kg\ grain\ kg^{-1}N)\\ =\ (yield\ with\ fertiliser\\ -yield\ without\ fertiliser)\ /\ (Total\ plant\ uptake\ with\ fertiliser\\ -\ total\ plant\ uptake\ without\ fertiliser) \tag{9}$$

The classical method to evaluate fertiliser use is the agronomic efficiency which is the increase in kg of grain harvested per kg of applied fertiliser or nutrient. The AE is expressed by the following equation:

$$AE\ (kg\ grain\ kg^{-1}N)\ =\ \frac{(yield\ with\ fertiliser\ -\ yield\ without\ fertiliser)}{level\ of\ fertiliser\ application} \tag{10}$$

Agronomic efficiency was essentially for grain yield but similarly crop biomass efficiency (BE) can be calculated from the biomass yield.

AE is the product of RE and PE [6] i.e. AE = PE × RE.

The efficiency values depend and vary *inter alia* by interaction of cropping systems, soil type and characteristics, plant genetics, fertilisation type and time of application, tillage system and crop rotation.

3.3.2. *Agronomic efficiency*

The agronomic efficiency was highest in 2014 compared to 2015 for all maize parts (Table 6). The AE varied from 1 to 19 kg of dry matter kg^{-1} N in plant parts in 2014, and from 1 to 8 kg of dry matter kg^{-1} N in 2015. The agronomic efficiency of N in the maize plant parts varied in the following manner: stem + ear > stem > ear> grain ≥ cob + husk > cob ≥ husk.

The stem dry matter yield showed the highest value, while the husk and cob showed the lowest values (Table 6). The use of 120 kg N ha^{-1} improved maize biomass yield. In 2014, the stem yield was 2 to 3 times higher compared to grain yield.

TABLE 6. YIELD, N CONCENTRATION AND N FERTILISER USE EFFICIENCY IN DRY MAIZE IN 2014 AND 2015

Year	Treatment	Yield ($t\ ha^{-1}$)			N concentration ($g\ kg^{-1}$)			AE (kg of dry matter kg^{-1} N)	RE (%)	PE (kg of dry matter kg^{-1} N)
		120 NPK	0 NPK	Control	120 NPK	0 NPK	Control			
2014	Husk	0.6	0.5	0.2	-	-	-	0.8	-	-
	Cob	0.7	0.4	0.3	-	-	-	1.9	-	-
	Cob + Husk	1.3	1.0	0.4				2.7		
	Grain	2.4	1.5	0.4	16.4	14.3	17.0	7.1	14.2	50
	Ear	3.6	2.5	0.8				9.7		
	Stem	6.8	4.5	1.8	5.8	3.2	10.3	19.0	20.6	92
	Stem + Ear	10.4	7.0	2.6				28.7		
2015	Husk	0.7	0.6	0.3	3.8	3.7	7.7	0.9	0.4	219
	Cob	0.6	0.5	0.1	7.0	7.1	24.8	0.6	0.4	151
	Cob + Husk	1.2	1.0	0.3				1.5		
	Grain	2.4	2.2	0.2	12.4	10.8	19.3	1.1	4.3	25
	Ear	3.6	3.3	0.5				2.6		
	Stem	3.8	2.9	1.0	6.7	6.6	9.3	8.1	6.2	129
	Stem + Ear	7.4	6.1	1.6				10.7		

Note: AE, Agronomic efficiency; RE, Recovery efficiency; PE: Physiological efficiency

For the grain, the AE was 1 and 7 kg of dry matter kg^{-1} of N in 2014 and 2015, respectively. The grain AE was 7-fold greater in 2014 than in 2015 when 120 kg N was applied. 7 kg grain yield kg^{-1} of N and 19 kg stem yield kg^{-1} of N were found in 2014 at 120 kg N ha^{-1}. In 2015, maize produced 1 kg grain yield kg^{-1}N and 8 kg stem yield kg^{-1} of N. For the maize grain, the AE in this study was low and very low in 2014 and 2015, respectively, when compared to Wortmann et al. [7], who found a value of 29 kg of dry matter kg^{-1} N for the AE.

A grain yield of 2.4 t ha^{-1} was obtained from 120 kg N ha^{-1} of N fertiliser in both 2014 and 2015 (Table 6). For the stem, the highest biomass of 6.8 and 3.8 t ha^{-1} were observed using 120 kg ha^{-1} of nitrogen fertiliser in 2014 and 2015, respectively. Also, the treatment of 120 kg N of nitrogen fertiliser had the highest N concentration of 5.8 and 16.4 g kg^{-1}, respectively, for the stem and grain in 2014. In 2015, higher values of 6.7 and 12.4 g kg^{-1} for the stem and grain, respectively, were obtained (Table 6).

3.3.3. Physiological efficiency

In 2014, physiological efficiency was 50 and 92 kg of dry matter kg^{-1} N for the grain and stem, respectively (Table 6). In 2015, the PE was 25 kg of dry matter kg^{-1} N for grain, 130 kg of dry matter kg^{-1} N for stem, 219 kg of dry matter kg^{-1} N for husk and 151 kg of dry matter kg^{-1} N for the stem. The lower PE indicates that maize plants were less efficient at producing grain and dry matter per unit of N uptake. In this experiment, the N uptake by the maize plant was allocated to grain N composition (grain N concentration) instead of grain yield. Wortmann et al. [7] found a PE of 44 kg of dry matter kg^{-1} N for maize grain yield.

