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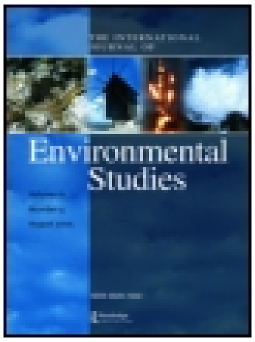

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Initiating conservation agriculture shows reduced soil CO_2 emissions and improved soil aggregate stability in the first season in rainfed cropping in India

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ABSTRACT

The reported study was undertaken to determine which soil health indicators showed measurable signs of improvement, during the first year of the process of introducing a Conservation Agriculture (CA) cropping system in rainfed areas in Madhya Pradesh, India. Soil health indicators of soil aggregate stability, soil-atmosphere CO_2 fluxes, water infiltration, soil moisture, potentially mineralisable nitrogen, soil organic content and bulk density were measured. Results demonstrate that generally, there were improvements in all measured soil health indicators in CA soils, with decrease in CO_2 emissions and increase in soil aggregates being statistically significant.

KEYWORDS

Conservation; sustainability; no-till; carbon; emission; aggregate

Introduction

Soil organic matter plays an important role in improving soil health and fertility. Tillage leads to depletion of soil organic matter in agricultural soils compared with soils under natural vegetation. The main reason for this loss is the increased rate of decomposition of soil organic matter through oxidation. In tillage systems, plant biomass from the soil surfaces is removed, causing soil organisms to starve. Tillage also destroys soil architecture that can only be built through soil biological processes. Consequently, soil structure and aggregate stability become weaker over time owing to tillage, increasing the risk of soil erosion and loss of topsoil. This loss process leads to decreases in rainfall infiltration, water retention capacity and nutrient content, and leads to increased soil compaction and loss of soil biodiversity [1–4]. Conservation Agriculture (CA) as a strategy in agricultural land management can improve soil health and biology [5–7]. CA is an agroecological approach to agricultural production based on the application of three interlinked

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principles: a) continuous no or minimum mechanical soil disturbance, b) permanent soil cover by crop residues and cover crops and c) diversified cropping with annuals and perennials, including legumes, and with rotations or sequences or associations [7].

By applying these three principles through locally formulated practices, along with other complementary good agricultural practices, soils can recuperate over time from degradation and become stable as in natural ecosystems. The process of regeneration may take several years depending on the initial level of soil degradation. In CA systems, soils are not disturbed mechanically except for opening a narrow slit and placing seeds and fertilisers, and are protected by a layer of mulch from the biomass of previous crops including cover crops [8,9]. Diversified cropping provides a source and presence of biomass for the accumulation of soil organic carbon [3]. Moreover, in CA systems, because of low mechanical soil disturbance, the decomposition rate of soil organic matter is reduced owing to reduced oxidation and organic carbon becoming sequestered and included in soil aggregates [10]. This leads to improved soil resilience and protection, which is particularly important during dry seasons in semi-arid regions to minimise soil erosion, water evaporation, surface crusting and temperature fluctuations [11–13]. Soil aggregate stability is improved by increasing organic materials such as humified organic matter from crop biomass being returned including roots, bacterial biomass and waste products, organic gels, fungal hyphae that produce a cementing compound, worm secretions and casts and mesofauna biomass [14,15]. When the soil is mechanically disturbed repeatedly, microbiota consume the young carbon pool through decomposition and mineralisation, depleting the major binding agents in macro and microsoil aggregates and reducing their stability and bearing capacity.

Soil mulch cover in CA systems, along with minimum soil disturbance, protects soil and improves water capture and water use efficiency and productivity through increased water infiltration and retention and reduction in evaporation from the soil surface. This leads to reduced water runoff and soil erosion, and to higher soil moisture content, which improves productivity especially in seasonally dry regions [16]. This is the result of three main processes: a) soil organic matter content increasing because of the core practices of CA, b) the increased presence of soil organic matter and higher amount of water-stable soil aggregates that improves soil resistance against water and soil erosion [17], c) water infiltration rate and water retention capacity has a direct relation to improved soil structure and pore volume and d) soil organic matter retaining moisture at lower soil matrix water potentials [18]. The distribution of soil porosity depends on soil texture and structure, aggregate stability and soil organic matter [8,9,12,19].

