Effectiveness of conservation agriculture in increasing crop productivity in low-input rainfed rice cropping systems under humid subtropical climate

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ABSTRACT

Since the early 2000s conservation agriculture (CA) has been promoted in the Lake Alaotra region of Madagascar for a more sustainable and profitable agriculture. There is, however, little known about its performance in low-input rainfed rice-based cropping systems. We conducted a study during two growing seasons (2013/14 and 2014/15) on an experiment that was established in 2009 at the agricultural research station of the National Center for Applied Research and Rural Development (FOFIFA) in the Lake Alaotra region of Madagascar. The experimental setup was a randomized block design with four replications. Two soil/residue management treatments were studied, conventional tillage without residue retention (CT) and no-tillage with residue retention (NT). These two treatments were tested for a 2-year rotation of maize + *Dolichos lablab* followed by rice (MD//R) and a 3-year rotation maize + *Stylosanthes guianensis*, followed by *S. guianensis* in the second year, and rice in the third year (MS//S//R). During the 2013/14 and 2014/15 seasons, two levels of weed pressure:

‘high’ and ‘low’ were introduced as a split-plot design on the rice plots. The main determining factors of rice yield in the study region were studied: radiation interception, weed infestation, soil moisture and soil mineral nitrogen (N). Our results showed that five to six years of continuous practice of NT with retention of high amounts of crop residues (more than 5 Mg DM ha^{-1}) on the soil surface had a significant ($p = 0.02$) positive effect on rice yield, irrespective of the level of weed pressure and type of crop rotation. CA systems significantly ($p < 0.05$) reduced weed density and biomass as compared to CT particularly during the vegetative stage of the rice crop in the two growing seasons, which to a certain extent explained the yield gains under CA. In contrast, treatment effects on soil moisture and mineral N contents were marginal. The positive effects of CA on reduced weed pressure may constitute an important benefit for smallholder farmers in regions such as Lake Alaotra, who face labour constraints with hand weeding, and usually cannot afford herbicides for weed control.

Keywords: Conservation agriculture; crop residue mulch; no-tillage; soil nitrogen; weeds

Highlights:

- The practice of CA with crop residue amounts of more than 5 Mg DM ha^{-1} has a positive effect on rainfed rice yield.
- CA reduces weed pressure in low-input rainfed rice systems.
- Rice yield gains under CA can be partly explained by the effects on weed infestation.
- Marginal effects of CA on soil moisture and mineral N during the rice growing season were observed.

1. Introduction

The Lake Alaotra region is one of the primary rice (*Oryza sativa*) producing areas of Madagascar. With more than 120 000 ha of rice fields, it provides about 13% of Madagascar's total rice production. The annual rice production in this region varied from 320 000 to 500 000 tons between 2008 and 2016, mainly depending on the amount and distribution of seasonal rainfall (FAO 2013, 2015a). In the early 1980s, the government introduced reforms in the rice sector aimed at increasing domestic rice production. This led to an expansion of rainfed rice cultivation into the upland areas, given the limited availability of land in the irrigated plains (Domas et al. 2008). Rainfed agriculture in the Lake Alaotra region is however constrained by low soil fertility, soil water stresses due to suboptimal rainfall and severe weed pressure, resulting in low rice productivity, that is, on average 2000 kg ha^{-1} compared to 4500 kg ha^{-1} for irrigated rice (FAO/UPDR 2000; Penot et al. 2009).

Conservation agriculture (CA) was introduced in Madagascar in the early 2000s to cope with the above constraints and to enhance crop productivity in the rainfed areas. Conservation agriculture is based on three principles: minimal soil disturbance, permanent soil cover and diversification of crop species grown in rotations and/or associations (FAO 2015b). The practice of CA can increase crop yields through a set of agro-ecological functions that are related to its principles (Ranaivoson et al. 2017). In low-input rainfed cropping systems of smallholders, it is expected that yield gains from the practice of CA depend to a large extent on its effects on soil water, soil mineral nitrogen (N) and weed dynamics.

It is generally known that CA can preserve soil moisture for increased crop water transpiration by increasing soil water infiltration and reducing evaporation and runoff (e.g. Hobbs 2007; Scopel et al. 2004). These effects may increase crop yields, especially in dry climates or during weather with dry spells. On the other hand, under high rainfall mulching with crop residues can lead to waterlogging, especially in poorly drained soils (Sissoko et al.

2013). Retention of crop residues on the soil surface in CA systems can also enhance soil nutrient cycling and availability (e.g. Iqbal et al. 2011; Turmel et al. 2014). Residue decomposition releases nutrients to the soil and increasing amounts of surface residues are expected to improve soil nutrient content, at least in the long term. In the short term, however, the use of cereal residues as mulching material leads to immobilization of soil mineral N that may cause N deficiency to the crop, especially in low-input cropping systems, resulting in lower yields (e.g. Beri et al. 1995; Govaerts et al. 2006).

Weed control remains one of the greatest challenges to the practice of CA on smallholder farms with low inputs (Lee and Thierfelder 2017). It has been argued that weed pressure in CA cropping systems increases as a result of eliminating soil tillage as a management practice to control weeds (Giller et al. 2009; Chauhan et al. 2012). Tillage physically removes weeds and may bury some weed seeds into deeper soil layers, thereby limiting their exposure to favorable germination conditions (Nakamoto et al. 2006). Besides, the presence of a mulch layer in CA systems can interfere with chemical and physical methods of weed control, lowering their efficacy (Bajwa 2014). Some studies, however, suggest that CA can reduce weed infestation through the mulch of crop residues that acts as a physical barrier to weed growth (e.g. Teasdale and Mohler 2000; Bilalis et al. 2003; Campiglia et al. 2012; Ranaivoson et al. 2018). It is recognized that effective mulch amounts for weed control are relatively high but vary widely depending on the agro-ecological conditions.

The objective of this study was to determine the effectiveness of CA in alleviating the major limiting factors for rice yield under low-input rainfed conditions in a humid subtropical climate. We, therefore, studied the dynamics of radiation interception, soil water content, mineral N content and weed infestation during the rice growing season under no-tillage with residue retention (NT) versus conventional tillage (CT) in two different crop rotations.

2. Materials and methods

2.1. Study site

The study was carried out during two growing seasons, 2013/14 and 2014/15, on a field experiment that was established in 2009 at the experimental station of the National Center for Applied Research and Rural Development (FOFIFA) located at Ambohitsilaozana in the Lake Alaotra region of Madagascar (17°30'S, 48°30'E, 780 m a.s.l.). The region has a humid subtropical climate, Cfa (Köppen classification) with mean seasonal rainfall of 1040 mm and mean annual temperature of 22°C (recorded data from 2004/05 to 2014/15). The soil of the experimental site was classified as an Orthic Ferralsol (FAO classification). At the start of the experiment in September 2009, soil samples were collected at eight randomly selected points in the experimental field from the 0-10, 10-20, 20-30, 30-60 and 60-90 cm layers for determination of selected physico-chemical properties (Table 1). Clay, silt and sand particles were isolated by successive sedimentation-decanting cycles (Christensen 1992). Soil pH (H_2O) was measured using a glass electrode (Kalra 1995). Available phosphorus (P) was determined by the Olsen method (King 1932), cation-exchange capacity (CEC) by the cobaltihexamine chloride method (Aran et al. 2008) and organic carbon (C) by the Walkley and Black method (Walkley and Black 1934).