3.3.4. *Recovery efficiency*

The average recovery efficiency of urea-N was 14 and 21% for the grain and stem in the 2014 growing season, but under 6.5% for the application of N in 2015 season. The recovery of N for the stem was higher (21%) than grain. The largest proportion of the maize plant N uptake was located in the stem vegetative tissue. These results overall (Table 6) show low recoveries of N fertiliser, particularly in 2015 due to the late urea application which did not correspond to maize growth needs. In 2014, 14% and 21% of the recovered fertiliser N were located in the dry stem and grain, respectively. The RE was markedly dependent of the growing season, being 3-fold greater in 2014 compared to 2015. In 2015, the RE was 4% and 6%, respectively, for grain and stem.

Ellen and Spiertz [8] demonstrated that fertiliser use efficiency, as reflected in grain yield, changed with rate of application and time. RE was very low in husk and cob, but also low for the grain and stem in 2015. RE in our study was low compared with the results of Motavalli et al. [9], who found that for low and high yields the apparent RE was14 and 104%, respectively. Wortmann et al. [7] found a high RE in the order of 65% for the corn.

The total quantity and the partition of N in different part of maize are shown in Table 7. In 2014 and 2015 the maize grain contained in total 17.1 and 5.1 kg N ha^{-1} from 120 kg N ha^{-1} of applied fertiliser N. In 2015, the total amount of N absorbed by aboveground biomass and grain was only 12.7 kg N ha^{-1} which was equivalent of 10.6% of 120 kg N ha^{-1}. In 2014, the result showed that only 14.2% of applied N was found in grain. This result was near that of Varvel and Peterson [10] who showed that at N rates of 68 and 180 kg N ha^{-1} for corn, only 20% to 30% of the applied N was accounted for by N removal in the grain. For the husk and cob, the percentage of N fertiliser uptake was very low; <0.5% of the total N fertiliser application.

TABLE 7. N TOTAL UPTAKE IN DIFFERENT PARTS OF MAIZE

		N total uptake (kg N ha^{-1})			N uptake from fertiliser N	
Year	Plant part	120 NPK	0 NPK	Control	(kg N ha^{-1})	(%)
2014	Grain	38. 1	21.5	6.4	17.1	14.2
	Stem	39.0	14.3	18.5	24.7	20.6
	TOTAL	na	na	na	na	na
2015	Husk	2.5	2.0	1.9	0.5	0.4
	Cob	3.9	3.5	2.5	0.5	0.4
	Grain	29.2	24.0	3.3	5.1	4.3
	Stem	25.4	18.9	9.5	6.6	5.5
	TOTAL	61.01	48. 3	17.2	12.7	10.6

na: not available

4. CONCLUSIONS

The interaction of factors fertiliser, tillage system and maize residues retention did not have any effect on the performance of two maize crops, but only a single factor fertiliser explained the performance. For both 2014 and 2015 analyses of variance showed no significant differences among treatments with and without residue applications or tillage on the grain and dry matter yields of plant parts. Maize yields responding significantly to urea fertilisation in 2014. Generally, maize recovery of N fertiliser was low compared with global estimates. The recovery of N fertiliser was an indirect (N difference) estimates as opposed to a direct estimate using ^{15}N-labelled fertiliser, and is based on the dubious ssumption of equal uptake of soil N in fertilised and control plots. The 120 NPK treatment showed the highest total dry matter of grain and shoot in maize in 2014 and 2015. The use of 120 kg N increased significantly the grain yield of maize in 2014, but not in 2015. In 2015, RE values were very low compared with 2014, due to the late application. Low nutrient availability is the factor limiting maize yield when fertilisers are not applied.

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CROP RESIDUE MULCHING: BENEFITS, CHALLENGES AND MANAGEMENT ISSUES UNDER CHANGING CLIMATE

M. ZAMAN
International Atomic Energy gency
Vienna, Austria

J. K. LADHA
International Rice Research Institute (IRRI) Philiphines

1. INTRODUCTION

It is estimated that demand for food and non-food commodities is likely to increase by at least 60% globally between 2010 and 2050, with many developing countries including those in Sub-Saharan Africa (SSA) having to double their food production [1]. Future food production will be limited on a global scale by the availability of land, water, and energy under climate forcing, therefore decoupling future agricultural growth from the unsustainable use of these resources for increasing food production has become one of the cornerstones for a new sustainable development agenda [2]. As a cornerstone of the new sustainable development agenda, the agricultural transformation in the next few decades have to be an eco-efficient revolution, with at least 30% to 50% increases in the efficiency of scarce resources used while also ensuring the availability of nutritious food for all and minimising many negative environmental impacts associated with contemporary food systems [2].

Intensive agriculture in Asia and Africa is associated with productivity and sustainability problems. The problems however differ from the largely irrigated intensive systems to those in the rain-fed ecologies which are characterised by smaller farms, weaker institutions including markets and greater poverty. These differences reflect significant gradients in the resource base, crop management and livelihoods across the agro-ecologies. With intensive tillage and crop residue removal and/or burning, the soil organic matter has declined globally to a lowest level [3] which has led to increasing use of synthetic fertiliser [4]. Low productivity in specially in rain-fed agriculture is largely due to degraded soil fertility associated with short supply of water and nutrients. Increasing usages of synthetic fertiliser specially nitrogen has also resulted in global warming potential and climate forcing [4]. During the last few years, several component technologies of conservation agriculture (CA) such as reduced or zero tillage (ZT), drill seeding, crop residue retention, and crop rotation have been evaluated in diverse cropping systems globally [5, 6, 7, 8, 9, 10, 11]. Globally, area under CA has increased from 2.8 million (m) ha in 1973/74 to 72 mha in 2003 with an approximate annual rate of increase of 7 mha during last decade or so [9].

