Influence of Long-Term Permanent Raised Beds and Contour Furrowing on Soil Health in Conservation Agriculture Based Systems in Tigray Region, Ethiopia

Tesfay Araya[1], Alemu Fanta[2], Frédéric Baudron[3], Mengsteab Hailemariam[4], Emiru Birhane[2], Jan Nyssen[5], B Govaerts[3], and Wim Cornelis[5]

[1]University of Fort Hare
[2]Mekelle University
[3]International Maize and Wheat Improvement Centre
[4]University of Science and Technology of China
[5]Ghent University

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Abstract

Conservation agriculture (CA) systems represent a set of three soil management principles that include minimal soil disturbance, permanent soil cover and crop rotations whereas the CA-based systems in this study add the bed and furrow tillage structures as integral elements of CA. This study aimed at investigating the long-term (2005-2013) influence of CA-based systems on soil health and crop productivity in northern Ethiopia. The treatments include two types of CA-based systems (permanent raised bed PRB and contour furrowing CF) and conventional tillage (CT). The experimental layout was arranged in a randomized complete block design. Soil samples were collected at 0-10 cm soil depth to assess soil health. Wheat root samples were used to measure arbuscular mycorrhizal fungi (AMF) colonization percentage using grid line intersect method. Piecewise structural equation modeling (PSEM) was used to understand linkages between management practices, soil health and crop productivity. Higher soil microbial biomass carbon (SMBC), AMF spore abundance and root colonization were recorded in PRB followed by CF as compared to CT ($P < 0.05$). Carbon sequestration rate, nutrient availability, plant available water capacity and air capacity were significantly higher in PRB and CF compared to CT. Outputs of the PSEM highlighted two pathways in which CA-based systems contributed to improved productivity: (1) via higher density of bacteria and improved hydraulic conductivity, and (2) via higher density of fungi and increase soil organic carbon content in the topsoil. The study concludes that CA-based systems have the potential to improve crop productivity through improved soil health.

1. Introduction

The farming practices in Ethiopia have to cope with minimizing risks of soil degradation, such as intensive and repeated tillage, complete crop residue removal, often intensive stubble grazing, and biomass burning that affect soil health. Repeated tillage using the *Mahresha* ard drawn by two oxen has been reported to be the main cause of land degradation in Ethiopia (Bezuayehu et al., 2002). This physical soil disturbance by tillage destroys soil structure, aggravates soil erosion, depletes the soil organic carbon (SOC), reduces soil fertility and thus, reduces crop productivity (Bezuayehu et al., 2002; Araya et al., 2016). Tillage practices can affect SOC through changing the different soil characteristics such as soil oxygen levels and thus, microbial activity (Lal, 2004a). For example, extensive hyphal network of Arbuscular mycorrhizal fungi (AMF) plays an important role in soil conservation by improving soil aggregation (Helgason et al., 2010), increased uptake of nutrients, especially phosphorus and improving water uptake (Miller, 1992). Repeated tillage, on the other hand, disturbs the hyphal network of AMF (He et al. 2003; Mozafar et al., 2000; Helgason et al. 1998). The farming system in the highlands of northern Ethiopia is a subsistence mixed crop-livestock system. Livestock production is an essential part of the farming system mainly for provision of draught power. However, the presence of high livestock population in the region has affected the ecosystem processes through overgrazing including the cropland resulting in biological disturbance, reduced root mass, increased runoff, and increased soil temperature that can aggravate rainwater loss by evaporation.

Maintaining and building soil health is an essential component of long-term sustainable agricultural management practices. For this reason, research on long-term management practices has been directed to devising measures of the health of soil, which could be used to monitor its condition and inform its management so that degradation is avoided. Soil health is defined as the continued capacity of the soil to function as a vital living ecosystem that sustains plants, animals and humans (Doran and Zeiss, 2000). Soil health and soil quality are often used interchangeably. According to Kibblewhite et al. (2007), use of the term soil quality will generally be associated with a soils' fitness for a specific use. Soil health is used in a broader sense to indicate the capacity of soil to function as a vital living system to sustain biological productivity, promote environmental quality, and maintain plant and animal health (Kibblewhite et al., 2007). On the other hand, Bünemann et al. (2018) conclude that the distinction between soil quality and soil health developed from a matter of principle to a matter of preference and they, therefore, consider the terms equivalent. Assessment of the soil health system may be achieved using diagnostic tests that include abiotic and biotic soil properties and soil functions. Abiotic soil properties are indicative of the state of the habitat (i.e. physical and chemical conditions such as soil bulk density, aggregate stability, pH, cation exchange capacity, etc.) and the levels of key energy and nutrient reservoirs (e.g. ratios of organic matter fractions and nutrient balances), while biotic soil properties describe the community composition, populations and biotic activities such as soil respiration and enzymatic activities of key functional groups of soil organisms. Soil ecosystem services depend on soil properties and their interaction, and are mostly influenced by its use and management. Only a few studies have linked soil properties to ecosystem services. The majority of these studies were relating soils to the defined soil functions that ultimately determined the delivery of ecosystem services. Adhikari and Hartemink (2016) reported that soil functions include availability of nutrients and water, carbon sequestration, food production, physical stability and support of plant systems and human structures, and promotion of biodiversity and habitat. They concluded that future evaluations of ecosystem services should focus on soil functions. However, there is no single definition of soil function (Hatfield et al., 2017).

Conservation agriculture (CA) involves three practical principles: reduction in tillage with a final goal to achieve zero tillage; retention of adequate levels of crop residue to cover at least 30% of the soil surface and use of crop rotations (FAO, 2018). CA has been widely promoted to overcome continued soil degradation and restore the soil physical, chemical and biological properties, and functioning of degraded soils (Powlson et al., 2016; Friedrich et al., 2012). CA practices can affect SOC either directly by increasing plant root biomass and the amount of C potentially returning to the soil as crop residues, or indirectly by changing the mineralization rate of SOC (Lal, 2004a). Farmers in the US, Canada, Latin America, Europe and certain parts of South Asia, for soil and water management and improved crop yield (Friedrich et al., 2012), have thus successfully adopted CA systems. Yet, acceptance of the practice is persistently low in Africa south of Saharan particularly in Ethiopia (Giller et al., 2009).*An in situ soil and water conservation (SWC) tillage practice that integrates* the principles of CA can reduce cropland degradation, improve soil health, thereby increasing crop productivity, and facilitate uptake of CA in Ethiopia. In this study, CA-based systems consider permanent raised beds (PRB) and contour furrowing (CF) as integral elements of CA. The shift from conventional tillage to CA-based system can alter the aforementioned soil functions. In this case, for developing sustainable agricultural practices, it is crucial to understand the multiple interactions between the soil biota and their abiotic environment as affected by soil management practices.

Our understanding of the linkage between soil properties and soil functions and the resultant ecosystem services is incomplete (Sarukhan et al., 2005). The ability of the soil to provide these functions will depend upon the state of the soil properties. Generally, Vertisols, the soil of interest in this study, have a high water holding capacity but are also characterized by high runoff rates and periodic waterlogging problems

(Araya et al., 2015; Sayre, 1998). Therefore, introducing*in situ* SWC tillage practices as a fourth principal components of CA systems (PRB and CF) can be useful to improve soil health. Previous studies from the same experimental plots focused on evaluating impacts of CA-based systems on soil water erosion, and soil water balance in the crop root zone (Opolot et al., 2016; Araya et al., 2015). The soil losses and runoff were significantly higher in CT systems while soil water storage was higher in CA-based systems (Araya et al., 2016). They also reported that permanently raised beds in CA systems protects the crops from water-logging, while excess water is drained from the raised bed to the furrows that enhance soil water storage. The assessment using selected indicators of soil properties and function becomes a key issue for assessing the impact of sustainable agricultural practices on soil health. In this study, the effects of long-term CA-based systems on soil health using abiotic and biotic soil properties and soil function indicators was evaluated.