Tillage has a significant impact on CO_2 emission. Generally, it boosts the loss of soil organic carbon by increasing its decomposition rate and through soil loss by erosion [20]. Moreover, in mechanised systems, tillage is a high energy-consuming operation that requires a high amount of fossil fuel consumption per hectare. Anthropogenic greenhouse gas (GHG) emissions have increased through global population and economic growth, but also because of conventional tillage-based agriculture, including traditional agriculture. Thus, there is a vital need to identify potential C sinks to store atmospheric CO_2 while at the same time reducing the use of fossil fuel. Terrestrial ecosystems are considered to have a high sink potential for carbon sequestration. When natural ecosystems such as grasslands or forests are converted to agricultural fields and subjected to tillage, a high amount of soil organic carbon is lost mainly as CO_2 [8,21]. In contrast to tillage-based agricultural systems, CA systems can increase both soil carbon sequestration and productivity, and reduce fossil fuel requirement [22]. Tillage over time can induce losses of soil organic carbon content by 50% or more because of increases in aerobic processes of microbial respiration [23]. Many studies have investigated the effects of conventional and CA systems on soil carbon loss by soil respiration [5,10,11,14,16,24] and the results are equivocal. Many authors have reported that CO_2 emissions are higher in conventional tillage agriculture compared to no-till CA systems [22,25–27]. In CA systems, air diffusion into the soils and air-filled pores is reduced compared to conventional tillage agriculture, causing low or minimum CO_2 emission [28]. But, in no-tillage systems, soil CO_2 emission can increase due to increased soil water content in the soil surface layers that can stimulate soil biological activity and CO_2 emission [1,4].

The aim of the study reported in this paper was to detect measurable effects on soil health and CO_2 emissions in rain-fed areas in Madhya Pradesh, India, during the first year of the transformation process of change from traditional tillage agriculture to CA. To transform a conventional tillage system to a CA system requires an initial rehabilitation phase of some five years, followed by a second phase of enhancement of soil health and functions [29]. Many studies have investigated the longer-term effects of CA transformation on soil health and functions, but the effects of CA transformation in the initial years of implementation are not well studied. This paper reports the effects of CA on soil health and functions during the first year of transformation during the Kharif and Rabi seasons.

Materials and methods

Study area and treatment details

The study site was located in Khandwa district in Madhya Pradesh in central India. The area is under a monsoon environment with rainfall during the warm period of June to September followed by a dry and cooler period until January. During the February to May period, temperature increases considerably until the start of the monsoon rains in June. In Khandwa, the average annual temperature is 26.6°C. The average annual rainfall is 932 mm. The driest month is February, with 2 mm of rain. The highest amount of precipitation occurs in July, with an average of 282 mm. The variation in temperatures throughout the year between the warmest and the coolest month is 14.5°C [30].

Four on-farm field trials were established, each consisting of two neighbouring plots. The distance between sites was about 1 km and plots were scattered across an area of about 1,000 ha of agricultural land. One plot (15 × 15 m) per pair was selected randomly and managed conventionally with the farmer's traditional practice and tillage was applied to prepare the land for crop establishment. CA practices were applied in the adjacent plot. The soil surface was covered with plant biomass (maize and wheat stubble, leaves and stems) and no-till seeding was carried out using a jab-planter (dibbler, Khedut Agro Co., Gujarat, India) on 18 May 2014 to establish the crop with minimal soil disturbance. The main crop in the Kharif (monsoon) season was maize, and for the Rabi (dry) season gram (chick pea) was planted on 7 November 2014. No mineral fertilisers or pesticides were applied to any of the treatments. Weeding was done manually.

Soil sampling

Each plot was flat and uniform and soil sampling was done using a grid. The field was divided into cells by means of a coarse grid (50 × 50 cm). A horizontal coarse cell was selected in the top row and kept the X coordinate the same but randomly select a new Y coordinate. The process was repeated for all the coarse cells in the top row [31]. About 2–3 cm of topsoil with coarse plant residues were removed, and soil samples in 10 cm depth were collected. In general, three soil samples were taken in each plot (n = 8) on 10 February 2015 (268 days after the sowing date). There were four blocks (four field trials) consisting of two neighbouring plots (CA and non-CA plots). The soil samples were placed in cold boxes and transported to the laboratory within 2 hours.