Cropping systems that incorporate CA components have shown significant potential to increase productivity and economic profitability. With more mechanised, labour-saving land management and crop establishment at centre stage, the transformation from conventional tillage-based agriculture to conservation tillage with crop residue recycling is considered to be a crucial direction for transforming agriculture [12]. However, achieving multiple economic and ecosystem benefits through CA remains a challenge in smallholder farming [10] and its potential for climate change mitigation is also questionable [13]. A recent meta analysis of global data reported either no gains or losses of grain yields of various crops with either full CA or with some components of CA [11]. However, while yield advantages are not always possible to achieve with CA practices alone over the short-term, gains in input use efficiency and economic benefits are attainable especially with judicious usages of crop residue in small landholding of Africa and Asia. Surface residue retention or soil mulching provides multiple benefits, including soil moisture conservation, modify soil temperature, suppression of weeds, and improvement in soil organic matter and soil structure.

2. SOIL MULCH OR SOIL COVER

Retaining crop residue as soil mulch or soil cover is one of the simplest and highly beneficial practices of good soil management. Mulching enriches and protects soil and thereby provides better growing environments for a plant or crop. Crop residue mulching (CRM) considered to combine both conservation and productivity effects and has been defined as a technology whereby at the time of crop emergence, at least 30% of the soil surface is covered by organic residue of the previous crop [14]. Mulch which is spread on soil surface is mostly organic but sometime also inorganic. An organic mulch includes materials such as crop straw/residue, cut grass, plant clippings, fallen leaves, compost/manure, peat whereas an inorganic mulch could be bark chips, stones, and plastic. In agriculture, mostly crop residue is used as an organic mulch and plastic as an inorganic mulch but in gardens, lawn or yard material such as grass or clippings is used as organic and stones as inorganic.

FIG. 1. Organic mulch in a vegetable system, Source: TNAU Organic mulch in a farmer field in Africa, Source: http://bryanwaters.org/farming/2014/04/15/power-of-mulching/

FIG. 2. Direct sowing on a crop mulch in Koumbia, Inorganic (plastic mulch), Source: TNAU Burkina Faso (© P. Djamen/CIRAD)

While inorganic mulches such as plastic have niche in certain landscape, they do not directly improve soil quality. However, since the plastic is impermeable to water, it prevents the direct evaporation of soil moisture thus reduces water losses and reduces rise of water containing salts. Plastic mulch may also (a) reduce fertiliser N losses from volatilisation, (b) provide barrier to soil pathogens, (c) reduce weed pressure by preventing germination, (d) maintain warm temperature during night, (d) have other positive benefits from solarisation.

3. BENEFITS OF CROP RESIDUE MULCH

Erenstein advocated that a crop residue mulch is strategically located at the soil-atmosphere interface influencing (a) soil conservation, (b) soil ecology, (c) crop yield, (d) labour and capital productivity, and (d) agricultural externalities [14]. The soil conservation and soil ecology together include multiple benefits of soil mulching [14]. The effects include improvements in soil structure, soil organic matter, soil biological activities leading to soil fertility and soil stability. Organic mulch on soil surface helps to (a) conserve and maintain moisture, (b) protects from the soil erosion, (c) maintains a more even soil temperature, (d) reduces weed pressure from preventing weed growth, and (e) improves soil biological, chemical and physical properties. Organic mulches because of slow decomposition builds soil organic matter which helps in enhancing the efficiencies of added inputs such as water, and nutrients.

4. EFFECTS ON SOIL MOISTURE CONSERVATION

There are numerous published reports on the positive effect of moisture conservation from the residue cover. Teame et al. [15] reported positive effects of four types of organic mulches (rice straw, sorghum straw, sesame straw, and sudan grass applied at the rate of 10 t ha^{-1}) on conserving soil moisture in Sudan Sesame (*Sesamum indicum* L.) in Ethiopia. The results indicated that organic mulching had significant effect on soil moisture content at 0–0.2 m, 0.21–0.4 m, and 0.41–0.6 m in every two-week interval after sowing and grain yield of sesame. Sesame straw conserved highest soil moisture content as compared with respective mulch material. The highest yield (664 kg ha^{-1}) was recorded with Sudan grass while the lowest grain yield (190 kg ha^{-1}) was recorded with no mulch.

Dan Brainard from the Michigan State University in their strip-tilled sweet corn trials, reported visible effect of rye or wheat cover crop on conserving soil moisture. They reported plots with rye residue on the soil surface had approximately 5 percent greater water content in the top 10 inches then plots without rye mulch (Fig 3). This is equivalent to about 0.5 inches of irrigation savings.

Residue mulching reduces evaporation of water which also contributes to the conservation of soil moisture. With residue on soil surface, less solar energy reaches the soil surface and wind speed is reduced. It has been reported that when soil surface is wet, evaporation from an uncovered soil will occur at a rate that equals the atmospheric demand. The evaporation rate will decrease drastically, because of a rapidly drying soil surface. Water that is deeper in the soil cannot be transported quick enough through this dry surface soil to satisfy atmospheric demand. If the soil is covered, the residue insulates the soil from solar radiation and reduces air movement at the soil surface. This reduces the evaporation rate from a residue covered surface, compared to an uncovered soil. If there is no rain or irrigation for a long period, the surface moisture under the residue will continue to slowly evaporate.