Therefore, the objectives of this study were to determine the impact of long-term *in situ* SWC tillage practices in CA systems on soil health using selected abiotic and biotic soil properties, and soil function indicators in northern Ethiopia. We hypothesize that CA and in situ SWC improve soil health compared to conventional tillage systems.

2. Materials and Methods

2.1. Description of the study area

A field study was conducted in permanently kept plots (2005-2013) at farmers' rain fed fields in semi-arid area at Gum Selasa (13deg14'N, 39deg32'E) and an altitude of 2100 m a.s.l. in northern Ethiopia (Fig. 1).

The soil type under the experimentation in the study site is a Vertisol (Araya et al., 2016). The mean annual rainfall over 33 years (1971–2013) at Gum Selasa in Adi Gudom town (3 km away from the experimental plot) was 498 mm with more than 89% falling from June to September (Araya et al., 2016). The mean average temperature is 19.4 oC.

Mixed farming system is dominant which includes livestock and subsistence crop production. Oxen are the only source of draft power used for plowing. The traditional ox drawn *mahresha* ard plow is made up of a metal and wood (Fig. 2). Three to four tillage operations are conventionally done with an oxen-drawn ard to control weeds, improve infiltration and prepare a fine seedbed, particularly for tef (*Eragrostis tef*). The temporal pattern of plowing depends on the availability of oxen, type of crop and rainfall. The most cultivated crops include tef, barley (*Hordeum vulgare*), wheat, and grass pea (*Lathyrus sativus*).

2.2. Experimental Treatments and Layout

In brief, the experimental treatments consisted of conventional tillage, contour furrowing and permanent raised bed (Fig. 3). The experiment was arranged in a randomized complete block design (RBCD) with three replications. The crops grown in rotation throughout the experimental period from 2005-2013 were wheat, teff, wheat, barley, wheat, teff, grass pea, teff and wheat, respectively. The three treatments that include tillage and crop residue management practices are described below.

(1) Conventional tillage (CT): soil was plowed at least three times in a similar pattern with the local tillage practices and the crop straw was completely harvested without leaving residue on the soil surface. Although aftermath overgrazing is a common conventional practice in the study area, mimicking of this practice was not adopted in the experimentation because the plots were too small for animal movement. The depth of first and second plowing was about 15 cm, while 10 cm at planting. (2) Contour furrowing (CF): it involved plowing only once at sowing, 30% of the total crop residue was left as standing stubble to cover at least 30% of the soil surface and furrows were made at 1.5 m interval along the contour. The depth of plowing was about 10 cm. (3) Permanent raised beds (PRB): contour furrows were made at 35 cm interval with 30% of the total crop residue retained as standing stubble to cover at least 30% of the soil surface. Furrows were refreshed at planting while there was no tillage on the raised beds that were maintained undisturbed for 9 years (2005-2013).

The experiment was conducted under rain fed conditions with plot size of 5 m x 19 m. The slope gradient of the experimental plot was 3%. In 2013, wheat was sown in the first week of July at the start of the long Kiremt rainy season using manual broadcasting at the rate of 120 kg ha^{-1}. Plowing and reshaping of furrows was made using oxen-drawn*mahresha* ard plow at planting after broadcasting the seeds. This led to move the soil and seeds from the furrow to an upper position on the beds. N and P fertilizers were applied uniformly to all plots at the rate of 46 P_2O_5 kg ha^{-1} and 64 N kg ha^{-1}. Glyphosate at 2 l ha^{-1} (360 g a.i. l^{-1}) was sprayed each year starting from the third year (2007) to control weeds emerged before planting in CA-based (CF and PRB) systems a week before sowing; it effectively kills annual and perennial weeds. Hand weeding was used to control weeds that emerged after planting in all treatments.

2.3. Soil chemical analysis

Composite soil samples from three sampling locations per plot were taken from the experimental plots at 0–10 cm soil depth at the end of August 2013. The soil samples were used to analyze soil pH (1:2.5 H_2O), total soil N (Kjeldahl N, Bremner and Mulvaney, 1982), Olsen phosphate (Olsen, 1954), CEC (ammonium acetate extraction, Scholenberger and Simon, 1945) and $CaCO_3$ (acid neutralization, De Leenheer, 1959). Soil organic C (SOC, Walkley and Black, 1934) was determined at three soil depths (0–10, 10-20 and 20–30 cm) from a composite sample of three sampling per plot.

Although the bulk density (BD) of the Vertisol in our study, which is subjected to swell and shrink, changed from 1 to 1.71 Mg m^{-3} with soil moisture content (Araya et al., 2016), value of 1.35 Mg m^{-3} was taken to calculate soil organic C stocks.

$SOCS = \mathrm{OC}_{\mathrm{conc}} * BD * D * A * 0.001$

where SOCS is the soil carbon stock (Mg ha^{-1}),$\mathrm{OC}_{\mathrm{conc}}$ is the soil carbon concentration, D is the depth of the soil sample (m), A is an area of 10000 m^2, BD is soil bulk density (Mg m^{-3}) for the soil sampling depth and 0.001 is the conversion factor from kg to Mg (Mg Kg^{-1}).

SOC sequestration was calculated using the change in soil carbon stock (SOCS) over years (between 2006 and 2013) divided by the number of years for the same period (7 years):

$$\text{SOC sequestration} = \frac{(SOCs\ in\ 2013 - SOCs\ in\ 2006)}{2013 - 2006}$$

where SOCS is the soil carbon stock (Mg ha^{-1}).

The data for 2006 was taken from Araya et al. (2016).

2.4. Soil physical analysis

Bulk density was derived from the soil shrinkage characteristics curve (SSCC) measured by the balloon method as described in Cornelis et al. (2006) for shrinking and swelling soils. Soil water retention curve (SWRC) was established using two soil samples taken per plot by measuring soil-water contents at matric potentials of 0,-1.0, -2.9,-5.9, -9.8, -33, -100, and -1500 kPa on 100 cm^3 undisturbed soil cores using tension tables (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands) for high soil matric potentials (0 to -9.8 kPa) and pressure chambers (Soilmoisture Equipment, Santa Barbara, CA, USA) for low soil matric potentials (-33 to -1500 kPa), following the procedure outlined in Cornelis et al. (2005). A single ring with constant head permeameter using the Mariotte system of a Guelph permeameter (Soilmoisture Equipment) was used to measure field saturated hydraulic conductivity (KFS) with two replications per plot as described in Cornelis et al. (2005). Soil aggregate stability index (SI) was determined at 0-15 cm and 15-30 cm soil depth using the wet sieving method (Kemper and Rosenau, 1986).

Water retention data were used to calculate plant-available water capacity, air capacity and macroporosity. The plant-available water capacity, PAWC (m^3 m^{-3}), indicates the amount of water the soil can store and provide for plant roots (White, 2006). This was calculated as:

$$\text{PAWC} = \theta_{\text{FC}} - \theta_{\text{pwp}}$$

where ϑ_{FC} and ϑ_{PWP} are water content at field capacity, here considered at -33 kPa, and permanent wilting point (PWP) at -1500 kPa, respectively (m^3 m^{-3}).