2.2. Rainfall

Rainfall was recorded at the experimental site using an automatic CimAGRO weather station (CIMEL Electronique, Paris, France). Cumulative seasonal rainfall in 2014/15 (1348 mm) was almost double of that in 2013/14 (757 mm) (Figure 1). The date of first rains occurred at the end of November in both growing seasons. The 2014/15 season was characterized by regular heavy (>40 mm day^{-1}) rainfall events which occurred from December 2014 to March

2015, whereas during 2013/14 they only occurred from mid-January to the end of February 2014.

2.3. Experimental design

The experiment was established in 2009 and conducted for six consecutive years on a field that had been fallow for several years. The experimental layout was a completely randomized block design with four replicates of two soil tillage/residue management treatments: (1) conventional tillage without crop residue retention (CT); and (2) no-tillage with residue retention on the soil surface (NT), combined with two crop rotation treatments: (1) a 2-year rotation of maize (*Zea mays*) + *Dolichos lablab*, followed by rice (MD//R), and (2) a 3-year rotation of maize + *Stylosanthes guianensis*, followed by *S. guianensis* in the second year, and rice in the third year (MS//S//R). The NT treatment applied along with the crop rotations represents the practice of CA. Each crop of the 2- and 3-year rotations was grown every year as schematically represented in Figure 2. The individual plot size measured 100 m² (10 x 10 m).

Tillage under CT consisted of plowing to a depth of 15 to 20 cm using the "*angady*", a hand-ploughing tool, whereas land preparation under NT consisted of manual mowing of standing crop biomass from the previous year, without any soil tillage.

Our study was carried out during the fifth (2013/14 season) and sixth (2014/15 season) year of experiment on the plots grown with rice. Each of these plots was subdivided into two subplots corresponding to two levels of weed pressure: a subplot with 'low' weed pressure (LW) resulting from three timely hand-weeding operations, and a subplot with 'high' weed pressure (HW) in which weeding was delayed as compared to the LW plots (Table 2). Each subplot in this split-plot design measured 50 m² (10 x 5 m).

The rice cultivar used was B22, a short-duration (120 days) upland rice variety from the Brazilian Agricultural Research Corporation (EMBRAPA) that is adapted to the agro-ecological conditions of the Lake Alaotra region. The dates of rice sowing, weeding and harvest are summarized in Table 2. Rice was sown manually using a planting stick in both the CT and NT treatments, with an inter-row spacing of 40 cm and intra-row spacing of 20 cm. No fertilizer, herbicides or insecticides were applied.

2.4. Agronomic measurements

2.4.1. *Crop residue biomass*

Standing crop biomass from the previous season that was used as residue cover in the NT plots was estimated before sowing of the rice crop in October 2013 and 2014. Measurements were done on four quadrats of 1 m^2 (1 x 1 m) in all subplots (50 m^2) under NT. Plants were cut at ground level, oven-dried at 70°C for 48 hours and weighed to obtain dry matter (DM).

2.4.2. *Rice grain yield*

All rice panicles were collected manually from the whole subplots (50 m^2) and hand-threshed by stripping the spikelets from the panicles. Unfilled spikelets were removed and filled spikelets were weighed to estimate grain yield. Moisture content of filled spikelets was determined by oven-drying at 70°C for 48 hours. Grain yield was adjusted to 14% moisture content on oven dry basis.

2.4.3. *Radiation interception*

Photosynthetically active radiation (PAR) was measured using a SW-11L PAR line sensor (S.W. & W.S. Burrage, Ashford, UK) by placing a control bar above the rice canopy and a second bar below the canopy above the ground. The ratio between the photosynthetic photon flux density (µmol photons m^{-2} s^{-1}) under and above the canopy determined the proportion of

PAR (%) intercepted by the rice canopy. Measurements were done on four quadrats of 1 m² (1 x 1 m) in each subplot (50 m^2) during the 2014/15 growing season at four development stages of rice, corresponding to tillering (S2), panicle initiation (S3), flowering (S4) and maturity (S5). Three measurements per quadrat were done by placing bars parallel, perpendicular and intersecting to the rice rows.

2.4.4. ***Weed density and biomass***

Following the method used by Teasdale and Mohler (2000) emerged weed seedlings were counted and removed every week during the 2013/14 and 2014/15 rice growing seasons in two replicate quadrats of 0.5 x 0.5 m in the HW subplots. Dicots and monocots were counted separately. Cumulative density of emerged weed seedlings [weed density (number m^{-2})] on a given date was calculated by taking the sum of all emerged weed seedlings from the first measurement to the date.

Weed biomass was measured in the HW subplots at each weeding event (Table 2) and at rice harvest in four replicate quadrats of 1 m² (1 x 1 m) in 2013/14 and 2014/15. Aboveground biomass was cut at soil level and oven dried at 70°C for 48 hours to obtain dry matter content. Dicots and monocots were measured separately. Cumulative weed biomass (Mg DM ha^{-1}) on a given date was calculated by taking the sum of all weed biomass measured from the first weeding to the date.

2.4.5. ***Soil water***

The TRIME-PICO IPH TDR probe (SDEC, Reignac Sur Indre, France) was used for soil water measurements. One access tube was installed per subplot (50 m^2) and volumetric soil moisture content (mm) was determined weekly during the 2014/15 rice growing season. Measurements were done at every 10 cm up to 2 m soil depth. The calibration of the probe was done on tubes installed aside the experimental field by comparing probe measurements with volumetric soil water contents that were calculated from gravimetric soil water and soil bulk density measurements. Calibration equations were established for each 10 cm soil depth interval.

2.4.6. ***Soil mineral nitrogen***

Soil sampling for mineral N was done in 2013/14 and 2014/15 at five development stages of rice: emergence (S1), tillering (S2), panicle initiation (S3), flowering (S4) and maturity (S5) during both growing seasons. At each stage, soil was sampled from the following depth intervals: 0-10, 10-20, 20-30, 30-60 and 60-90 cm in five locations of each subplot. Composite samples from the five locations were placed in plastic bags and stored in a freezer at -4 ^{o}C. Ammonium and nitrate were extracted from soil with 2 N KCl solutions by shaking the suspension for 1 hour (30 g soil per 100 ml of solution). Samples were allowed to decant for one hour before recovering the supernatant using a syringe. The supernatant was then filtered with a 0.2 µm Millipore filter (Merck, Damstadt, Germany) and stored in a sterile tube before analysis. A subsample of the soil sample (50 g) was oven dried at 105°C for 48 hours to determine the dry weight of the extracted soil. Nitrate-N concentration was determined using the colorimetric cadmium reduction and the Griess-Ilosvay reaction (Henriksen and Selmer 1970) and ammonium-N concentration using the indophenol blue method (Anderson and Ingram 1989).

Mineral N content (the sum of nitrate and ammonium, kg N ha^{-1}) of a particular soil layer was calculated from the nitrate- and ammonium-N concentrations of the corresponding soil samples and using the soil bulk density value of the soil layer, that was measured by collecting undisturbed soil cores (502 cm^{3}). The core samples were oven dried at 105°C for 48 hours and weighed. Total mineral N content in the 0-90 cm soil layer was determined by taking the sum of the contents of all individual soil layers. The missing data at S2 and S3 in 2014/15 was due to an external contamination of the extracts with ammonium.