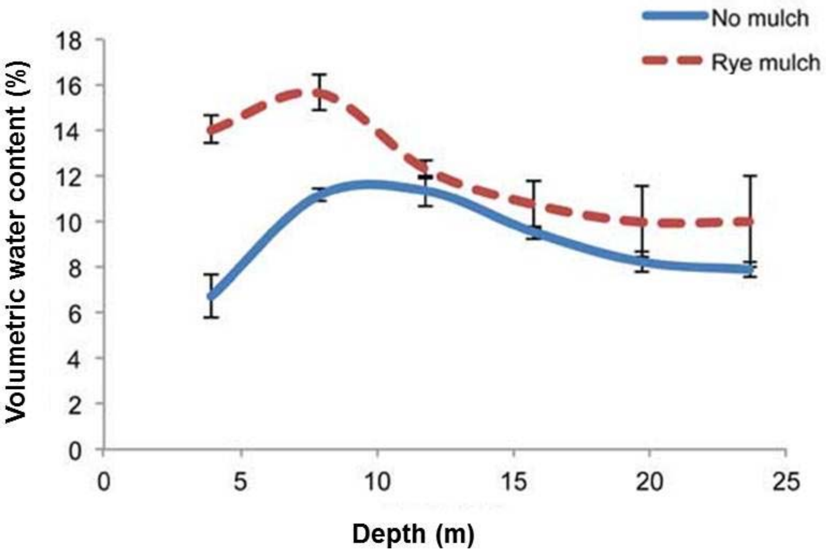

FIG. 3: Effects of cover crop mulch on soil moisture. Source: Dan Brainard (http://msue.anr.msu.edu/news/conserving_soil_moisture_in_vegetables_effects_of_weed_management_and_cover) Figure provide by Dan Brainard, Michigan State University Extension.

5. Effects on Soil Erosion Control

A 7-year (1988–1995) mulch study conducted in Zimbabwe using maize showed that maize yields increased marginallyfrom 3.2 t ha^{-1} without mulch to 4 t ha^{-1} with mulch in well drained soil. However, the effect of mulch application on surface runoff and soil losses were substantial. For example, mulch treatment reduced the surface runoff by an average of 68% under well drained and poor drained soils. Simialrly, mulch application reduced soil losses by 82% compared to no mulch under well drained and poorly drained soils [14].

Laften and Colvin [16] showed a generic relationship between crop residue coverage and soil erosion compared to that occurring on a bare soil. They reported that to reduce soil erosion by about 50% of that occurring for a bare soil surface, 30 percent of the soil surface needs to be covered by crop residues following planting.

6. EFFECTS ON WEEDS

Crop residue management influences weed count due to their influence on weed seed germination by altering top soil temperature, moisture, releasing allele-chemicals and by controlling weed seed distribution in soil profile. Residue retention over soil on the surface is usually done before or after the crop is sown.

The mulching of residues such as that of rice, wheat, sorghum and sunflower significantly control weeds typically by smothering and through allelopathic effects [17]. Normally, under an adequate layer of mulch on top of the soil, mulch prevents up to 80% of weeds from germinating.

Covering the soil surface using crop residues can reduce weed problems by preventing weed seed germination or by suppressing the growth of emerging weed seedlings [18]. This weed growth inhibition by mulches is attributed to the release of allelo-chemicals, changes in soil temperature and physical barrier due to mechanical hindrance. Mulching (a) increases heat due to their low heat conductance and kill the weeds, (b) poses a barrier to the germinating seedlings, (c) prevent penetration of light which is needed for weed seed germination, and (d) inhibits photosynthesis by prevent light penetration. With increase in amount of residue cover weed emergence and growth decreases [19].

7. EFFECTS ON SOIL QUALITY

Mulch has several beneficial effects through improvements in soil biological, physical, and chemical properties. Mulch through (a) conserving moisture, (b) preventing weeds from taking up nutrients, and (c) adding nutrients to the soil during decomposition help micro-organisms thrive and encourage the presence of biological activities such as growth of earthworms. Mulch affects soil physical environment through improvements in soil structure leading to better root growth and soil aeration and water-holding capacity. Returning crop residue as mulch also recycles nutrients. On an oven dry weight basis, various crop residue contains N ranging from 0.58% to 4.0%, P from 0.1% to 1.1% and K from 0.2% to 3.4% which is equivalent to about 6 to 40 kg N t^{-1} residue, 1.0 to 4 kg P t^{-1} residue and 17 to 58 kg K t^{-1} residue (Table 2).

TABLE 2. NUTRIENT CONTENTS (KG PER TONNE) IN DIVERSE CROP RESIDUE

	Kg per tonne			
Crop/species	**N**	**P**	**K**	**Total**
Cowpea stem	10.7	11.4	25.4	47.5
Cowpea leaves	19.9	1.9	22.0	43.8
Rice	5.8	1.0	1 3.8	20.6
Maize	5.9	3.1	13.1	22.1
Oil palm (fibre)	12.4	1.0	3.6	17.0
Sesbania leaves	40.0	1.9	20.0	61.9
Crotolaria spp.	28.9	2.9	7.2	39.0
Tephrosia spp.	37.3	2.8	17.8	57.9
Water hyacinth	20.4	3.7	34.0	58.1
Azolla spp.	36.8	2.0	1.5	40.3
Typha.spp	13.7	2.1	23.8	39 6

Source: FAO 1990

8. EFFECTS ON CROP YIELDS

There are numerous published and unpublished reports over the years from all the over the World including Sub Saharan Africa which showed crop yield improvements from the crop residue mulch. Returning crop residue as mulch may also have synergistic effects with fertiliser use. Residue with relatively lower C:N showed higher yield increases then that of higher C:N. A recent meta-analysis comprising data from 19 countries including Sab Sahara Africa showed an average yield increases of 20% of each of wheat and maize with straw mulch [20] While the yield increases of wheat were similar with straw and plastic mulch but that of maize yields were about 60% higher with plastic mulch than that of straw mulch. It was also found that response of yields to residue mulch varied with factors such as different water input levels, N input levels and temperature.

Data from Alfisols in Nigeria showed significant increases of yields of Cassava, Maize, Cowpea and Soybean on soil without residue compared to diverse residue including plastic residue (Table 3). Likewise, on an Ultisol in eastern Nigeria the yield of plantain and bananas was drastically improved with residue mulch [21]. Plantain yield was five times more with mulch than with chemical fertilisers alone.