The air capacity, AC (m^3 m^{-3}), indicates the soil aeration (Reynolds et al., 2009) and was defined by White (2006):

$$\text{AC} = \theta_s - \theta_{-10kpa}$$

where ϑ_s and $\vartheta_{\text{-10kPa}}$ are water content at saturation and at a matric potential of -10 kPa. The macroporosity, MacPOR (m^3 m^{-3}), gives the volume of large pores (i.e., > 300 µm equivalent diameter according to the capillary equation), and represents the ability of the soil to quickly drain excess water and facilitate root proliferation (Reynolds et al., 2009). It can be formulated as:

$$\text{MacPOR} = \theta_s - \theta_m$$

where ϑ_m is the soil-matrix porosity (MatPOR, m^3 m^{-3}). According to Greenland (1977), MacPOR can be seen as drained pores with an equivalent diameter of >50 µm. Then, using the capillary equation, the soil-matric potential corresponding to this pore diameter is -6 kPa.

2.5. Soil biological analysis

Two composite soil samples per plot were taken at 0-10 cm depths in the first week of August 2013 when the soil moisture was at about field capacity to determine the soil microbial biomass carbon (SMBC) using substrate-induced respiration (SIR) method (Anderson and Domsch, 1978). Soil microbial biomass carbon was calculated according to (Schinner et al., 1996) using the following equation.

$$\text{RQ} = \frac{(B - D)\, x2.2x100}{4xSWxDM}$$

Where RQ is respiratory quotient in milligram of CO_2 per 100 gram of soil per hour, B is volume of HCl consumed by blanks (ml), S is volume of HCl consumed by samples (ml), 4 is incubation time (h), 100 is conversion factor (100 g dm), 2.2 is a conversion factor (1 ml 0.1 M HCl corresponds to 2.2 tolerant mg CO_2), SW is the initial soil weight (g), DM is the soil dry matter (%). It is assumed that a respiratory quotient of 1.1 mg CO_2 .100 g^{-1} dm. h^{-1} corresponds to 20.6 mg biomass-C.100g^{-1} dm (Erkossa et al., 2007). Thus, this factor was used to convert CO_2 to SMBC.

Two soil samples per plot were also taken at 0-10 cm soil depth during the growing season in mid-August 2013 to determine soil bacteria and fungi. The bacteria and fungi populations in the soil were determined by culture methods as described in Benson (2001).

Two composite soil samples per plot were taken during the growing season in mid-August 2013 to assess AMF spore density. AMF spores were separated from each dried soil sample by wet sieving and decanting process, followed by flotation centrifugation in 50% sucrose as described in Brundrett et al. (1996). Spore density was enumerated as spore number per gram of air-dry soil.

Samples of wheat roots were taken mid-August 2013 to measure percent root length colonized by AMF structures such as AMF hyphae, arbuscules and vesicles. A portion of each root sample was washed with 10% KOH and autoclaved (121 ^{0}C for 15 min), acidified with 3% HCl (v/v) for 30 min at room temperature. Cleared roots were transferred into a staining solution of Trypan blue (0.05% w/v) in lactoglycerol (1:1:1, lactic acid: glycerol: distilled water), and autoclaved at 121^0C for 15 min (Brundrett et al., 1996). Then, stained roots were left in a de-staining solution (50% glycerol). Finally, percentage of root AMF colonization was assessed using the gridline intersect method (Giovannetti and Mosse, 1980) under a compound microscope (100–400 times magnification) (Mc Gonigle et al., 1990). Presence of arbuscules, internal hyphae and vesicules was recorded from each intersect and expressed as a percentage of total root intersect. At each intersection, there were six possible mutually exclusive outcomes (Brundrett et al., 1996) and the line might intersect at p, q, r, s, t and u.

where p is the intersection at no fungal structures are seen, q is arbuscules, r is mycorrhizal vesicles, s is arbuscules and mycorrhizal vesicles, t is mycorrhizal hyphae but no arbuscules or mycorrhizal vesicles, and u is hyphae not seen to be connected to arbuscules or mycorrhizal vesicles.

A reasonable estimate of percentage of root length colonization was done from 100 or more intersections for each root sample:

$G = p + q + r + s + t + u$

where G is the total intersect inspected. The percentage of root length colonization by hyphae of all types was calculated as hyphal colonization (HC):

$$HC = 100 \left[\frac{G - P}{G} \right]$$

The percentage of root length colonized by AMF hyphae (MHC) was calculated as:

$$MHC = 100 \left[\frac{q + r + s + t}{G} \right]$$

The percentages of root length colonization by arbuscules, and the percentage of root length colonized by mycorrhizal vesicles, was calculated as arbuscular colonization (AMC)

$AMC = 100 \left[\frac{q+s}{G} \right]$ and vesicle colonization (VC):$VC = 100 \left[\frac{r+s}{G} \right]$.

2.6. Crop yield and straw

The crop grown in rotation during this study period in 2013 was wheat. Grain and straw yield of wheat was determined at harvest from areas of 1 m × 1 m in three replicates per plot.

2.7. Data Analysis

ANOVA was used with student t-tests at $\alpha = 0.05$ to test for statistical differences in soil properties and crop yield between the treatments. The data on percentage of AMF colonization and spore density was transformed using a logarithmic function followed by ANOVA analysis to test the statistical differences on the effects of treatments on AMF. Data were analyzed using the SAS statistical software (JMP version 11.0), and the standard error of treatment means was used for separation of means.

To understand the pathways linking management practices (CT, CF and PRB) to soil health (soil biology and soil properties) and ultimately to crop productivity, we used piecewise structural equation modelling.

Structural equation modelling (SEM) has been used extensively in psychology (MacCallum and Austin, 2000) and to a lesser extent in ecology (Pugesek et al., 2003). Its use remains limited in soil science, though it is a powerful method to develop causal understanding of the drivers of ecological interactions and processes in soils, instead of focusing solely on patterns, as argued by Eisenhauer et al. (2015). SEM is based on the use of cause-effect (i.e., structural) equations (two or more) to model multivariate relationships (Grace, 2006). It is related to regression, principal components analysis, and path analysis, but in addition to these methods, SEM provides a means to evaluate the structure of the model (i.e., direct and indirect relationships among variables) as well as the model parameters using observed data (McCune and Grace, 2002). As such, SEM can be used to test construct models (i.e., hypothesized models) and quantify relationships between model components (Grace, 2006).

A construct model was developed to test the pathways linking management practices to indicators of soil biology, indicators of soil properties, and wheat grain yield (Fig. 4). Because of the limited degree of freedom, only indicators of soil biology and soil properties could be used, and not the whole range of variables measured in this study. The density of bacteria and the density of fungi were used as proxy of soil biology. Regarding soil properties, the soil organic carbon in the top 10 cm of soil was used as proxy of soil fertility, the KFS as proxy of soil hydraulic properties, and the SI as proxy of soil structural properties.

Management practices were represented by two binary variables: contour furrowing (yes/no) and permanent raised bed (yes/no). Due to these two factorial variables and because SEM assumed a normal distribution for all the variables included in the model, we used piecewise structural equation modelling (PSEM). In this extension to SEM, paths are estimated in individual models and then pieced together to construct the causal model (www.jonlefcheck.net/2014/07/06/piecewise-structural-equation-modeling-inecological-research). This was performed using the R package *piecewise SEM* .