2.5. Data analysis

Rice yield, radiation interception by the rice canopy, weed density, weed biomass, soil water and soil mineral N contents were subjected to analysis of variance (ANOVA) for linear mixed effects models for split plot design data. Experimental treatments (soil tillage/residue management, crop rotation, level of weed pressure), block and season, and their two-, and three- way interactions were considered as fixed effects, whilst the interaction season x block x crop rotation x soil tillage/residue management was considered as the split-plot random effect. The means of treatments were compared using the Tukey's honestly significant difference test (HSD). Statistical analyses were done with R software (R-3.5.1) using the packages lmerTest (Kuznetsova et al. 2016) for tests of linear mixed effects model fits, and agricolae (De Mendiburu 2016) for Tukey's HSD tests.

3. Results

3.1. Crop residue biomass in the no-tillage, NT, treatment

The amount of residue biomass from the previous crop in the NT plots, measured in October before rice sowing, was significantly higher in 2014 than in 2013 ($p < 0.01$) irrespective of the type of crop rotation (Figure 3). Residue biomass amounted to 7.68 Mg DM ha^{-1} in October 2014 (average for the two types of residue), against 5.02 Mg DM ha^{-1} in October 2013. No significant ($p > 0.05$) differences between type of crop rotation were observed (Figure 3).

3.2. Rice grain yield

Rice grain yield was significantly ($p = 0.02$) higher under NT than CT irrespective of the growing season, level of weed pressure and crop rotation (Table 3). Besides, as expected, the level of weed pressure treatment (LW versus HW) had a significant ($p < 0.001$) effect on yield irrespective of growing season, crop rotation and soil tillage/residue management.) Yield was on average 811 and 895 kg ha^{-1} higher under LW than HW, respectively in the CT and NT treatment (Figure 4).

3.3. Radiation interception by the rice canopy

ANOVA results showed that crop rotation, soil tillage/residue management and the level of weed pressure had significant effects on radiation interception at panicle initiation (S3, 77 days after seeding, DAS), flowering (S4, 94 DAS) and maturity (S5, 123 DAS) of rice. At tillering stage (S2, 66 DAS), only crop rotation showed a significant effect ($p < 0.05$) (Table 4).

3.4. Weed infestation in the high weed pressure, HW, treatment

3.4.1. Weed density

ANOVA results showed significant effects of soil tillage/residue management on the cumulative weed density at the end of rice growing season. The density of all weeds ($p < 0.01$), monocots ($p = 0.02$) and dicots ($p = 0.02$) was significantly lower under NT than CT (Table 5) irrespective of growing season and crop rotation. A significant effect of the interaction of growing season and crop rotation was also observed for total and dicot weeds ($p = 0.02$). The 3-year rotation had lower weed densities than the 2-year rotation in 2013/14, whereas there was no significant ($p > 0.05$) difference between the two crop rotations in 2014/15.

3.4.2. Weed biomass

In 2013/14, cumulative total weed biomass was significantly ($p < 0.05$) lower under NT than CT at the first weeding (43 DAS) under MS//S//R, whereas there was no significant ($p > 0.05$)

effect of soil tillage/residue management under MD//R (Figure 5a). At the second (74 DAS) and the third measurement (117 DAS), cumulative total weed biomass was significantly ($p < 0.05$) lower under NT than CT, and under MS//S//R than MD//R. In 2014/15, cumulative total weed biomass did not significantly ($p > 0.05$) differ between MD//R and MS//S//R at all weeding dates. Furthermore, there was no significant ($p > 0.05$) difference between NT and CT at the first (26 DAS), third (105 DAS) and fourth (122 DAS) measurement. In contrast, at the second weeding (65 DAS), cumulative total weed biomass was significantly ($p < 0.05$) higher under CT than NT (Figure 5b). Observed trends for monocot weed biomass were similar as for the total weed biomass (Figure 5c,d). Dicot weed biomass was significantly ($p < 0.05$) higher under MS//S//R than MD//R in 2013/14 at all weeding dates, whereas no significant ($p > 0.05$) treatment effect was found in 2014/15 (Figure 5e,f).

3.5. Soil water content

Figure 6 shows the seasonal dynamics of soil water content for the CT and NT treatments during the 2014/15 rice growing season, averaged over the crop rotation and weed pressure treatments that had no significant ($P > 0.05$) effect on soil water content. The rainfall pattern shaped the soil water dynamics, with a large increase of soil water content from 10 DAS onwards for both treatments (Figure 6). Soil tillage/residue management had a significant ($p < 0.05$) effect on soil water content in the upper soil layers (0-20 cm and 0-40 cm) at 23 and 30 DAS (Figure 6a,b). On the other hand, soil water content in the 0-60 cm and 0-150 cm layers showed no significant ($p > 0.05$) differences between the CT and NT treatments throughout the rice growing season (Figure 6c,d).

3.6. Soil mineral nitrogen dynamics

Mineral N content (0-90 cm) decreased during the rice vegetative phase in the two growing seasons with a larger decrease in 2014/15 than in 2013/14 (Figure 7 for the LW treatment). Mineral N increased at S4 and then decreased until S5 in 2013/14, whereas it showed a continuous decline until S4, and then increased slightly in S5 in 2014/15. In 2013/14, there were no significant ($p > 0.05$) treatment effects on mineral N content in the 0-90 cm soil layer at S1, S2, S3 and S4, whilst at S5 a significant ($p < 0.05$) effect of the weed pressure and crop rotation treatments was observed (Supplementary Materials, Table S1). In 2014/15, the 3-way interaction of weed pressure, crop rotation and soil tillage/residue management were significant ($p < 0.01$) at S1. Under LW, NT with MS//S//R showed higher soil mineral N content as compared to CT (Figure 7b), whilst under HW there was no significant ($p > 0.05$) 2-way interaction of crop rotation and soil tillage/residue management (Supplementary Materials, Table S1). At S4, CT showed significantly ($p < 0.05$) higher soil mineral N contents as compared to NT. There were no significant ($p > 0.05$) treatment effects at S5 (Supplementary Materials, Table S1). Ammonium which accounted for most of the soil mineral N in 2013/14 showed the same patterns as total mineral N with higher contents under MS//S//R than MD//R, and under LW than HW at S5 (Supplementary Materials, Table S2). In 2014/15, treatments had no significant ($p > 0.05$) effect on ammonium contents at S1, S4 and S5. In 2013/14, nitrate content was significantly ($p < 0.05$) higher under LW than HW at S1 (Supplementary Materials, Table S3). There were no treatment effects ($p > 0.05$) at S2, S3, S4 and S5 (Figure 7). In 2014/15, the 3-way interaction of weed pressure, crop rotation and soil tillage/residue management were significant ($p < 0.01$) at S1. Under LW, nitrate content was higher under NT than under CT in case of MS//S//R (Figure 7d), whilst under HW the 2-way interaction of crop rotation and soil tillage/residue management was not significant ($p > 0.05$).

4. Discussion

Effect of CA on rice grain yield

In our study, CA (NT treatments in combination with a 2- or 3-year crop rotation) had a positive effect on rice growth (as observed through PAR interception measurements, Table 4) and grain yield (Table 3). This is in agreement with findings from other studies with rainfed rice (Saito et al. 2006; Nascente and Stone 2018). In these studies, medium-term yield benefits were mainly explained by the positive effects of CA on soil organic matter and soil nitrogen availability, whilst short-term benefits were attributed to effects on soil physical changes affecting soil water and air flows.