Soil moisture

To determine the soil moisture, 10 g of the soil samples (3 samples per plot) was dried in an oven at 60°C, and then sieved with 2 mm mesh size and weight of the evaporated water from oven drying was calculated.

Soil texture

Soil texture has a profound effect on soil behaviours such as ability to retain nutrients and water. Coarser soils generally have a lesser ability to hold and retain nutrients and water than finer soils. Texture also affects water permeability, and heavier finer soil can suffer from drainage problems, if soil structure is poor. Soil texture is determined in order to characterise the particle size composition of the soil. To determine the soil texture, a subsample of about 14 g (± 0.1 g) of sieved soil was taken and added to a 50 ml centrifuge tube containing 42 ml of 3% soap (sodium hexametaphosphate) solution. This tube was placed on a shaker for 2 hours to disperse the soil fully into a suspension. In the next step, the entire content of the centrifuge tube was washed onto a 0.053 mm soil sieve assembly. The sieve assembly consisted of a 0.053 mm sieve on top of a plastic funnel above a 600 ml beaker. Sand captured on top of the sieve was washed into a metal can and set aside. Silt and clay particles collected in the 600 ml beaker were re-suspended by stirring and allowed to settle for 2 hours. The clay in suspension was then carefully decanted. The settled silt at the bottom of the beaker was washed into a second can. Both cans (one containing the sand fraction and the other the silt fraction) were dried overnight at 105°C to constant weight before weighing [32]. Clay, silt and sand content were calculated as below:

$$\text{Sand}\,(\%) = \text{dry weight sand}\,(\text{g})/\text{dry weight}\,(\text{g})\text{soil added to centrifuge tube}$$

$$\text{Silt}\,(\%) = \text{dry weight silt}\,(\text{g})/\text{dry weight}\,(\text{g})\text{soil added to centrifuge tube}$$

$$\text{Clay}(\%) = 100\% - \text{Sand}(\%) - \text{Silt}(\%)$$

Aggregate stability

Aggregate stability is a measure of the extent to which soil aggregates resist falling apart when hit and wetted by raindrops. It is related to soil structure stability and affects soil's load bearing capacity. In CA soils, aggregate stability improves with time as soil microbiota and soil organic matter content increases and soil micro and macro aggregates are formed through the action of microorganisms. Aggregate stability can be measured using a rain simulation sprinkler that steadily rains on a sieve containing the known weight of soil aggregates between 0.5 mm and 2 mm. The unstable aggregates slake (fall apart) and pass through the sieve. The fraction of the soil that remains on the sieve is used to calculate the per cent aggregate stability.

Gugino et al. protocol [33] was used to measure aggregate stability. Samples of 10 g of the soil were oven-dried at 40°C. Using stacked sieves of 2.0 mm and 0.25 mm with a catch pan, the dried soil was shaken for 10 seconds on a Tyler Coarse Sieve Shaker to separate it into different size fractions, small (0.25–2.0 mm) and large (2.0–8.0 mm). Then, a single layer of small aggregates (0.25–2.0 mm) was spread on a 0.25 mm sieve (sieve diameter is 200 mm). Sieves are placed at a distance of 500 mm below a rainfall simulator, which delivers individual drops of 4.0 mm diameter. The test was run for 5 minutes and delivered 12.5 mm depth of water as it drops to each sieve. This was equivalent to a heavy thunderstorm. A total of 0.74 J of energy thus impacts each sieve over this 5-minute rainfall period. Since 0.164 mJ of energy was delivered for each 4.0 mm diameter, it can be calculated that 15 drops per second impact each sieve. The slaked soil material that fell through during the simulated rainfall event, and any stones that were remaining on the sieve were collected, dried and weighed, and the fraction of stable soil aggregates was calculated using the following equation [33]:

$$\mathrm{WSA} = \mathrm{Wstable}/\mathrm{Wtotal}$$

$$\mathrm{Wstable} = \mathrm{Wtotal} - (\mathrm{Wslaked} + \mathrm{Wstones})$$

where W = weight (g) of stable soil aggregates (stable), total aggregates tested (total), aggregates slaked out of sieve (slaked), and stones retained on the sieve after the test (stones). Corrections were made for stones.

Water infiltration

The infiltration rate is a measure of how fast water enters the soil. Water entering too slowly may lead to waterlogging and ponding or to surface runoff and soil erosion. It is the downward entry of water into the soil. The velocity at which water enters the soil is the infiltration rate. The infiltration rate is typically expressed in mm per hour. Water from rainfall or irrigation must first enter the soil for it to be of value to the crop and to the catchment.