TABLE 3. CROP YIELD RESPONSE TO 22 DIFFERENT MULCH MATERIALS APPLIED ON ALFISOLS IN NIGERIA

	tonnes ha^{-1}			
Mulch	Cassava (fresh roots)	Maize	Cowpea	Soybean
Bare soil (control)	16.4 def	3.0 e	0.6 a	0.6 de
Maize stover	16.4 def	3.3 cd	1.1 a	1.5 abc
Maize cobs	17.8; cdef	3.3 cd	1.1 a	1.4 abed
Oil palm leaves	17.1 def	3.2 cd	1.2 a	0.9 bcde
Rice straw	17.9 cdef	3.5 bed	1.0 a	1.5 abc
Rice husks	28.3 a	3.7 abc	1.1 a	0.8 de
Kikuyu grass straw	14.2 ef	3.3 cd	1.2 a	1.4 abed
Elephant/napier grass *(Pennisetum)*	16.6 def	3.3 ed	0.9 a	1.3 bed
Guinea grass	15.5 f	3.6 bed	2.1 b	1.5 ab
Andropogon straw	18.5 cdef	3.5 bed	1.0 a	1.2 bcde
Cattail straw (Typha)	16.7 def	3.1 cd	1.0 a	1.1 bcde
Cassava stem (chipped)	20.9 cd	3.8 abc	0.9 a	1.4 abcd
Pigeon pea tops	22.9 be	3.7 abc	1.1 a	0.9 cde
Pigeon pea stem (chipped)	19.9 cdef	3.5 bed	1.0 a	1.3 bcd
Legume husks	26.4 ab	4.4 a	1.0 a	1.5 abc
Soybean tops	22.9 be	4.2 ab	1.0 a	1.2 bcde
Hemp (Eupatroium)	18.8 cdef	3.6 abc	1.0 a	1.2 bcde
Mixed twigs (chipped)	18.5 cdef	3.4 bed	1.0 a	1.2 bcde
Sawdust	20.5 cde	3.7 abc	0.9 a	1.9 a
Black plastic	30.5 ab	3.0 cd	0.9a	1.1 bcde
Transluscent plastic	27.7 ab	2.7 d	1.0 a	1.1 bcde
Fine gravel	22.9 be	3.1 cd	1.0 a	1.0 bcde

Figures followed by similar Letters are spastically similar within vertical roust [22]

Sharma et al [23] in India compared the effects of in situ grown live mulching with legumes viz. sunnhemp (*Crotalaria juncea* L.), dhaincha [*Sesbania aculeata* (Pers.)] and cowpea [*Vigna unguiculata* (L.) Walp.], with that of weed mulching at 30 and 45 days of maize (*Zea mays* L) growth on moisture conservation, crop productivity and soil properties in maize-wheat (*Triticum aestivum* L.) cropping system. Legume mulching accumulated 1.09–1.17 t ha^{-1} dry biomass and added 27.9–31.3 kg N ha^{-1} compared with 1.31 t ha^{-1} biomass and 10.3 kg N ha^{-1} with weed mulching at 30 days; which increased further by 68.5–74.8% when applied at 45 days. Maize productivity was about 6–9% higher with legume mulching at 30 days when compared with no mulching. Wheat yields increased by 13.3–14.0% due to legume mulching in previous maize following enhanced soil moisture and nutrient conservation. Mulching with weed biomass was inferior to legume mulching in both the crops. Mulching at 45 days adversely affected maize growth and yield but was more beneficial to the following wheat due to addition of greater biomass and N. There was an improvement in organic C and total N, and a decrease in bulk density with a corresponding increase in infiltration rate due to mulching at the end of 3 cropping cycles. It was concluded that live mulching with legumes in maize was beneficial for improving soil moisture conservation, productivity, profitability and soil health in rain-fed maize-wheat cropping system under Doon valley, India conditions.

Under the CRP D1.50.12, a set of 7 long-term trials in 7 countries focusing on nitrogen, water and carbon management under maize mulch-based cropping systems in Sub-Saharan Africa reported site specific effects. Mulch application in combination with nitrogen fertiliser was demonstrated to improve maize yield and soil fertility in Benin. In Zimbabwe, under drought conditions the benefits of nitrogen addition under mulch or without mulch to yield improvement were limited, although RT with mulch generally improved grain yields over time. Whereas in Pakistan under irrigated conditions mulch application without tillage improved crop yield. However, in Mauritius mulch with tillage improved crop yield under irrigation. In Kenya, there was a trend of increased crop yield under mulch application but this was not statistically significant. In Mozambique, mulch reduced nitrogen use efficiency probably due to immobilisation. These results showed that performance of mulch-based systems is location specific and depends strongly on soil water availability. Time will show how mulch-based cropping systems can reduce impact of changing and more variable climatic conditions. Therefore, it is essential to keep the established trials for long-term studies to gain further insights.

9. CHALLENGES

9.1. Residue Availability: Excess Supply Resulting in Burning

The Green Revolution began around 1960's was successful in producing enough food grains for reducing poverty and malnutrition throughout the World but specifically most populated Asian countries. But increased grain production also resulted in over production of crop residue which is often difficult to manage resulting in to *in situ* burning. Crop residue burning contributes to atmospheric pollution that has serious environment, soil, and human health as well as economic implications due to release of large amounts of air pollutants. The major pollutants emitted by crop residue burning-CO_2, CO, CH_4, N_2O, NOx, SO_2, black carbon, non-methyl hydrocarbons (NMHC), volatile organic compounds (VOC) and particulate matter (PM 2.5 and PM 10), contribute enormously to global warming. It is estimated that one tonne rice residue on burning releases 13 kg particulate matter, 60 kg CO, 1460 kg CO_2, 3.5 kg NOx, 0.2 kg SO_2. The black carbon emitted during residue burning warms the lower atmosphere and it is the second most important contributor to global warming after CO_2.