In our study, the practice of CA had little to no effect on soil water and soil mineral N dynamics (Figure 6, Figure 7) that were largely influenced by rainfall amount and its distribution during the cropping season. Instead, yield gains in the CA treatments could to a certain extent be explained by the reduction of weed infestation. Weed density and subsequent weed biomass were lower under NT compared to CT during the vegetative stage of rice growth in the two growing seasons of the experiment (Table 5, Figure 5). Weeds compete with rice for the limited resources, such as radiation, water and nutrients, and this can induce important yield losses (Oerke 2006). As expected, in our study rice yields were higher under low weed pressure than under high weed pressure conditions irrespective of crop rotation and soil management (Table 3). We found a significant ($r^2=0.239$, $p < 0.005$) negative relationship between rice grain yield and the cumulative weed biomass at the time of the second weeding (Figure 8). The second weeding was carried out 74 and 65 days after rice sowing, respectively in 2013/14 and 2014/15, which corresponds to the end of the vegetative stage of rice growth. Cumulative weed biomass up to this stage is a good indicator of the rice-weed competition for resources, since it is during this stage that resource requirements by the rice crop are highest. The critical period of weed competition for rainfed rice is usually defined as the period from

17 to 53 days after sowing (Micheal et al. 2013). It has been found that tillering, and consequently potential number of panicles of rice, are very sensitive to weed competition during this critical period (Moreau 1987).

The positive effect of CA on rice yield occurred, however, also in the low weed pressure treatment that received timely hand-weeding operations (Figure 4, Table 3). This finding suggests that yield benefits from CA systems are the results of effects on other crop production factors. CA is known to improve soil structure resulting in better aeration and water drainage, thereby facilitating root growth and access to soil moisture and nutrients (Smets et al. 2008). Less compacted soils, i.e with lower soil bulk density, may enhance growth of rainfed rice (Guimarães and Moreira 2001). Besides, the practice of CA may improve the supply of other nutrients than soil N, such as available potassium and phosphorous (Pradhan et al. 2011; Iqbal et al. 2011; Feng et al. 2014). Some reports have also stated that the practice of CA can reduce densities of the rice cyst nematode, *Heterodera elachista* (Ito et al. 2015), and limit the adverse effects of blast disease caused by *Magnaporthe oryzae* (Dusserre et al. 2017).

Effect of CA on weed infestation

The observed reduction of weed density under CA can be attributed to the mulch of crop residues, which amounted to 5 Mg DM ha^{-1} and 8 Mg DM ha^{-1}, respectively in 2013/14 and 2014/15. It is known that surface crop residues form a physical barrier to seedling emergence (Teasdale and Mohler 1993; Bilalis et al. 2003). Reduced weed density under CA is also linked with lower light transmittance and day-time soil temperature in the upper layer of mulched soils (Mohler and Teasdale 1993). Besides, some reports suggest that decomposition of crop residues, such as those from pearl millet, brachiaria and rye, releases allelopathic substances that inhibit weed emergence and development (e.g. Gavazzi et al. 2010; Oliveira Jr et al. 2014). Finally, the absence of tillage in CA systems has an effect on the vertical distribution of weed seeds in the soil profile that affects their germination rate and predation by granivores (Bajwa 2014; Nichols et al. 2015). No-tillage restrains redistribution of weed seeds to the top zero to five centimeters of soil and tends to leave more weed seeds on the soil surface (Swanton et al. 2011). While the likelihood of seed desiccation and predation is larger at the soil surface than at deeper soil depths, weed seeds within the upper five centimeters of soil are also exposed to more favorable germination conditions (Chauhan et al. 2012). As a result, small-seeded weed species that are more dependent on light for germination than large-seeded species will likely become the dominant species in CA systems (Chauhan et al. 2006). In our study, the relative weed density of monocots versus dicots did not change between CT and NT (Table 5). Some studies reported a shift in weed community with the conversion of CT to NT, from mostly annual species to perennial ones, thereby increasing the challenge of weed control in CA systems (e.g. Trichard et al. 2013; Bajwa 2014; Rafenomanjato 2018).

Our study also showed that practice of NT with crop residue mulching generally decreased total weed biomass as compared to CT, particularly during the vegetative stage of rice (Figure 5). This can be explained by the unfavorable environment for weed growth that is created below the mulch of crop residues. Surface crop residues induce a shading effect that reduces light and soil temperature affecting weed growth (Teasdale and Mohler 1993). This shading effect is most pronounced when the crop canopy is not fully developed. Finally, the CA effect on weed biomass could partly also be attributed to an indirect effect via the rice canopy. Light interception, thus shading, by the rice canopy from rice panicle initiation to rice harvest was significantly higher under NT than CT, which may also have affected weed growth (Table 4).

The effect of CA on weed biomass varied, however, across the two cropping seasons. Weed biomass under NT was lower as compared to CT throughout the rice growing in 2013/14, while this effect was only observed at the start of the season in 2014/15. This was consistent with the results of Mhalanga et al. (2017) who showed that the suppressive effect of CA on weed growth depends on rainfall amount and its distribution during the cropping season. Indeed, the absence of treatment effect from the third weed biomass measurement onwards in 2014/15 can probably be related to the continuous rainfall which accelerated residue decomposition leading to a relative rapid disappearance of the physical barrier created by the mulch. Additionally, moisture of the topsoil was around field capacity for most of the cropping season during 2014/15 (Figure 6), which is a favorable condition for weed development (Calado et al. 2009). Other studies have observed that continuous rainfall promotes weed infestation irrespective of the type of soil tillage and residue management (Chauhan et al. 2012).

Effect of CA on soil water content

Crop residues retained on the soil surface enhance soil water infiltration and reduce water losses from soil evaporation and runoff, thereby contributing to conservation of soil water for increased crop uptake (Scopel et al. 2004; Verhulst et al. 2011; Ranaivoson et al. 2017). Observed CA effects in 2014/15 on soil water content as a result of mulching (NT versus CT) were, however, marginal in our study, most probably because of high rainfall. The seasonal rainfall in 2014/15 was about 40% higher than the average rainfall for the past 20 years. In our experiment, continuous rainfall from 30 DAS onwards in 2014/15 resulted in high soil water contents throughout the soil profile irrespective of the experimental treatments (Figure 6). Consequently, it can be assumed that there was no water stress on rice growth, and thus no mulching effects on rice yields through moisture conservation. This is consistent with the findings of Bruelle et al. (2017) for the same region. These authors showed through a crop growth modeling analysis that the effect of residue cover on crop yields was minor in situations with high rainfall and on soils with high water holding capacity.

Effect of CA on soil mineral nitrogen dynamics

The practice of CA had generally a small effect on soil mineral N dynamics in our study. Overall, mineral N contents in the soil of the experiment were high, i.e. up to 200 kg N ha^{-1} in the 0-90 cm soil layer at the start of the season, irrespective of the treatments (Figure 7). Therefore, it may be assumed that rice growth was generally not limited by soil N supply (in both the CT and NT treatments in both crop rotations). Although positive effects of CA on soil mineral N contents have been frequently reported (e.g. Lal 2009; Turmel et al. 2014), other studies also found no effects (Karlen et al. 1994; Maltas et al. 2009; Iqbal et al. 2011).