To measure water infiltration, a metal ring with 15 cm diameter was inserted about 20 cm vertically into the soil by using a hammer. To minimise the disturbance to the soil surface inside and outside the ring a block of wood was placed on top of the ring to avoid direct hammering to the ring. The ring was lined with plastic wrap. As the next step, the soil surface was lined inside the ring with a sheet of plastic wrap to cover the soil and ring completely. This procedure prevented any disturbance to the soil surface when adding water. The plastic bottle was filled up to the 500 ml mark with distilled water, and 500 ml of water was gently poured into the ring. Then, the wrap was removed, and time was recorded. Timekeeping was stopped when the soil surface was just glistening. The infiltration test was repeated 3 times in each plot in three different randomly selected spots. The test was done on 12–14 February 2015 (270–272 days after the sowing date).

Bulk density

Bulk density is the weight of the soil in a given volume. This is directly related to soil aggregate stability and pore space. In well-aggregated soil, the pore content is higher and the bulk density is lower. In our study, the bulk density was measured near (between 30 and 60 cm) the sites of the respiration measurement and the infiltration tests on 10 February 2015 in three randomly selected spots in each plot. The ring was driven into the soil using hand sledge and block of wood. A ring with a 12 cm diameter was inserted about 8 cm into the soils. Four measurements (evenly spaced) were taken of the height from the soil surface to the top of the ring, and the average was calculated. In the laboratory, the volume of the soil in the tube was calculated. In the next step, samples were placed in a bag and labelled. The samples were transported to the laboratory with as little touching as possible. In the laboratory, samples were weighed. To calculate the water content of the soils, two sub-samples (20 g) were oven-dried at 105°C, and water content was calculated. Bulk density was calculated as shown below:

$$\text{Dry soil weight}(\text{g}) = \text{Wsoil} - -\text{Wwater}$$

$$\text{Bulk density}(\text{g/cm}^3) = \text{Dry soil weight}(\text{g})/\text{Soil volume}\ (\text{cm}^3)$$

Potentially mineralisable nitrogen

Immediately after sampling, the mixed composite bulk soil sample (stored at 4°C) was sieved, and two 8 gm soil samples were removed and placed in 50 ml centrifuge tubes. Then, 40 ml of 2.0 M potassium chloride (KCl) was added to one of the tubes, shaken on a mechanical shaker for 1 hour, centrifuged for 10 minutes, and then 20 ml of the supernatant was collected and analysed for ammonium concentration ('time 0' measurement).

In the next step, 10 ml of distilled water was added to the second tube, it was hand shaken and stored (incubated) for 7 days at 30°C. After 7 days of anaerobic incubation, 30 ml of 2.67 M KCl was added to the second tube (creating a 2.0 M solution), the tube was shaken on a mechanical shaker for 1 hour, centrifuged for 10 minutes, and then 20 ml of the supernatant was collected and analysed for ammonium concentration ('time 7 days' measurement). The difference between the time 0 and time 7-day ammonium concentration was the rate at which the soil microbes can mineralise organic nitrogen in the soil sample.

Soil organic matter content

The percentage of soil organic matter was measured using the method of weight loss on ignition. For this purpose, 10 g of soil sample was dried at 105°C to remove all soil water. The sample was then ashed for 2 hours at 500°C, and the percentage of weight loss was calculated. The % loss on ignition [34] was converted to % organic matter (OM) using the following equation [33]:

$$\%OM = (\%LOI \times 0.7) - 0.23$$

Soil respiration rate

The Kirita procedure [35] of measuring soil respiration rate was followed. Three static chambers were inserted about 7 cm into the soils in each plot. In traditional agricultural treatment plots, before placing the chambers between row spaces, soil was tilled up to 12 cm depth by a traditional animal-drawn wooden hoe plough. A sponge (11.6 cm in diameter, 2.5 cm in height) containing up to 25 ml of 2 N NaOH solution for a CO_2 absorbent was placed on a wire holder in a chamber (12.6 cm in diameter, 23 cm in height). The chamber was quickly covered and tightly sealed with plastic tape. Measuring periods were normally 24 h to avoid any daily influence on the soil respiration estimate. After measuring, the NaOH solution was squeezed from the sponge, stored in a vial and carried to the laboratory. A part of this solution (5.0 ml) was titrated with 0.2 N HCl using a titration device. This measurement was done in three randomly selected spots in each plot on 10 February 2015 (268 days after the sowing date).