Apart from the damage caused by air pollution, burning of rice residue also results in loss of soil organic matter and plant nutrients and adversely affects soil health. About 90% of N and S and 15–20% of P and K contained in rice residue are lost during burning**.** In addition, in field burning of crop residues also destroys the beneficial micro-flora and fauna of soil causing adverse impact on soil health.

Increase in the concentration of PM 2.5 and PM 10 during the large scale burning of rice residues is a major health hazard to human and animals. For example, the children are more sensitive to air pollution (smog), as rice residue burning poses some unrecoverable influence on their pulmonary functions.

Crop residue burning is an enormous challenge in countries such as India. Extensive crop burning, resulted in Delhi air becoming the most polluted in the World in the first week of November 2016, compelling the Government to declare Delhi air pollution an emergency (www.theguardian.com/World/India).

9.2. Residue Availability: Short Supply resulting in Trade offs

Crop residue (CR) has several other uses such as livestock keeping, cooking, construction which pose competition with its use for soil conservation. It is also a limited resource particularly in mixed crop-livestock farming system in the developing world [24]. In the mixed systems of SSA, where crop residue is in short supply and livestock keeping is a key livelihood component, there are spatial and temporal tradeoffs and crop residue a fundamental feed source [25]. This has been a challenge for the proponents of CA packages promoting the use of CR as mulch to enhance medium-term crop production through improving soil fertility, despite the direct and short-term benefits of feeding CR to livestock or selling them [7]. Obviously, there is a need to increase crop production and thereby residue production to reduce the tradeoffs.

FIG. 4. Farmers burning rice residue in India.

FIG. 5. Maize residue being transported for animal feed in SSA.

9.3. Customised Crop Management

Erenstein [14] pointed out that crop residue mulching is not a single component or simple add-on technology but it affects both crop growth (output) and crop management (input). Crop growth is affected by abiotic and biotic factors. Instead it is a complete package of cultural practices and not likely to fit in a widely varying production system. Its adoption would require a customised crop management practices and suitability will depend on both biophysical and socio-economic factors and their interactions. Erenstein [14] identified the need of two types of crop management practices i.e. necessary and complementary. Erenstein [14] proposed that the necessary crop management practices include minimum tillage, no biomass burning, limited extraction and weathering with sufficient crop production. The complementary crop management practices consist of the right sowing time, taking good management of weed, diseases, pests and application of essential plant nutrients at the right plant growth stage.

10. OPPORTUNITIES

10.1. Integrated Soil Fertility Management for Africa

The continent of Africa continues to grapple with many episodes of hunger and low crop productivity in multiple locations. With the ever-growing population in the continent, farmers continue to grow crops on the same land year after year. Under such continuous use, soil fertility declines if nutrients removed in crop products are not returned to the soil. To deal with this problem mineral fertilisers are essential. But as fertilisers are more expensive in Africa than anywhere else, most farmers use none at all. Integrated soil fertility management, commonly referred to as integrated soil fertility management (ISFM), has been proposed to address Africa's low soil and crop productivity problems of the main staples including maize, beans, rice, cassava, bananas, sorghum, millet and other crops [26]. ISFM is defined as a set of soil fertility management practices that include the integrated use of mineral fertilisers, organic inputs, and improved germplasms combined with the knowledge on how to adapt these practices to local conditions which are aimed at optimising efficient agronomic use of the applied nutrients and thereby improving crop productivity. In this definition, all inputs need to be managed following sound agronomic and economic principles.

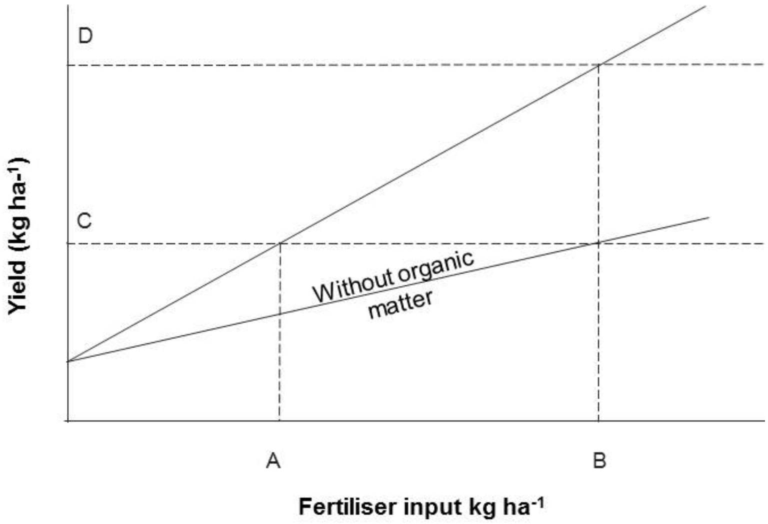

FIG. 6. Positive interaction between fertiliser and organic inputs resulting in extra yield due to ISFM practices.

Organic inputs (crop residues and animal manures) are also an important source of nutrients, but their N, P, Mg and Ca content is only released following decomposition. By contrast, K is released rapidly from animal manures and crop residues because it is contained in the cell sap. Further, the amount of nutrients contained in organic resources is usually insufficient to sustain required levels of crop productivity and realise the full economic potential of a farmer's land and labour resources.

The ISFM emphasises the importance of optimising the use of organic resources after exploring their opportunity cost (e.g. comparing the retention of organic resources in the field with their use for livestock feed, mulch, or compost production).