3. Results

3.1. Effects on biotic soil properties

Soil microbial biomass C, bacterial colony and fungi population were higher in PRB compared to CF systems and lowest CT (Table 1). Soil microbial biomass C was highest with PRB and least with CT at 0-10 cm soil depth, while CF showed intermediate values. Higher populations of bacteria colonies and fungus mycelia were recorded with PRB followed by CF compared to CT treatment (Table 1). The bacterial and fungi populations were highest under PRB and lowest in CT (Table 1 and 2).

AMF spore abundance and root colonization of wheat crops by the different AMF structures were significantly ($P<0.05$) affected by the treatments (Table 2). Higher AMF colonization was observed in PRB in HC, MHC, AC and VC as compared to CT (Table 1). There was significantly higher percentage of wheat root length colonized by AMF hyphae with PRB (88%) compared with CF (74%) and CT (58 %) systems.

3.2. Effects on abiotic soil properties

Soil aggregate stability index was significantly higher in CA-based treatments as compared with CT at 0-15 cm depth (Table 3) but not at 15-30 cm depth. The highest soil aggregate stability was observed on PRB and CF compared to CT on both soil depths (Table 3). PRB had higher KFS than CT treatment. However, CF did not show a significant different KFS in comparison with PRB and CT. The bulk density of the topsoil (0-10 cm) as derived from SSCC was, at higher soil water potential with higher soil moisture content, lower with PRB compared to CF and CT treatments. However, there was no significant difference in bulk density among treatments at low soil water potential when the soil was dry. The bulk density changed from about one Mg m^{-3} (at higher soil matric potential, swelling) to 1.71 Mg m^{-3} (at lower soil matric potential, shrinking) (Fig. 5).

The SWRC in Fig. 6 indicates significantly higher soil water content in PRB followed by CF and lowest in CT at higher soil matric potential while there was no significant difference at lower soil matric potentials.

The SOC was significantly higher ($p < 0.05$) with PRB than CF and CT at zero – 10 cm soil depth (Fig. 7). Similarly, SOC was significantly higher with CA-based treatments as compared to CT at both the subsoil depths (10-20 cm and 20-30 cm). Also higher total soil N was recorded in CA-based treatments (PRB and PC) than CT treatment (Table 4). The highest soil C: N ratio was found in CT followed by CF and the lowest with PRB (Table 4). Besides, available P was significantly higher in PRB followed by CF as compared to CT at 0-10 cm soil depth (Table 4). As expected, neither CEC nor texture was affected by the treatments, and change in soil pH was not significant (Table 3).

3.3. Effects on soil functions

The average SOC sequestration rates (Mg C $ha^{-1}yr^{-1}$) within the 0–10 cm soil depth was higher in PRB (0.62) followed by CF (0.49) and lowest with CT (0.25) over 8 years between 2006 and 2013 following the implementation of CA-based practices (Table 4). The total SOC added to the soil over 8 years (between 2006 to 2013) in the topsoil (0–10 cm soil depth) was significantly higher with PRB (4.31 Mg ha^{-1}) followed by CF (3.45 Mg ha^{-1}) and lowest with CT (1.72 Mg ha^{-1}) (Table 4).

PAWC, MacPOR and AC were significantly higher with PRB compared to CT (Table 4) indicating the improvements in water storage capacity, internal drainage and soil aeration in PRB. Soil N and available P were significantly higher in PRB as compared to CT signifying the improvements in nutrient availability in the CA-based systems.

Wheat grain and straw yields were significantly higher ($P < 0.05$) with PRB followed by CF as compared to CT (Table 5) demonstrating the improvement in soil functioning in terms of food production in the CA-based systems (Table 6).

3.4 Structural equation modeling

Outputs of the PSEM revealed two pathways linking CF and PRB to improved wheat yield in the conditions of the study: (1) via an increase of the density of bacteria and an improvement of KFS, and (2) via an increase in the density of fungi and an increase of soil organic carbon content in the topsoil.

Both CF and PRB were found to have a positive effect on the density of both fungi and bacteria, though the effect of PRB was around twice the effect of CF on these microorganisms (Table 6; Fig. 8). A positive relationship between the density of bacteria and KFS, and a positive relationship between, the density of fungi and SOC content in the topsoil, were found. Both KFS and SOC content in the topsoil were found to have a positive impact on wheat grain yield. No statistically significant relationship between SI and wheat grain yield was found. Similarly, no statistically significant relationship between the densities of bacteria and fungi on SI was found (thus, SI doesn't feature on Fig. 8).

4. Discussion

4.1. Effects on biotic soil properties

The highest SMBC was obtained in PRB at the upper soil surface followed by CF, confirming that CA-based systems can improve microbial activities (Madejón et al., 2007). The increase in SMBC in PRB and CF corresponds to the increased SOC and soil N. Higher SMBC may indicate increased potentially available N (Hart, et al., 1986). Retaining crop residue was not only relevant to improve SOC and N but also to enhance soil water storage by mulching the soil surface that limits water loss in the form of evaporation (Araya et al., 2015). The main sources of crop residue during the experimental period that have better soil surface cover were crops with high C: N ratios that include wheat (80:1) and barley (85:1) (Flower et al., 2012), while grass pea and tef residues (low C: N ratio crops) had short life span as soil surface cover due to fast decomposition rate. The residue of tef retained from previous season (2012) was completely decomposed before planting in June 2013 while residue of wheat and barley resist decomposition until next cropping season (personal observation). Wheat and barley had higher impact on SOC while lower on soil N as the crop straw has higher C and smaller N content. On the other hand, the legume crops have higher capacity to generate soil N whereas its role in terms of soil surface cover was negligible. Tef residue covers only about 20% of the target soil surface immediately after harvest as compared to the 60% residue cover in barley and wheat, although there was no straw retained during grass pea cropping. Growing dryland legumes such as grass pea in rotation or as cover crop with low C: N ratio as part of the CA-based systems can improve soil N availability (Flower et al., 2012). However, the fresh crop residue retained in CA-based systems might increase immobilization of soil N substantiating the need for N fertilizer application as part of the early stages of CA-based systems (Chávez-Romero et al., 2016).

There was significant difference in bacteria and fungi population among treatments indicating the improvements in CA-based systems. The highest bacterial and fungi population in PRB followed by CF could be attributed to the increased SOC and N source and reduced soil disturbances in the CA-based treatments.

Similar results were reported in other CA studies (Six et al., 2002; Lienhard et al., 2013). Wang et al. (2011) and Fierer et al. (2012) reported that CA had significantly higher SOC, soil N and microbial biomass and higher association of AMF with the crops as compared to CT.