In our study, N supply from residue decomposition, calculated from the decomposition rates observed in litter bag experiments (data not shown) and the initial N concentrations of the residues, is estimated at about 60 and 150 kg N ha^{-1} respectively for 2013/14 and 2014/15. These amounts were, however, not retrieved in the soil mineral N measurements as they were probably taken up by the crop or lost by leaching. For instance, the observed decrease of mineral N during the rice growing season in 2014/15 was related to plant N uptake, and nitrate leaching. The latter could be inferred from the observed accumulation of nitrate in the 60-90 cm soil layer (Supplementary Materials, Figure S1). The more pronounced decrease of soil mineral N under NT as compared to CT in 2014/15 could probably be explained by the increased plant N uptake as a result of the higher rice yields, and by more pronounced N leaching resulting from higher water infiltration and drainage under residue cover in CA (Scopel et al. 2004; Ranaivoson et al. 2017).

5. Conclusions

Overall, our study showed that five to six years of continuous CA practice with high amounts of crop residues retained on the soil surface (5 to 8 Mg DM ha^{-1}) had a positive effect on yields of rainfed rice. This effect could to a certain extent be attributed to the reduced weed pressure under CA. No-tillage with crop residue mulching reduced weed density and weed biomass from seedling up to vegetative stage of the rice crop as compared to the practice of CT. Soil water contents were not affected by CA because of the high seasonal rainfall, leading to low water stress on growth and yield of the rice crop. Moreover, CA had limited effects on soil mineral N contents during the rice growing season, and due to the high initial soil mineral N content no effect on rice yield was observed.

The positive impact of a CA system with high residue cover from cover crops on weed pressure may constitute an important benefit for smallholder farmers in regions such as Lake Alaotra, who face labour constraints with hand weeding, and usually cannot afford herbicides for weed control. It remains to be seen whether farmers will be able to produce and retain large amounts of crop residues on their field.

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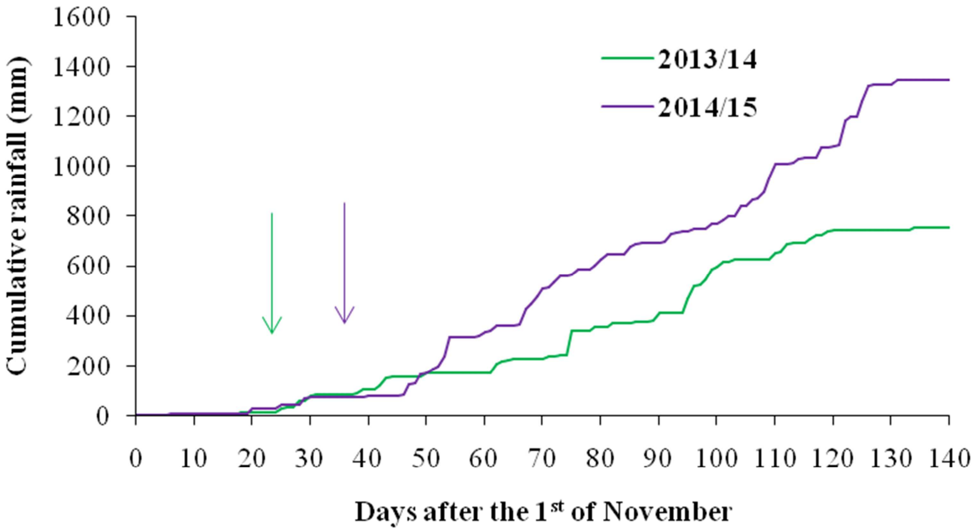

Figure 1: Cumulative rainfall (mm) at the experimental site during the 2013/14 and 2014/15 rice growing seasons. Arrows indicate the sowing dates of rice in the experiment.

Treatments		2009/10	2010/11	2011/12	2012/13	2013/14	2014/15
CT	2-year rotation (MD//R)	MD	R	MD	R	MD	R (LW) / R (HW)
		R	MD	R	MD	R (LW) / R (HW)	MD
	3-year rotation (MS//S//R)	MS	S	R	MS	S	R (LW) / R (HW)
		S	R	MS	S	R (LW) / R (HW)	MS
		R	MS	S	R	MS	S
NT	2-year rotation (MD//R)	MD	R	MD	R	MD	R (LW) / R (HW)
		R	MD	R	MD	R (LW) / R (HW)	MD
	3-year rotation (MS//S//R)	MS	S	R	MS	S	R (LW) / R (HW)
		S	R	MS	S	R (LW) / R (HW)	MS
		R	MS	S	R	MS	S

Figure 2: Schematic representation of the experimental treatments and plots (crops in the rotations) from 2009/10 to 2014/15. The 2 x 2 factorial treatments were replicated four times in a completely randomized block design. The rice plots that were used in this study are shown in grey and were subdivided in two subplots corresponding to two levels of weed pressure. CT: conventional tillage without crop residue retention; NT: no-tillage with crop residue retention; MD: maize + dolichos; MS: maize + stylosanthes; S: stylosanthes; R: rice; LW: low weed pressure; HW: high weed pressure.

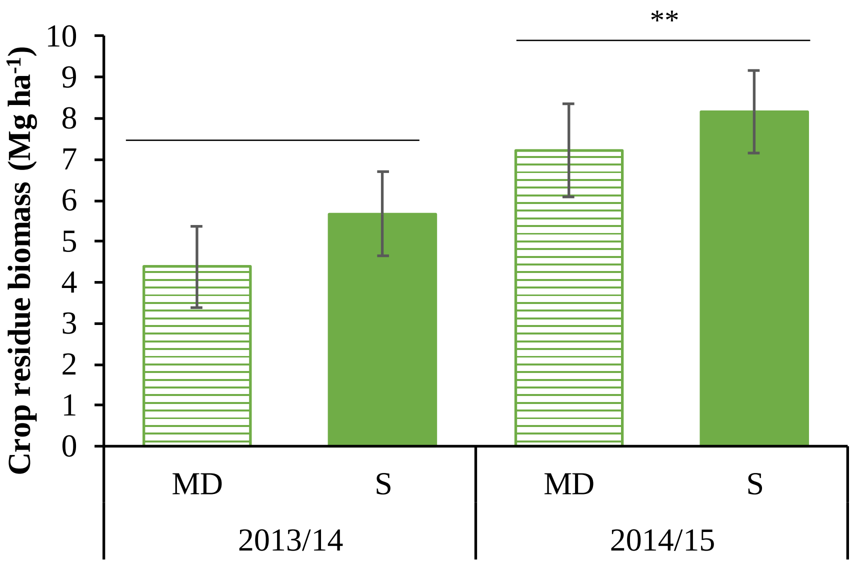

Figure 3: Amount of crop residue biomass in the no-tillage (NT) treatment before rice sowing in October 2013 (2013/14 season) and October 2014 (2014/15 season) following the maize + dolichos (MD) and stylosanthes (S) cropping phase in a 2-year and 3-year crop rotation respectively (see Figure 2). Vertical bars represent standard errors of the mean. ** indicates a significant effect of season at $p < 0.01$.