Yield improvement is usually greater when organic inputs and fertilisers are applied together. For example, in Sadore, Niger, the yield of millet was increased by about 1.0 t ha^{-1} by adding crop residues and by 1.5 t ha^{-1} by adding fertilisers. When fertilisers and crop residues were applied together, the yield increase was larger and yields increased progressively over the long-term.

11. CONSERVATION AGRICULTURE WITH TREES FOR SMALL HOLDING AFRICAN FARMERS

There are a number of constraints to smallholder adoption of residue mulch that are hindering its more rapid uptake notably which includes competing uses for crop residues where livestock production is common, inadequate biomass accumulation of cover crops in the offseason, increased labour demands for weeding when herbicides are not used, variable yield results across soil types, and the need for greater application of organic and inorganic nutrients [27]. Giller et al. [6] pointed out that most African smallholders are engaged in both crop and livestock production, and that their available fodder resources are usually very inadequate. Therefore, farmers typically use all of their available crop residues for animal fodder or fuel, and cannot afford to retain these valuable materials as a soil cover. This highlights the need to find other ways to increase plant biomass. Garrity et al. [27] addressed the question of producing increasing amount of biomass through integrating fertiliser trees and shrubs into conservation agriculture with tree (CAWT) systems to dramatically enhance both fodder production and soil fertility. Practical systems for intercropping fertiliser trees in maize farming have been developed and are being extended to hundreds of thousands of farmers in Malawi and Zambia [27]. The portfolio of options includes intercropping maize with Gliricidia sepium, Tephrosia candida or pigeon peas, or using trees such as Sesbania sesban as an improved fallow. One particularly promising system is the integration of the Faidherbia albida into crop fields at a 10 m by 10 m spacing. Faidherbia is an indigenous African acacia that is widespread on millions of farmer's fields throughout the eastern, western, and southern regions of the continent. It is highly compatible with food crops because it is dormant during the rainy season. It exhibits minimal competition, while enhancing yields and soil health [28]. Several tonnes of additional biomass can be generated annually per hectare to accelerate soil fertility replenishment, provide additional livestock fodder.

12. THE HAPPY SEEDER AS NO-BURN PLANTING OF WHEAT FOR INTENSIVE SYSTEM OF SOUTH ASIA

Residue mulch technology is emerging as a potential solution to widespread rice residue burning in North Western Indo-Gangetic Plains of India where air pollution has become a serious problem. The agriculture in this part of India is highly intensive and mechanised rice-wheat cropping system where 23 million tonnes (mt) of rice residue burnt every year. Due to serious labour constraint, farmers have been unable to manage the residue other than to burn. However, scientists developed the "Happy Seeder" technology which is a tractor mounted implement that allows no-till and no burn-planting of wheat into fields mulched with rice crop residue [29]. The Happy Seeder with a spreader attached to a Combine Harvester, residue is deposited around the seed as mulch in one simple operation (Fig 7). In addition to removing the need for burning crop residue, the use of Happy seeder lowers energy and water use and improves soil health and carbon sequestration [30].

FIG. 7. Combine harvester (extreme right) is harvesting rice in BISA (Borlaug Institute for South Asia) farm in Ludhiana, India and other four machines are Happy Seeders direct seeding wheat with residue mulch. Source: [29].

13. SUMMARY

Retaining crop residue as soil mulch or soil cover is a proven beneficial soil water management practice which is known to enrich and protect soil and thereby provides better growing environments for a plant or crop. Mulch which is spread on soil surface is mostly organic but sometime also inorganic. An organic mulch includes materials such as crop straw/residue, cut grass, plant clippings, fallen leaves, compost/manure, peat whereas an inorganic mulch could be bark chips, stones, and plastic. In agriculture, mostly crop residue is used as an organic mulch and plastic as an inorganic mulch but in gardens, lawn or yard material such as grass or clippings is used as organic and stones as inorganic. Organic mulch on soil surface helps to (a) conserve and maintain moisture, (b) protects from the soil erosion, (c) maintains a more even soil temperature, (d) reduces weed pressure from preventing weed growth, and (e) improves soil biological, chemical and physical properties. Organic mulches because of slow decomposition builds soil organic matter which helps in enhancing the efficiencies of added inputs such as water, and nutrients. These multiple beneficial effects of residue mulch are known to increase crop yields on short to long-term basis. However, there are many limitations to its widespread adoption which includes competition with other usages of crop residue, labour intensive nature and need of customised crop management practices. For these reasons, residue mulch is not likely to have widespread adoption. In agriculture, there seems to be two niches where residue mulch holds promise: (a) in subsistence rain-fed agriculture including SSA where labour availability is relatively not yet a serious constraint and synthetic fertilisers are not readily available, and (b) in intensive mechanised agriculture for example South Asia where residue supply exceeds demand and is therefore burnt causing environmental pollution, mulch will be a solution.

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ABBREVIATIONS AND ACRONYMS

AE	Agronomic efficiency
AE_N	Agronomic efficiency of applied N
Al	Aluminium
ANI	Added nitrogen interaction
ANOVA	analysis of variance
BASICS	Building a Sustainable, Integrated Seed System for Cassava
Bρ	Bulk density
BE	biomass efficiency
C	Carbon
Ca	Calcium
CA	Conservation Agriculture
CAWT	conservation agriculture with tree
CH_4	Methane
CIAT	International Centre for Tropical Agriculture
cm	centimeter
CO	Carbon monoxide
CO_2	Carbon Dioxide
CR	crop residue
CRM	crop residue mulching
CRP	coordinated Research Project
CT	Conventional tillage
CTCRI	Central Tuber Crops Research Institute
CTR	conventional tillage with residue
CTW	conventional tillage without residue
Cu	Cupper
cv.	Cultivar
DAS	day after sowing
df	degree of freedom
DM	Dry matter
DW	dry weight
ECe	Electrical conductivity
FAO	Food and Agriculture Organization of United Nations
FBWt	Fresh bulk weight
Fe	Iron
F_N	amount of (fertiliser) N applied
FNUE	Fertiliser N use efficiency
FYM	Farm yard manure
FW	fresh weight
g	gram
GHGs	Greenhouse gases
H	Hydrogen
ha	hectare
HCN	Hydrogen cyanide
HI	harvest index
HQCF	High quality cassava flour
H_2O	water
IAEA	International Atomic Energy Agency
IITA	International Institute of Tropical Agriculture
IPCC	International Panel on Climate Change