Higher AMF spore density and colonization of wheat roots in CA-based treatments as compared to CT indicates that minimizing soil disturbance in CA-based treatments increases the spore (Table 2; Fig. 8). Jansa et al. (2002) reported an increase in mycorrhizal spores and root colonization on several crops with minimum tillage compared with CT practices. Minimal soil disturbance and the stability of the soil surface in CA-based treatments could prevent the fungi mycelium from being fragmented and promote production and expansion of AMF (Mc Gonigle et al., 1990; Kabir, 2005). If the AMF hyphal network is not disrupted, the next crop could be more rapidly connected to the network and have higher nutrient absorption capacity. Helgason et al. (2010) also reported AMF hyphae are sensitive to physical disruption by tillage. AMF spores germinate under suitable conditions of the soil matrix, temperature, CO_2 concentration, pH and P concentration (Helgason et al., 2010), and increase in the carbon supplied by the plant to the AMF can increase the uptake of P (Miller, 1992). AMF has reportedly increased nutrient uptake, salinity tolerance, drought tolerance, water uptake, root disease resistance, and photosynthesis (Srivastava, 1996; Sharmaet al., 1994). AMF extension of the plant root surface facilitates potential uptake and translocation of P, N, K, Ca, S, Cu, Mo, and Zn (Srivastava, 1996; Frey and Ellis, 1997). However, nutrient uptake by plants grown in CT can be lower than grown in CA-based systems (Miller, 1992). Kabir (2005) also reported that P concentrations were significantly greater with CA than with CT. The higher association AMF in the PRB and CF could help to increase the availability of P in the root zone and direct uptake by the crops. Al-Karaki et al. (2004) AMF colonization of roots has been shown to increase the uptake of water and drought resistance of wheat. Similarly, the wheat root colonization of AMF in this study was found to be higher in CA-based systems as compared to CT.

4.2. Effects on abiotic soil properties

The soil aggregate stability was significantly higher in CA-based systems as compared to CT (Table 3) implicating improvements for a number of soil physicochemical properties including water infiltration, water holding capacity, oxygen supply, and organic matter mineralization rates (Feller et al., 1996; Six et al., 2004). Minimum soil disturbance and increased SOC through retaining crop residue can improve aggregate stability, bulk density and porosity as well as the soil moisture and air regime that, altogether, stimulate the activities of the soil organisms. The bulk density was decreased significantly with PRB followed by CF planting systems compared to CT at higher soil water potential but non-significantly at lower matric potentials. The lowest bulk density at higher soil water potential with PRB planting system indicates higher capacity to conserve water in the root zone and improves soil productivity. It is well established that addition of SOM can not only reduce bulk density and increase water holding capacity, but also effectively increase soil aggregate stability (Kay and Angers, 2001). Similarly, higher soil water content were observed in CA-based systems as compared to CT at higher soil matric potentials indicating the impacts of SOC. Field saturated hydraulic conductivity were shown to increase with PRB and CF as compared to CT (Table 3) confirming the improvement in porosity of the soil at higher soil matric potentials.

Soil biological constituents such as bacteria and fungi can influence the formation and stabilization of soil aggregates (Table 6; Fig. 8; Six et al., 2004; Lavelle and Martin, 1992). Beare et al. (1997) showed that fungal hyphae were responsible for about 40% of the macroaggregation (>2000 um) and significantly greater retention of SOM under no-tillage soils than in CT. Mathew et al. (2012) reported that the population of bacteria and fungi like AMF and actinobacteria was higher in CA systems due to improvement in physicochemical and microbiological characteristics of the soil.

4.3. Effects on soil functions

Soil function indicators encompass carbon transformation, nutrient cycling, soil water and nutrient availability, soil structure, gas exchange, adequate rooting depth and food production (Adhikari and Hartemink, 2016). SOM provides nutrients and habitat to soil biota and contributes to particle aggregation, enhancing the physical structure of soils and then promoting aeration, water infiltration, and resistance to erosion and crusting (Horwath, 2007). The SOC sequestration rate (Mg C ha^{-1} yr^{-1}) was higher with PRB (0.62) followed by CF (0.49) and lowest with CT (0.25) (Table 4) indicating the potential of CA-based systems to play a role in the mitigation of greenhouse gases. The highest SOC sequestration rate reported in humid climates regions under no-till system was 0.22 Mg C ha^{-1} y^{-1} while 0.10 Mg C ha^{-1} y^{-1} in arid climates (Six et al., 2002). Lal (2004a) reported that an average long-term rate of SOC sequestration with no-tillage practices is 0.2 to 1 Mg C ha^{-1} y^{-1} for humid temperate regions while 0.05 to 0.25 Mg C $ha^{-1}y^{-1}$ for dry tropical regions. These rates are low compared to the average sequestration rate of 0.48 Mg C ha^{-1} y^{-1} reported by West et al. (2002). The weed biomass retained after killing by glyphosate in CA-based systems in our study and incorporated by tillage in CT instead of being grazed by livestock as at nearby farmers' crop fields might contribute to increase the SOC stock and sequestration rates in all treatments. Also the crop rotations and fertilizers added in all treatments might enhance root biomass and absence of aftermath overgrazing after harvesting in CT like that of CA-based systems might have increased the SOC stock in CT. The rate of SOC sequestration is also affected by the quantity and quality of biomass returned to the soil. Several studies revealed that the high potential of CA system for SOC sequestration (Lal, 2004a; Lal, 2004b; de M et al., 2001). Soil organic matter plays an important role in soil function determining soil biological quality (provision of substrate and nutrients for microbes), chemical quality (buffering and pH changes) and physical quality (water holding capacity and stabilization of soil structure) properties and susceptibility of soil to degradation (Kabir et al., 1998). Soil aeration is one of the most important determinants of soil productivity because it determines the level of oxygen in the soil (Kibblewhite et al., 2007). CA-based systems had higher AC as compared to CT indicating a better wheat growth rate in CA-based systems. Plants are sensitive to the soil aeration status of the soil (Hatfield et al., 2017).

The higher bulk density in PRB followed by CF as compared to CT at higher soil water potential and a similar trend in aggregate stability among treatments confirms the improvement in soil structure. The higher aggregate stability in CA-based systems as compared to CT could imply high resistances of the soil to erosion, raindrop and surface sealing. Thus, PAWC was significantly affected by treatments due to the improved soil structure in PRB in comparison with CT. The higher bulk density in CA-based systems as compared to CT at higher soil water potential while there was no significant change at lower soil water potential indicates as the improvement in PAWC was due to enhanced soil structure but not soil texture. Higher PAWC in CA-based systems as compared to CT system shows the importance of CA-based systems for climate change adaptation. Higher macroporosity (MacPOR) was observed in PRB than CF and CT proving the improvement in the ability of the soil to quickly drain excess water and facilitate root proliferation (Reynolds et al., 2009). Improving drainage in Vertisols can reduce the denitrification process while it can enhance aerobic condition in the soil and nutrient availability. The study area receives the highest amount of rainfall in August every year that made waterlogging a common phenomenon in the study area with poorly drained crop fields (Araya et al., 2015). On the other hand, the high oxygen demands due to crop residue retention that increased microbial activities in general might be a cause for oxygen deficiency and nitrate respiration in CA-based systems. MacPOR refers to the void spaces with diameter > 50 µm formed by soil aggregate formation in finer textured soil with higher SOM. The higher SOC sequestration rates and storage with an increase in PAWC in CA-based systems demonstrates that they can play a vital role to reduce net CO_2emissions and protect the livelihoods of the poor through adapting and mitigating climate change. Adaptation strategies of CA-based systems are related to improvement in PAWC in the root zone and thus minimize the effects of declining rainfall and dry spells and high soil surface temperature through retaining crop residue on crop yields (Giller et al., 2009). In addition, the improvements in MacPOR in CA-based systems contribute to draining excess rainfall and reduce crop yield loss due to waterlogging.