Statistical analysis

The unit of replication in the study was the field plot. In this study, we analysed data using one-way ANOVA with CA as a fixed effect and field plots (n = 8) as replicates. Effects with $P < 0.05$ are referred to as significant, and effects with $P < 0.1$ as marginally significant.

The relationship between CO_2 emission, aggregate stability, soil organic content, water infiltration, potentially mineralisable nitrogen, and bulk density was tested using generalised linear models (GLM). For instance, water infiltration rate and soil aggregate stability or soil organic content were tested. The CO_2 emission data were also log-transformed to meet the requirements of parametric statistical tests.

Results

Soil texture

Soils were mostly clay to sandy clay loam. Details for each plot are in Table 1.

Soil moisture

Soil moisture in CA treatment was 9.6% higher compared with traditional tillage agriculture plots (Non-
CA), and this difference was not statistically significant ($p = 0.12$). Figure 1.

Table 1. Soil texture results for each plot.

Plot number	Silt (%)	Sand (%)	Clay (%)	Soil texture
Plot1	5.2	57.8	36.9	Sandy clay loam
Plot2	4.8	34.8	60.6	Clay
Plot3	3.8	56.5	39.8	Sandy clay
Plot4	3.8	41.0	55.2	Clay

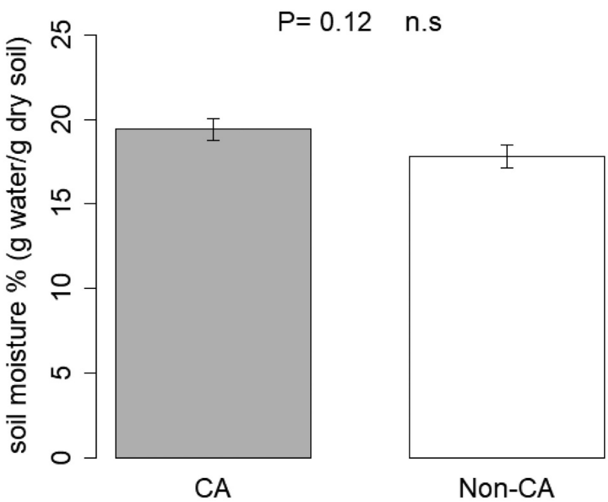

Figure 1. Soil moisture (%) in CA and traditional agriculture (Non-CA) treatments.

Soil aggregate stability

Soil aggregate stability was 30% higher in CA treatment compared with traditional tillage agriculture plots (Non-CA), and this elevation was statistically significant ($p < 0.0001$). Figure 2.

Water infiltration

The infiltration rate was higher (64%) in plots with CA treatment compared with traditional tillage agriculture plots (Non-CA), but this difference was not statistically significant ($p = 0.228$). Figure 3.

Bulk density

Soil bulk density in CA plots was about 3% less than in traditional tillage agriculture plots (Non-CA), and this difference was not statistically significant ($p = 0.38$) Figure 4.

Potentially mineralisable nitrogen

Potentially mineralisable nitrogen in soils in CA plots was higher by about 27% than in soils in traditional tillage agriculture plots (Non-CA), and this difference was not statistically significant ($p = 0.346$). Figure 5.

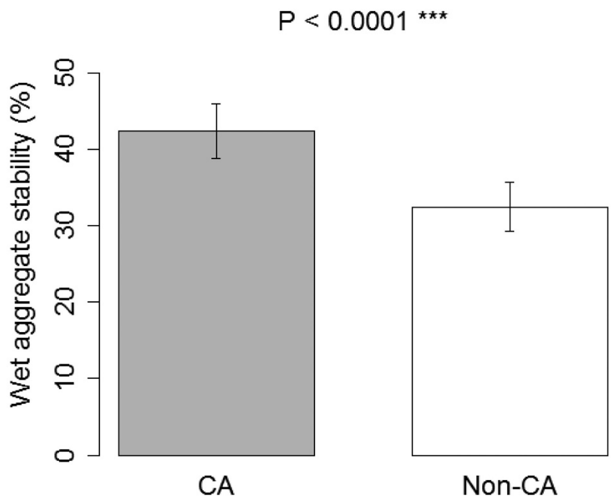

Figure 2. Wet aggregate stability in CA and traditional agriculture (Non-CA) treatments.