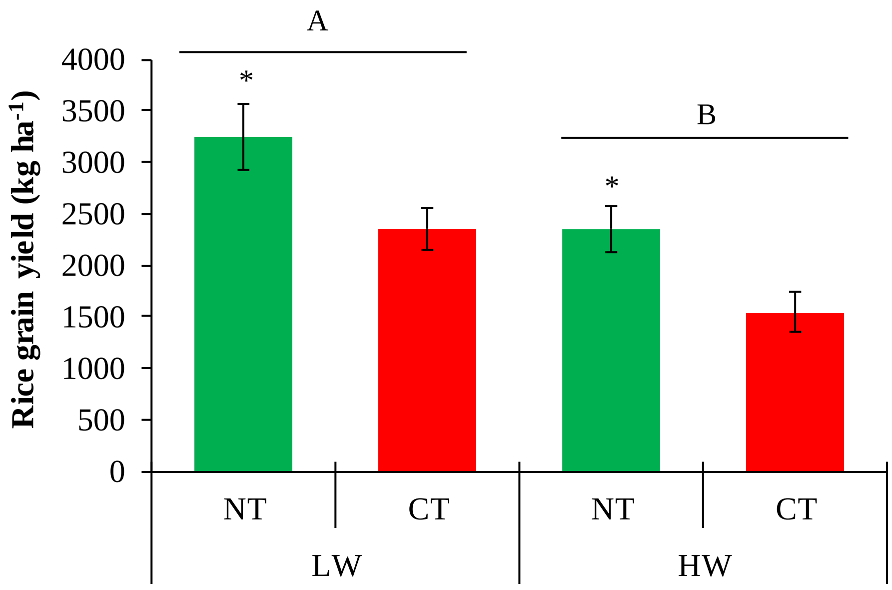

Figure 4: Rice grain yield in relation to the weed pressure treatments (LW: low weed pressure; HW: high weed pressure) and soil tillage/residue management (NT: no-tillage with crop residue retention; CT: conventional tillage without crop residue retention). Vertical bars represent standard errors of the mean. * indicates a significant effect of soil tillage/residue management at $p < 0.05$. Letters A and B indicate a significant yield difference between the level of weed pressure at $p < 0.001$.

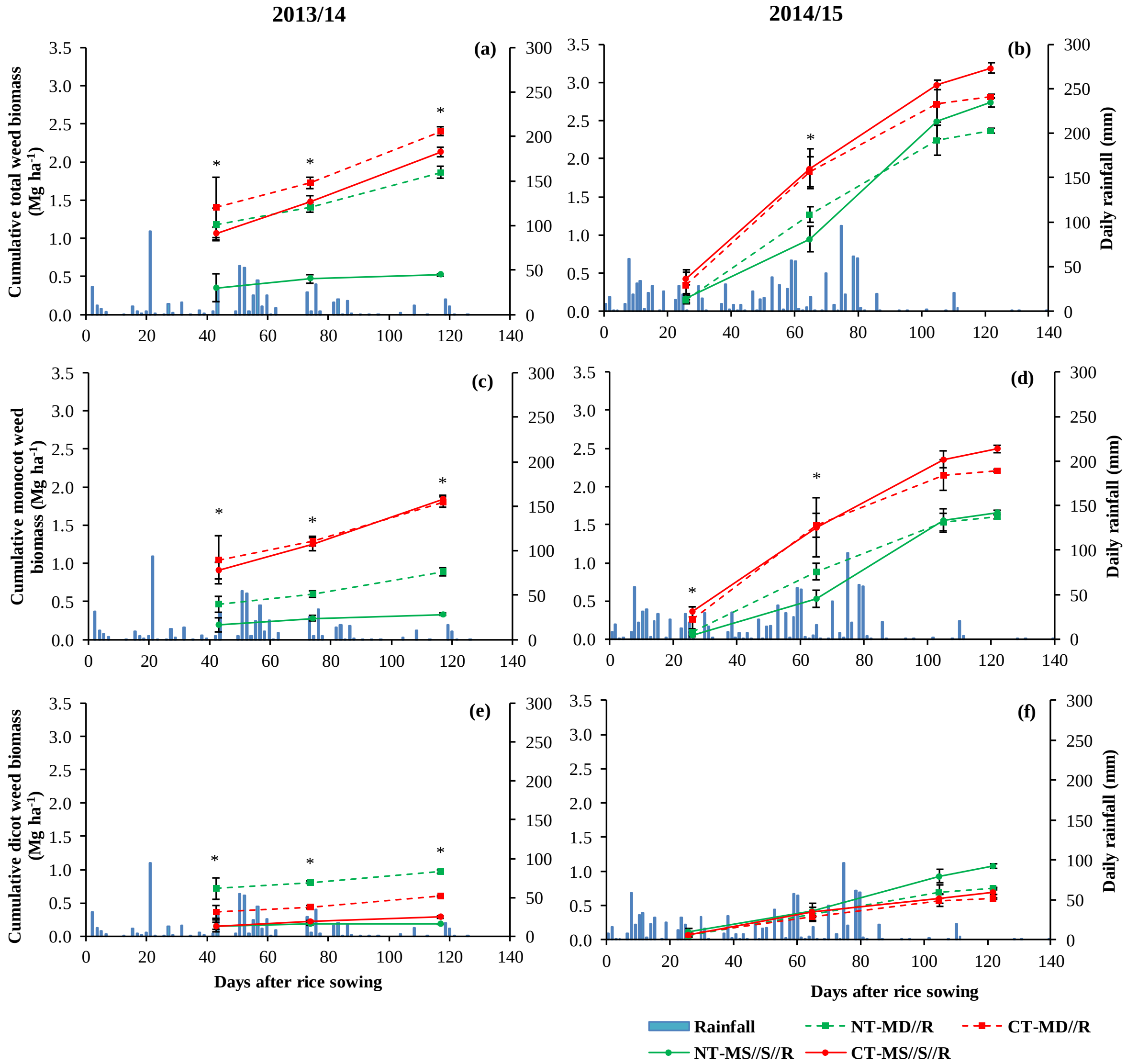

Figure 5: Cumulative weed biomass during the 2013/14 and 2014/15 growing seasons in relation to the soil tillage/residue management (NT: no-tillage with crop residue retention; CT: conventional tillage without crop residue retention) and crop rotation (MD//R: maize + dolichos - rice rotation; MS//S//R: maize + stylosanthes - stylosanthes - rice rotation) for total (a, b), monocot (c, d) and dicot weed (d, e). * indicates a significant effect of treatments (rotation, soil/residue management and interaction rotation x soil/residue management) at $p < 0.05$. Vertical bars represent standard errors of the mean.