The suitability of soil for **s** ustaining plant growth and biological activity is a function of its physical properties (porosity, infiltration rate, water holding capacity, soil structure). Food production such as crop yield is an indicator of the soil functioning (Hatfield et al., 2017). The highest grain and straw yields were recorded in PRB compared to CF and lowest in CT (Table 5 and 6) indicating an improvement in soil properties of the PRB treatments (Table 6; Fig. 8). The higher wheat yield with CA-based practices as compared to CT was due to cumulative positive changes that occurred on bacteria, fungi, SOC and KFS in the CA-based systems (Table 6; Fig. 8). CA-based systems compared to CT improved SMBC and bacteria and fungi density of microorganisms (Table 1 and 2). An increase in SMBC, bacteria and fungi density can improve nutrient cycling and absorption of nutrients by plant roots (Kabir et al., 1998; Chávez-Romero et al., 2016) that might support the improvements in crop yields under CA-based systems. FAO (2018) also reported from the same experimental plots that the greater yield in CA-based systems was due to lower weed density, reduced tillage, crop residue management, in-situ water and soil conservation and less runoff and higher rainwater use efficiency. Chávez-Romero et al. (2016) reported similar findings.

4.4 Structural equation modeling

CA-based practices (PRB and CF) influenced soil biological properties such as density of bacteria and fungi significantly and thus, enhanced KFS and SOC, respectively (Table 6; Fig. 8; Six et al., 2004). Increased density of bacteria in CA-based systems positively affected KFS and improved wheat yield with PRB followed by CF as compared to CT (Table 6; Fig. 8). Frankenberger (1979) and many other authors reported that an increase in bacteria density reduced KFS in short-term experiments because of blockage of pores by the bacteria. However, long-term effects of bacteria improved KFS that led to improvements in wheat yield (Fig. 8) in this study might be associated to the incorporation of dead bacteria into the soil. Similar to the bacteria effects, increased fungi density have a positive effect on SOC accumulation (Table 6; Fig. 8). On other hand, an increased SOC have improved wheat yield in CA-based systems as compared to CT. Plants allocate a substantial portion of their photosynthetic products belowground to support their root systems (Gill and Finzi, 2016). The fate of this carbon includes root structures, root symbionts, autotrophic (root and root symbiont) respiration, storage compounds, exudates, volatile organic compounds, and the extraradical fungal hyphae associated with mycorrhizal roots. The fungal hyphae provides an efficient mechanism for distributing plant carbon throughout the soil, facilitating its deposition into soil pores and onto mineral surfaces, where it can be protected from microbial attack (Frey, 2019). According to Frey (2019), mycorrhizal exudates and dead tissues contribute to play a dominant role in SOC formation and stabilization.

5. Conclusions

The present study suggests clearly that CA-based systems can significantly alter physical, chemical and biological characteristics of the soil and influence the functional capacity of the soil as compared to CT systems. Abiotic soil properties such as bulk density, aggregate stability and KFS were significantly higher in CA-based systems compared to CT while there was no significant difference in pH and CEC. SMBC, bacteria and fungi population and AMF spore density were significantly improved with PRB followed by CF and lowest in CT. SOC sequestration rates, nutrient availability such as soil N and P, water availability (PAWC), drainage for excess rainwater (MacPOR), soil aeration (AC) and food production (wheat grain yield) were significantly improved with CA-based systems as compared to CT through minimizing soil disturbance and retention of crop residues at harvesting in CF and PRB systems. AMF spore abundance and root length colonization was also enhanced due to low level of soil disturbance in PRB and CF. However, the full benefit of permanent raised beds plus CA can only be expected after several years. Notwithstanding the overall better results of PRB compared to CF, the latter tillage system can be recommended as a first step for improving soil health whilst increasing crop yield. The long-term goal should be to achieve a permanent raised bed planting system along with the use of crop residues (PRB). Hence, CA-based systems (PRB and CF) can be recommended for large-scale dissemination and implementation to improve soil health and wheat yield on Vertisols and possibly on other soils in northern Ethiopia.

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Table captions Table 1. Soil microbial biomass carbon content, bacteria and fungi population in the different treatment under CA (PRB and CF) and CT in Gum Selasa**Table 2.** Mycorrhizae spore abundance and root colonization of wheat roots under the different conservation agriculture based systems in Gum Selasa**Table 3.** Selected physicochemical soil properties in conservation agriculture based systems during the 2013 rainy season in Gum Selasa experimental site**Table 4.** Effects of conservation agriculture based systems on soil function at the topsoil (0-10 cm) in in 2013 at Gum Selasa experimental site**Table 5.** Effects of conservation agriculture based systems on wheat grain and straw yield during the 2013 rainy season in Gum Selasa**Table 6.** Estimates and their confidence intervals and associated P-values derived from piecewise structural equation modelling for the predictors of wheat grain yield (YLD), soil organic carbon in the top 10 cm (SOC), hydraulic conductivity (KFS), and soil aggregate stability index (SI). Predictors with an associated P-value lower than 0.1 are in bold

Table 1

Soil function category	**Soil function indicators**	**PRB**
Soil carbon stock and sequestration (between 2006 and 2013)*	SOC sequestration rates (Mg C ha^{-1} yr^{-1})	0.62a
	SOC stock (Mg ha^{-1}) over 8 years	4.31a
Nutrient availability	Soil N (g kg^{-1})	1.4a
	Available P (ppm)	6.7a
Water availability	Plant-available water capacity (PAWC, m^{3}m^{-3})	0.16a
Drainage for excess rainwater	Macroporosity (MacPOR, m^{3}m^{-3})	0.13a
Soil aeration	Air capacity (AC, m^{3}m^{-3})	0.21a

PRB = permanent raised bed, CF = contour furrowing, CT = conventional tillage, MBC = microbial biomass carbon. Means with the same letter are not significantly different at (P< 0.05).

Table 2

Treatment	**Spore abundance (100 g^{-1})**	**Root colonization percentage of mycorrhiza**	**Root colonization percentage of mycorrhiza**	**Root colonization percentage of mycorrhiza**	**Root colonization percentage of mycorrhiza**
		HC (%)	**MHC (%)**	**AMC (%)**	**VC (%)**
PRB	529a	88a	61a	20a	20a
CF	287b	74b	44b	11b	10bc
CT	123c	58c	24c	5c	5c

Means with the same letter (letters) are not significantly different at (P< 0.05). PRB = permanent raised bed, CF = contour furrowing, CT = conventional tillage, HC = root length colonized by hyphea of all types, MHC = root length colonized by mycorrhizal hyphae, AMC = root length colonization by arbescules, VC = vesicle colonization

Table 3

Soil properties	Soil properties	PRB	CF	CT	CT
CEC (meq/100g soil)	CEC (meq/100g soil)	46a	46a	46a	43a
CEC of clay (meq/100g soil)	CEC of clay (meq/100g soil)	116a	116a	116a	106a
$CaCO_3$ (%)	$CaCO_3$ (%)	18a	18a	18a	18a
pH	pH	7.58a	7.60a	7.60a	7.61a
C: N ratio	C: N ratio	13b	14ab	14ab	17a
Soil aggregate stability index	Soil aggregate stability index	3.5a	3.0a	3.0a	1.8b
KFS (cm hr^{-1})	KFS (cm hr^{-1})	2.61a	1.37ab	1.37ab	1.04b
Texture (%)	Sand	29a	31a	31a	34a
	Silt	31a	30a	30a	26a
	Clay	40a	39a	39a	40a