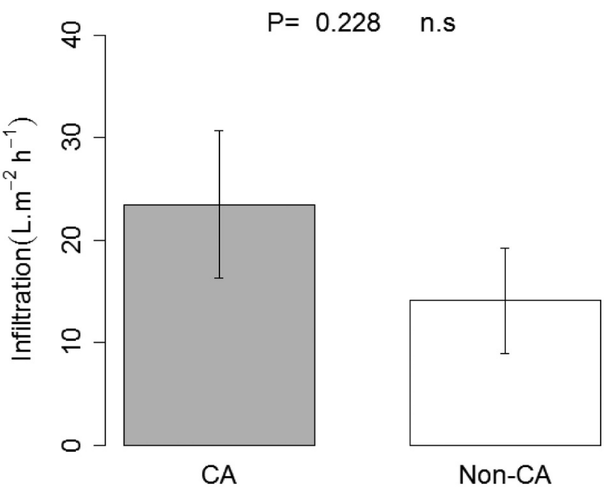

Figure 3. Water infiltration in CA and traditional tillage agriculture (Non-CA) treatments.

Organic matter content

Organic matter content was higher in soils from CA plots by about 38% than soils in traditional tillage agriculture plots (Non-CA), but this elevation was not statistically significant (p = 0.16). Figure 6.

Soil respiration rate

CO_2 emission in soils from traditional agricultural plots (Non-CA) was about 16% higher than that from soils in CA plots, and this difference was statistically significant (p = 0.00948). Figure 7.

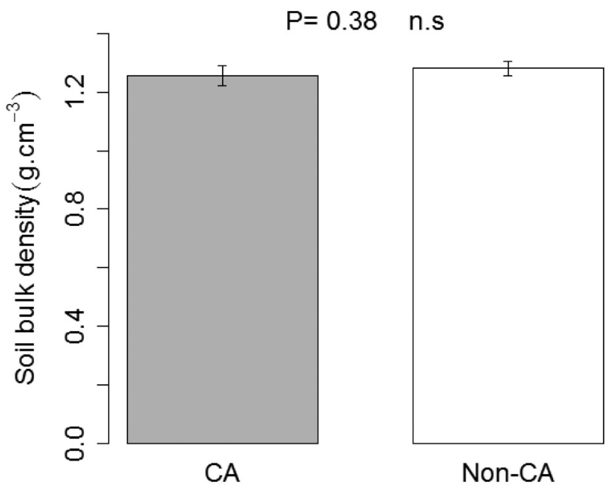

Figure 4. Soil bulk density in CA and traditional agriculture (Non-CA) treatments.

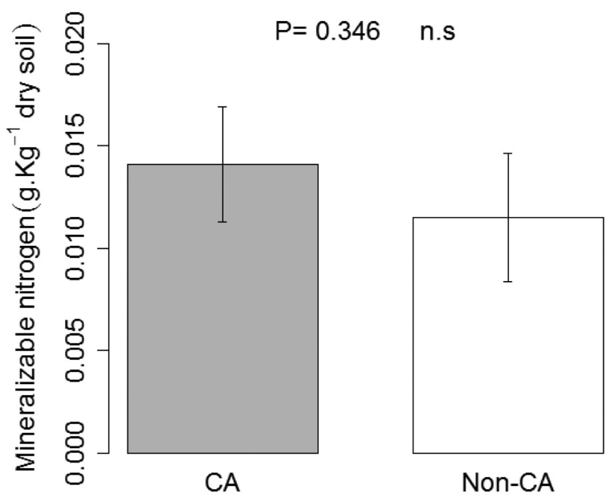

Figure 5. Potentially mineralisable nitrogen in CA and traditional agriculture (Non-CA) treatments.

Discussion

Soils during the first year of transformation to CA with practices of no-till and soil mulch cover began to show measurable differences in major soil health indicators after the first Kharif season of the study. CO_2 emission was significantly lower and soil aggregate stability significantly higher in CA treatment plots, and all other soil health indicators such as soil organic content, water infiltration, potentially mineralisable nitrogen, and bulk density showed an improvement, but the differences were not statistically significant. Soil moisture content in CA treatment plots was about 9% greater than in plots under traditional tillage agriculture treatment, but this difference was not statistically significant.