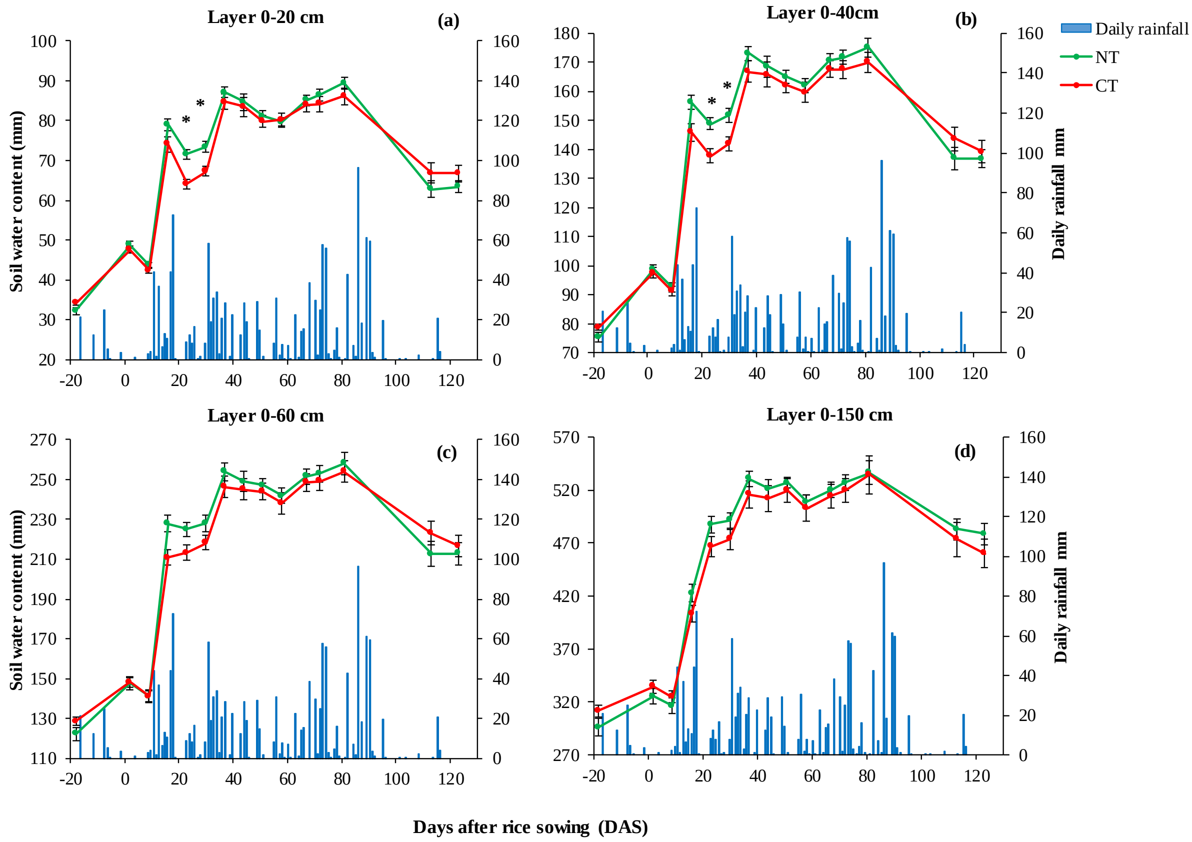

Figure 6: Dynamics of soil water content averaged over the crop rotation and weed pressure treatments in the 0-20 cm (a), 0-40 cm (b), 0-60 cm (c) and 0-150 cm (d) soil layers during the 2014/15 growing season in relation to the soil tillage/residue management (NT: no-tillage with crop residue retention; CT: conventional tillage without crop residue retention). The blue bars represent daily rainfall amounts in mm. * indicates a significant effect of soil tillage/residue management at $p < 0.05$. Vertical bars represent standard errors of the mean.

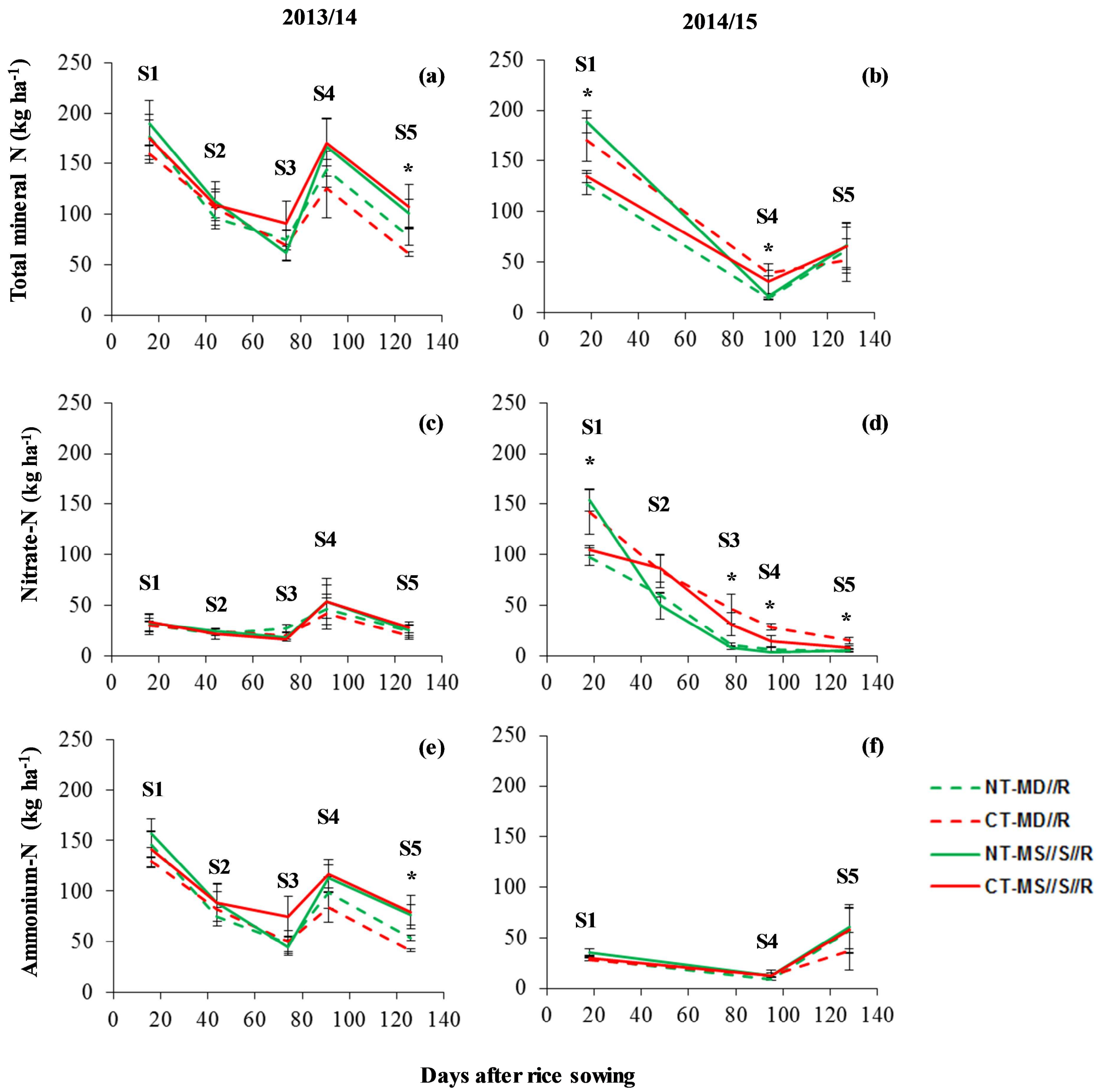

Figure 7: Dynamics of mineral N content (total (a,b), nitrate (c,d) and ammonium (e,f)) under low weed pressure during the two growing seasons (2013/14 and 2014/15) at S1: germination, S2: tillering, S3: panicle initiation, S4: flowering and S5: maturity stages of rice in the soil profile (0-90 cm) in relation to soil tillage/residue management (NT: no-tillage: CT: conventional tillage) and crop rotation (MD//R: maize + dolichos - rice; MS//S//R: maize + stylosanthes - stylosanthes - rice). * indicates a significant effect of treatments (rotation, soil/residue management and interaction rotation x soil/residue management) at $p < 0.05$. Vertical bars represent standard errors of the mean.