SOC is soil organic carbon, N is nitrogen, CEC is cation exchange capacity and P is extractable phosphate by Olsen method, KFS is Field saturated hydraulic conductivity. PRB = Permanent raised bed, CF = Contour furrowing, CT = Conventional tillage. Means followed by the same letter within the column are not significantly different

Table 4

*Note that the soil carbon stock and sequestration was calculated at 1.35 Mg m^{-3} bulk density

Table 5

Treatment	Grain yield (t ha^{-1})	Straw yield (t ha^{-1})
PRB	4.3a	12a
CF	3.5b	10b
CT	2.8c	8c

* Means with the same letter are not significantly different at (P< 0.05). PRB = permanent raised bed, CF = contour furrowing, CT = conventional tillage

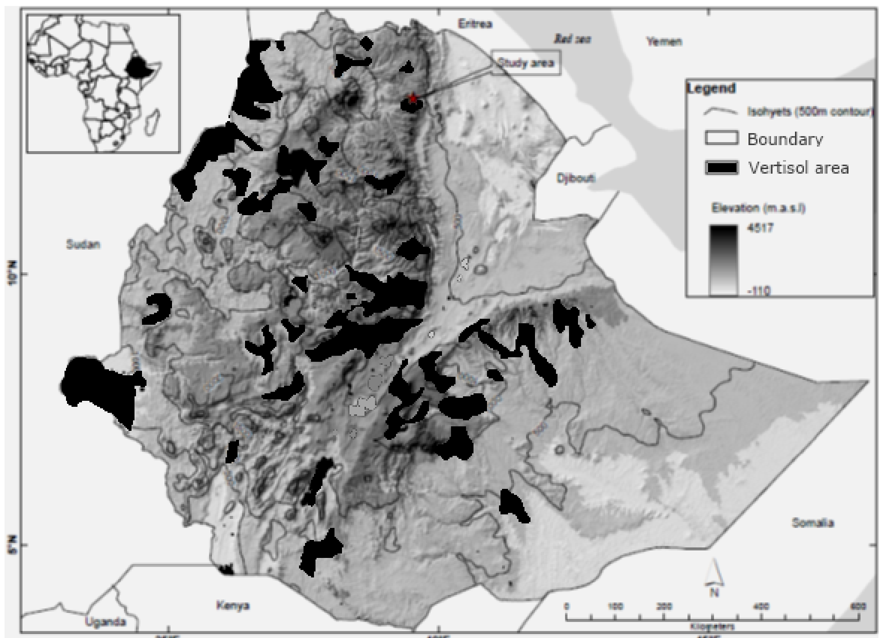
Table 6

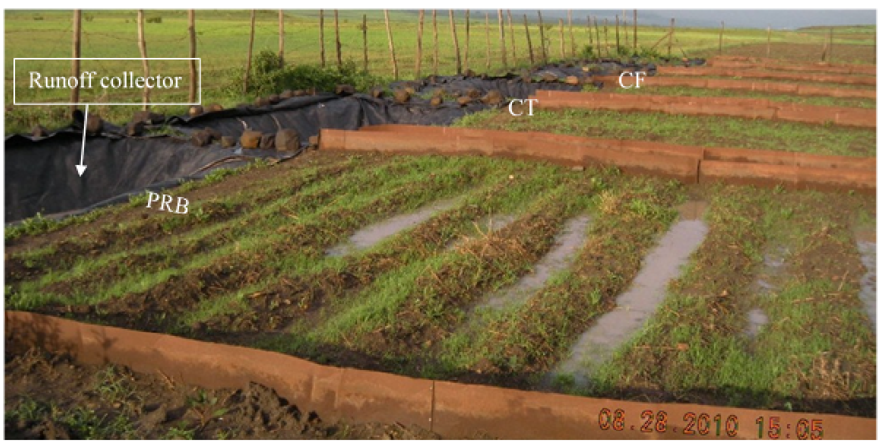
Predictor	Predictor	Estimate	Standard error	*P*-value
YLD	YLD			
	SOC	**5.3739**	**1.6151**	**0.0208**
	KFS	**0.4333**	**0.1407**	**0.0275**
	SI	-0.0020	0.0035	0.5946
SOC	SOC			
	BCT	0.0004	0.0006	0.4872
	FNG	**0.0019**	**0.0008**	**0.0608**
KFS	KFS			
	BCT	**0.0249**	**0.0099**	**0.0452**
	FNG	-0.0085	0.0133	0.5461

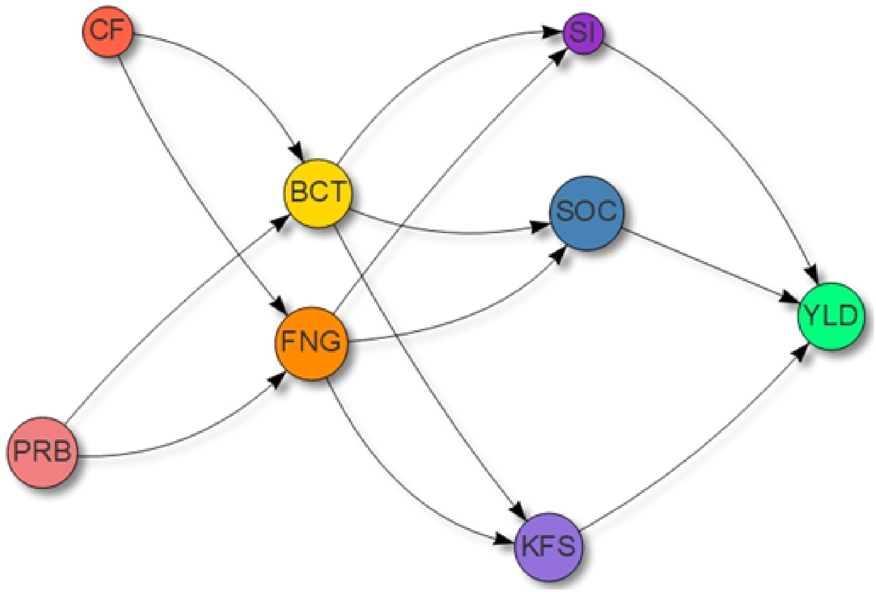
Predictor	**Predictor**	**Estimate**	**Standard error**	***P*-value**
SI				
	BCT	0.6040	0.4757	0.2512
	FNG	-0.4884	0.6393	0.4739
BCT	BCT			
	CF	**38.6667**	**9.8583**	**0.0078**
	PRB	**76.0000**	**9.8583**	**0.0002**
FNG	FNG			
	CF	**26.3333**	**10.3351**	**0.0436**
	PRB	**53.6667**	**10.3351**	**0.0020**

CF = contour furrowing, PRB = permanent raised bed, BCT = bacteria, FNG = fungi

Global goodness-of-fit: Fisher's C = 18.941 with P -value = 0.526 and on 20 degrees of freedom