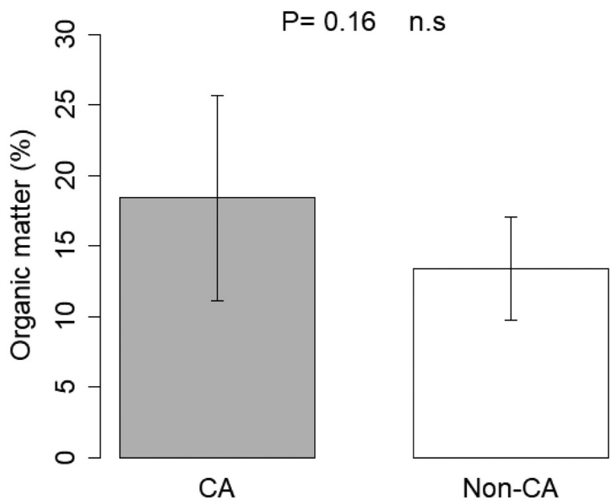

Figure 6. Organic matter content in CA and traditional agriculture (Non-CA) treatments.

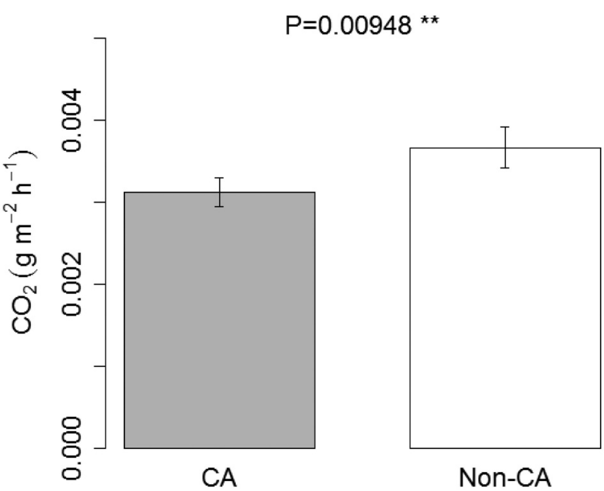

Figure 7. Soil respiration in CA and traditional agriculture (Non-CA) treatments.

Generalised linear modelling (GLM) with a quasipoisson error model was used to analyse the interspecific relationships between water infiltration rate, CO_2 emission, soil organic content and soil moisture. CO_2 emission decreased and the soil organic content increased significantly with increase in water infiltration rate ($F = 14.1$, $P < 0.001$, $R^2 = 0.34$ and $F = 11.08$, $P < 0.001$, $R^2 = 0.26$).

Water infiltration is related to aggregate numbers in soils. In well-aggregated soils, water storage and transmission are facilitated by increased soil porosity. In addition, CO_2 emission resulting from decomposition is reduced owing to soil organic carbon inclusion in soil aggregates [20], although basal soil respiration can also be higher in soils that are rich in microorganisms and organic matter compared to soils that are low in carbon and microorganisms as is the case with regularly tilled soils. Well-aggregated soils showing higher infiltration rate and low soil CO_2 emissions and soil organic content appear to be protected within soil aggregates.

Tillage increases air diffusion into the deeper soil layers that leads to an increase in organic matter decomposition (similar to 'stoking the fire' effect) leading to increased soil respiration and CO_2 emission, mostly as a result of bacterial activity. The study found that the respiration rate of soils in CA plots was significantly less than from soils in plots under traditional tillage agriculture. The results agreed with several other studies [1,2,16,25,36] which have reported that CA practices can decrease CO_2 emissions from soils and enhance their sink capacity for carbon. CA practices increase micro- and macro-soil aggregate numbers and related soil quality aspects such as soil structure and aeration, water infiltration and retention, and load bearing capacity. Maintenance of soil mulch covered with biomass can improve carbon sequestration in the soil. Improved soil aggregate stability also reduces soil respiration rates and CO_2 fluxes. Moreover, the rhizodeposition of organic carbon compounds in exudation from plant roots can increase soil carbon storage noted by other research [2,19,37], and roots are a major source of carbon for sequestration and can be added to carbon stock as soil organic matter pool. Furthermore, organic soil cover and soil organic matter in CA make higher level nutrients accessible to plant roots in required proportions and thus over time can lead to lower mineral fertilisation requirements and N_20 emissions as well as more efficient nutrient use and nutrient productivity [38]. Moreover, by using less fuel energy input because of no-till seeding and weeding, CA systems can reduce CO_2 emissions further [20].