IPM	Integrated pest management
ISFM	Integrated Soil Fertility Management
K	Potassium
KCL	Potassium chloride
Kg	Kilogram
K_2O	Potassium chloride
LR	Long Rains
LR13	Long rains 2013
LR14	long rains season 2014
LS	Loamy sand
LSD	least significant difference
MAP	Month after planting
m	Million
mm	millimeter
M	Mulch, Mulched
mg	milligram
Mg	Magnesium
mha	million hectare
Mn	Manganese
mt	million tonnes
MT	minimum tillage
MTR	minimum tillage with residue
MTW	minimum tillage without residue
N	Nitrogen
na	not applicable
NAQS	National Agricultural Quarantin Services
Ndff	N derived from fertiliser
NH_3	Ammonia
NO_X	Knox, a mixture of ammonia, nitric oxide and nitrous oxide
N_2O	Dinitrogen monoxide
NPK	Nitrogen, phosphorus and potassium fertiliser
NRCRI	Nigerian Root Crops Research Institute
ns	not significant
NT	No tillage
NUE	Nitrogen use efficiency
P	Phosphorus
PE	physiological efficiency
PE_N	Physiological efficiency of applied N
pH	measure of acidity or alkalinity of a solution
PM	particulate matter
PPD	Postharvest physiological deterioration
PVC	Polyvinyl chloride
RCB	Randomised Complete Block
RCBD	randomised completed block design
RE	Recovery efficiency
RE_N	Apparent recovery of applied N
RF	Ridges and furrows
RT	Reduced tillage
RTB	Research Program on Roots, Tubers and Bananas
SaCL	Sandy clay loam
SaL	Sandy loam

SDWt	Subplot dry weight
SFWt	Subplot fresh weight
SO_2	Sulfur dioxide
SOC	Soil organic carbon
SOM	Soil organic matter
SR	Stratification ratios
SR	Short Rains
SR13	Short rains season 2013
SR14	Short rains 2014
SSA	Sub-Sahara Africa
SSNM	Site specific nutrient management
SWMCN	Soil and Water Management & Crop Nutrition
t	tonne
TSP	Triple Superphosphate
U_0	Total N in aboveground biomass at maturity in a plot that receivedno N
U_N	Total plant N in aboveground biomass at maturity in a plot thatreceived N
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCC	United Nations Framework Convention on Climate Change
v	volume
VOC	volatile organic compounds
W_d	Soil water concentration
WHO	World Health Organization
WSA	water stable aggregates
Y_0	crop yield in a control treatment with no N
Y_N	crop yield with applied N
Zn	Zinc
ZT	Zero tillage, zero-till
°C	degrees centigarde
°N	degrees north of the earth's equatorial plane

CONTRIBUTORS TO DRAFTING AND REVIEW

Akplo, T.M.	Faculté des Sciences Agronomiques, Université d'Abomey-Calavi, Bénin
Chikwari, E.	Chemistry and Soil Research Institute, Zimbabwe
Chipangura, T.	Chemistry and Soil Research Institute, Zimbabwe
Gotosa, J.	Bindura University of Science Education, Zimbabwe
Hashmi, Z.H.	Nuclear Institute for Agriculture & Biology, Pakistan
Heng, L.K.	International Atomic Energy Agency, Austria
Hountongninou, A.	Faculté des Sciences Agronomiques, Université d'Abomey-Calavi, Bénin
Houngnandan, P.	Faculté des Sciences Agronomiques, Université d'Abomey-Calavi, Bénin
Ishaque, W.	Nuclear Institute for Agriculture & Biology, Pakistan
Kouelo Alladassi, F.	Faculté des Sciences Agronomiques, Université d'Abomey-Calavi, Bénin
Ladha, J.K.	International Rice Research Institute (IRRI), Philiphines
Mahmood, T.	Nuclear Institute for Agriculture & Biology, Pakistan
Malek, F.	Pakistan Institute of Nuclear Science & Technology, Pakistan
Manyanga, A.	Chemistry and Soil Research Institute, Zimbabwe
Mapanda, F.	University of Zimbabwe, Zimbabwe
Mhaka, L.	Chemistry and Soil Research Institute, Zimbabwe
Mucheru-Muna, M.W.	Kenyatta University, Kenya
Mugendi, D.N.	Embu University College, Kenya
Mugwe, J.N.	Kenyatta University, Kenya
Mukungurutse, T.	Chemistry and Soil Research Institute, Zimbabwe
Ngetich, F	Embu University College, Kenya
Njogu-Murithi, E.W.	Embu University College, Kenya
Nyapwere, N.	Chemistry and Soil Research Institute, Zimbabwe
Rabeharisoa, L.	Université d'Antananarivo, Madagascar
Rabenarivo, M.	Université d'Antananarivo, Madagascar
Riaz, M.A.	Nuclear Institute for Agriculture & Biology, Pakistan
Taassob-Shirazi, F.	Consultant, Austria
Zaman, M.	International Atomic Energy Agency, Austria

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