Runoff collector
CF
CT
PRB
08.28.2010 15:05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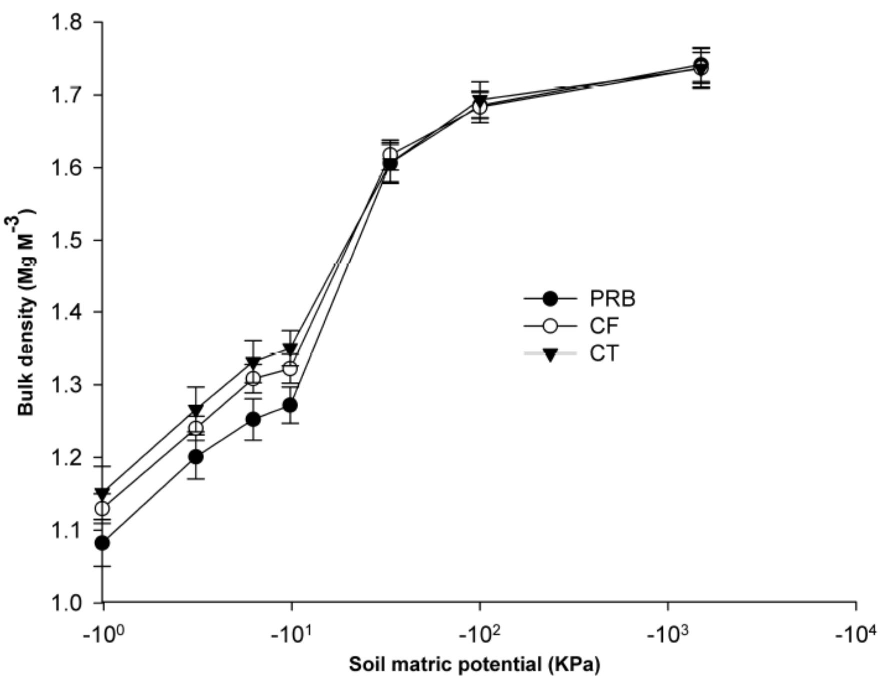
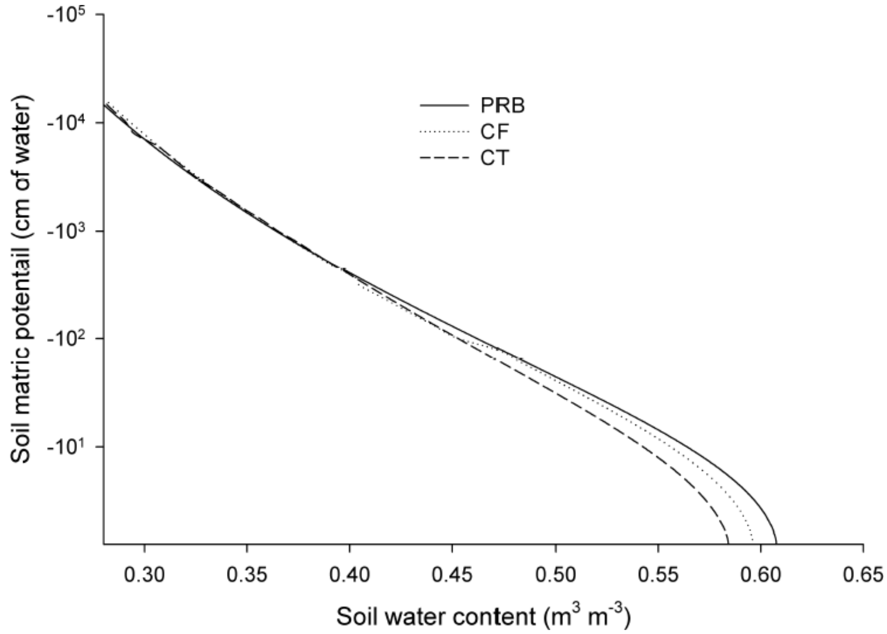
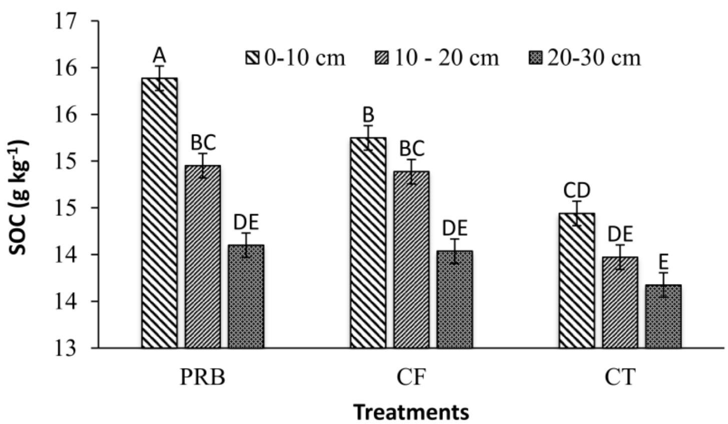
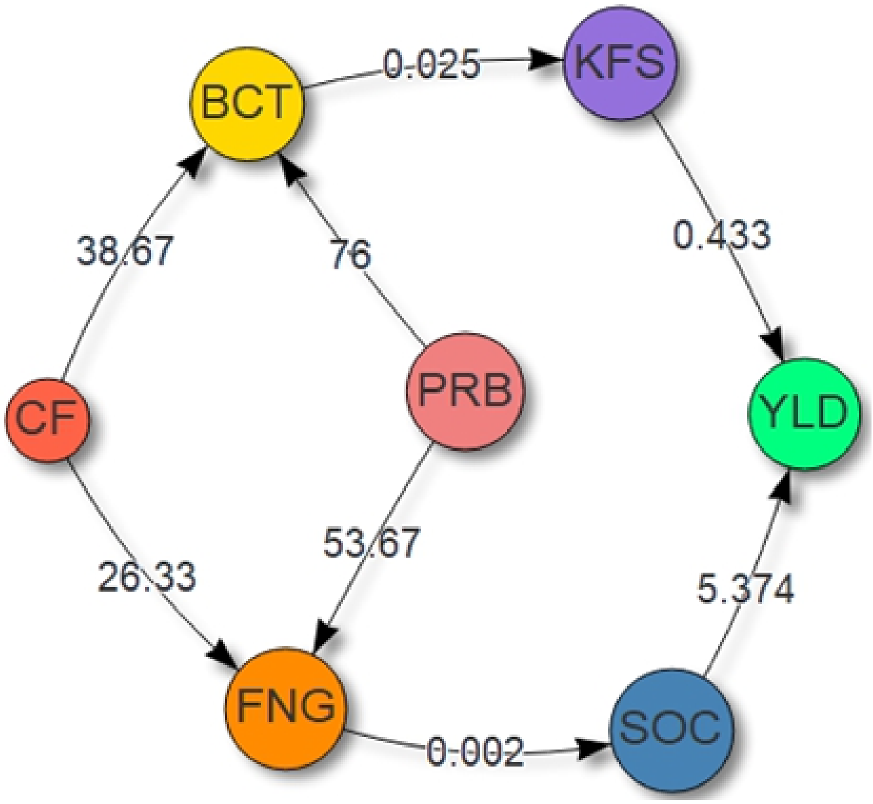
SI
BCT
SOC
YLD
FNG
PRB
KFS


1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
Bulk density (Mg M^{-3})
PRB
CF
CT
-10^0
-10^1
-10^2
-10^3
-10^4
Soil matric potential (KPa)


-10^5
-10^4
-10^3
-10^2
-10^1
PRB
CF
CT
Soil matric potentail (cm of water)
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
Soil water content (m^3 m^-3)



SOC (g kg-1)
17
16
16
15
15
14
14
13
A
BC
DE
B
BC
DE
CD
DE
E
0-10 cm
10 - 20 cm
20-30 cm
PRB
CF
CT
Treatments


BCT
0.025
KFS
38.67
76
0.433
CF
PRB
YLD
53.67
26.33
5.374
FNG
0.002
SOC