Results from soil aggregate test showed an improvement in soil aggregate stability in CA treatment as has been shown in most studies [11,20,39]. Soil microbial activities increase because of organic materials such as mulch and root biomass. A higher presence of fungal hyphae, bacterial waste products, organic gels, worm secretions and casts in CA soils can improve aggregate formation [14,15,19]. Microbial-derived carbohydrates in silts and clay fractions in no-tilled soils were higher than in conventionally tilled soils [40]. Soil fungi play a key role in soil aggregate formation and stabilisation by a network around soil particles and the hyphal exudation as an aggregate binding agent called glomalin. Glomalin acts as biological glue, binding soil particles into small aggregates. The accumulation of glomalin in soils is central to the soil aggregate stability [41,42]. Aggregate protection is important in land management in general. In soils where aggregates are mechanically disrupted regularly, soil bacteria and fungi consume a pool of young carbon. Therefore, the binding agents that are produced by microorganisms, especially fungi, which hold soil mineral particles together into micro- and macro-aggregates, are lost and the soil aggregates are dispersed. When macropores are disrupted mechanically, the carbon pool with soil cations creates cohesion forces that contribute to soil compaction [8,43].

Land management under CA can affect soil organic matter accumulation. CA practices foster the build-up of new soil organic carbon by protecting soil surface via plant residues or cover crops [3,9,12,19]. Furthermore, decomposition rate and carbon loss have been shown to be reduced by the inclusion of soil organic carbon in soil aggregates [10,24,44]. Soil organic content accumulation in soils is a reversible process, and even a single event of soil disturbance every growing season may lead to substantial loss of soil carbon over the years. Stable soil aggregate formation in conventional agricultural systems is inhibited by tillage-based practices [19,20]. Results from this study showed a similar pattern of increased soil organic matter in CA treatment as many other studies have [1–4], although the difference between CA and Non-CA treatment in this study was not statistically significant.

Soil moisture content in CA soils was higher (9.6%) than in tilled soils, but this difference in the first year of study was not statistically significant. Soil protection by the mulch layer decreases water evaporation from the soil surface and over time improves rainfall infiltration and water retention. Further, as soil erosion and runoff are decreased in CA fields, more available water can be accessible to plants during the dry season [16,45].

Potentially mineralisable nitrogen was higher in CA soils in the study, but the difference was not statistically significant. Many studies have documented increased nutrient availability in CA soils [2,5,8,17,21]. N availability is directly related to the carbon mineralisation rate. In CA systems, N availability can be low owing to higher immobilisation by plant residues, but the net immobilisation rate is higher. This temporary immobilisation of N in CA systems over the long-term decreases soil N leaching and denitrification losses [46,47]. Furthermore, plant residues from leguminous cover crops provide more carbon and nitrogen in soils under CA than do soils under tillage systems.

Generally, in CA treatment plots, soil organic content, water infiltration rate, potentially mineralisable nitrogen, and bulk density showed an improvement, but the differences were not statistically significant. Nonetheless, the positive pattern in soil quality parameters is consistent with other studies investigating the long-term effects of CA [3,7,8,18,25]. For instance, it was shown that after 4 years, there was a significant improvement in the water infiltration rate and soil moisture content during the dry season in Zambia and Zimbabwe [18]. The effects of CA treatment on the soil health indicators in the first year of conversion are rarely discussed in the research literature [48]. The results of this study confirm that it is possible to detect measurable changes in some of the soil health indicators and functions in the first year of the process of conversion to CA.

Concluding remarks

Most studies on changes in soil parameters produced by CA have examined the longer-term, not the short-term, effects. The results reported in this paper demonstrated that all the soil health indicators measured in this study, such as soil CO_2 emissions, soil aggregate stability, water infiltration, water content, potentially mineralisable nitrogen, soil organic content and bulk density, showed a change in the first year of the process of transformation from traditional tillage system to CA. In only two parameters were these changes statistically significant: decrease in the soil CO_2 emissions and the improvement of the soil aggregate stability. The lesson is that to meet the goals of sustainability, one must be patient, but there is abundant evidence that CA works better than tillage.

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