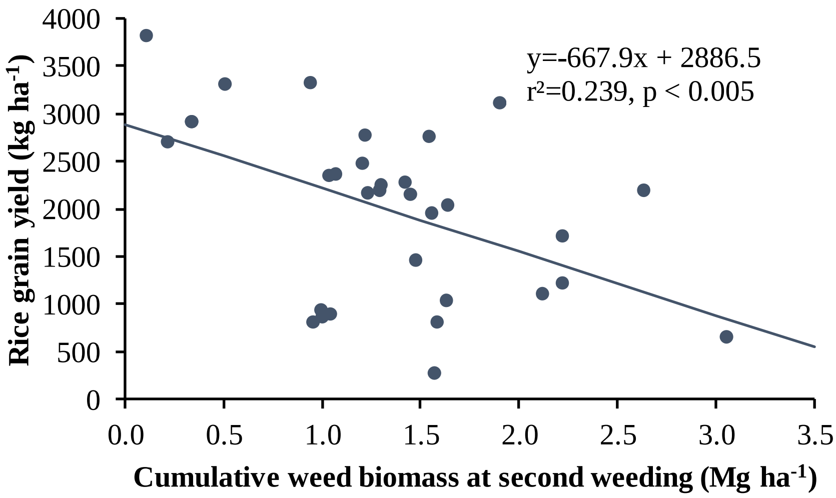

Figure 8: Effect of cumulative weed biomass at the second weeding operation (See Table 2) on rice grain yield. The points represent the observations from 32 experimental plots (2 crop rotation x 2 soil tillage/residue management treatments x 2 growing seasons x 4 replications under high pressure weed treatment).

Table 1: Selected physical and chemical properties (mean and standard deviation, n = 8) of the soil of the experimental field at the FOFIFA research station located in the Lake Alaotra region, Madagascar.

Soil layer (cm)	**pH (H_2O)**	**Olsen P (mg kg^{-1})**	**CEC (meq 100 g^{-1})**	**Organic C (g kg^{-1})**	**Clay (%)**	**Silt (%)**	**Sand (%)**
0-10	5.2 (±0.2)	317 (±42)	7.0 (±2.8)	34.6 (±4.1)	31.3 (±6.3)	41.9 (±3.4)	26.8 (±4.7)
10-20	5.2 (±0.2)	316 (±42)	7.0 (±2.8)	33.8 (±4.7)	31.2 (±6.2)	41.9 (±3.4)	26.9 (±4.7)
20-30	5.3 (±0.2)	309 (±48)	6.3 (±2.2)	31.0 (±8.3)	35.6 (±8.3)	42.3 (±5.0)	22.2 (±4.5)
30-60	5.4 (±0.2)	289 (±51)	5.7 (±1.9)	18.2 (±6.6)	35.4 (±9.8)	42.2 (±6.1)	22.4 (±5.9)
60-90	5.6 (±0.2)	219 (±30)	4.0 (±0.9)	8.8 (±2.9)	35.1 (±8.9)	43.4 (±4.3)	21.5 (±5.6)

Table 2: Dates of field operations during the 2013/14 and 2014/15 growing seasons.

	2013/14				**2014/15**			
	LW		**HW**		**LW**		**HW**	
	Date	**DAS**	**Date**	**DAS**	**Date**	**DAS**	**Date**	**DAS**
Rice sowing	26/11/2013	-	26/11/2013	-	08/12/2014	-	08/12/2014	-
First weeding	28/12/2013	32	08/01/2014	43	30/12/2014	22	03/01/2015	26
Second weeding	05/01/2014	40	08/02/2014	74	16/01/2015	39	11/02/2015	65
Third weeding	16/01/2014	51			06/02/2015	60		
Rice harvest	03/04/2014	128	03/04/2014	128	13/04/2015	126	13/04/2015	126

DAS: days after sowing; LW: low weed pressure; HW: high weed pressure treatment

Table 3: Rice grain yield (kg ha^{-1}) and effect of growing season, level of weed pressure, crop rotation and soil/residue management.

	Rice grain yield (kg DM ha^{-1})
2013/14	2481
2014/15	2280
p-value	0.75
SED	286
LW	2802
HW	1962
p-value	**<0.001*** **
SED	264
MS//S//R	2601
MD//R	2157
p-value	0.15
SED	280
NT	2787
CT	1950
p-value	**0.02***
SED	262

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$ SED: standard error of difference between means; MD//R: maize + dolichos - rice rotation; MS//S//R: maize + stylosanthes - stylosanthes - rice rotation; NT: no-tillage with crop residue retention; CT: conventional tillage without crop residue retention; LW: low weed pressure; HW: high weed pressure.

Table 4: Photosynthetically active radiation (PAR) interception (%) by the rice canopy in 2014/15 at tillering (S2), panicle initiation (S3), flowering (S4) and maturity (S5) and effect of level of weed pressure, crop rotation, soil tillage/residue management.

	PAR interception by the rice canopy			
	S2	**S3**	**S4**	**S5**
LW	0.47	0.49	0.60	0.68
HW	0.45	0.39	0.49	0.48
p-value	0.23	**<0.001*****	**<0.001*****	**<0.001*****
SED	0.04	0.05	0.05	0.06
MS//S//R	0.50	0.52	0.60	0.64
MD//R	0.42	0.35	0.48	0.53
p-value	**0.04***	**<0.001*****	**<0.01****	**0.04***
SED	0.03	0.04	0.05	0.06
NT	0.48	0.50	0.59	0.65
CT	0.44	0.38	0.49	0.51
p-value	0.33	**<0.01****	**0.02***	**0.02***
SED	0.04	0.05	0.05	0.06

*** p < 0.001; ** p < 0.01; * p < 0.05; SED: standard error of difference between means; LW: low weed pressure; HW: high weed pressure; MD//R: maize + dolichos - rice rotation; MS//S//R: maize + stylosanthes - stylosanthes - rice rotation; NT: no-tillage with crop residue retention; CT: conventional tillage without crop residue retention

Table 5: Weed density (number m^{-2}) at rice harvest for total, monocot and dicot weeds and effect of growing season, crop rotation, soil tillage/residue management and their interactions.

	Total	**Monocots**	**Dicots**
2013/14	1109.75	313.38	796.38
2014/15	1211.75	406.69	805.06
p-value	0.59	0.24	0.94
SED	211.82	84.08	147.72
MS//S//R	1175.94	353.88	821.69
MD//R	1145.94	366.19	779.75
p-value	0.88	0.88	0.75
SED	212.56	85.75	147.53
NT	914.25	267.88	646.38
CT	1407.25	452.19	955.06
p-value	**<0.01****	**0.02***	**0.02***
SED	192.64	78.91	136.56
p-value			
season x rotation	**0.02***	0.08	**0.02***
season x management	0.59	0.46	0.72
rotation x management	0.12	0.11	0.21
season x rotation x management	0.39	0.38	0.52

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; SED: standard error of difference between means; MD//R: maize + dolichos - rice rotation; MS//S//R: maize + stylosanthes - stylosanthes - rice rotation; NT: no-tillage with crop residue retention; CT: conventional tillage without crop residue retention