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Rémy Kulagowski[a,b,c,d,e], Alexis Thoumazeau[f,g], Audrey Leopold[c], Pascal Lienhard[d,e], Stéphane Boulakia[d,e], Aurélie Metay[f], Tobias Sturm[a,b,c], Philippe Tixier[h,i], Alain Brauman[j], Bruno Fogliani[b,k], Florent Tivet[l,e]

[a] Province Sud, Direction du Développement Rural, 98890, Païta, Nouvelle-Calédonie
[b] IAC (Institut Agronomique néo-Calédonien), ARBOREAL, 98890, Païta, Nouvelle-Calédonie
[c] IAC (Institut Agronomique néo-Calédonien), SolVeg, 98848, Nouméa, Nouvelle-Calédonie
[d] CIRAD, UPR AIDA, F-34398 Montpellier, France
[e] AIDA, Univ Montpellier, CIRAD, Montpellier, France
[f] ABSys, Univ Montpellier, CIHEAM-IAMM, CIRAD, INRAE, Institut Agro, Montpellier, France
[g] CIRAD, UMR ABSyS, F-34398 Montpellier, France
[h] CIRAD, UR GECO, F-34398, Montpellier, France
[i] GECO, Univ Montpellier, CIRAD, Montpellier, France
[j] Eco&Sols, CIRAD, INRA, IRD, Montpellier SupAgro, Univ Montpellier, F-34398, Montpellier, France
[k] ISEA, Université de la Nouvelle-Calédonie, BP R4, 98851, Nouméa cedex, Nouvelle-Calédonie
[l] CIRAD, UPR AIDA, Phnom Penh, Cambodge

Abstract

Conservation agriculture (CA) is one strategy with which both sustainability and productivity can be achieved by improving soil health. However, linkages between practices, soil health and cropping system performance remain poorly disentangled. We assessed the relationships between soil health and cropping system performance for three maize-based cropping systems in New Caledonia. Two CA systems, one with direct seeding into a mixed species dead mulch (CA-DM) and one into a stylo living mulch (CA-LM), were compared to a conventional tillage (CT) system. CA *vs.* CT experiment started in 2011, whereas the differentiation between CA-DM and CA-LM was initiated in 2017 only. In 2018, soil health was evaluated using Biofunctool®, a set of ten in-field tools that assess soil carbon transformation, structure maintenance and nutrient cycling functions. The performance of the three cropping systems were assessed by monitoring weeds, maize growth and yield components. Structural equation modelling (SEM) was used to disentangle the links between agricultural management, soil health and cropping system performance. Soil structure maintenance and nutrient cycling functions were higher under CA-DM and CA-LM than under CT, and carbon transformation function was higher under CA-DM than under CT and CA-LM. Overall, the soil health index (SHI) was 1.3-fold higher under CA systems than under CT. Cropping system management had both direct and indirect effects on soil functioning and crop productivity leading to a 1.3-fold higher yield under CA than under CT. The direct and indirect effects of CA systems on soil health had positive impacts on ecosystem services (*i.e.*, productivity, weed regulation and soil ecosystem services). Such integrative approaches that account for the relationships and possible trade-offs between cropping system components enable a better understanding of the effects and the performance of practices, and support adaptive agricultural management.

Keywords Cover crop; Living mulch; Magnesic fluvisol; No tillage; Soil functions; Systemic approach

1. Introduction

Agricultural practices are key drivers of agroecosystem functions and their negative impacts have increased in recent decades. Land use changes, intensive use of chemical inputs, and fragmentation of habitats have contributed to the depletion of soil fertility, biodiversity, water quality and availability, and to the magnitude of climate change (Foley et al., 2011; Rockström et al., 2017). These rapid changes have also had positive effects including increasing food production at global scale, but significant trade-offs have been observed, to preserve environmental integrity (Tilman et al., 2011). Soil is one of the key components of ecosystems and is under serious pressure from human activities. To mitigate the negative impacts of agricultural systems, some approaches promote agronomic technical levers such as soil conservation practices or agroforestry (Altieri and Nicholls, 2013; Wezel and Soldat, 2009).

Agriculture represents less than two per cent of the gross domestic product of New Caledonia where the economy is mainly driven by the nickel industry and the service sector (ISEE, 2016). However, islands in the South Pacific need to increase their agricultural production to respond to population growth and to increasing demand from the commercial sector (Murray, 2001; Naidu, 2010). Like in many developing countries, agricultural intensification in these islands has had positive impacts on agricultural production and food security (Naidu, 2010; van der Velde et al., 2007). Unfortunately, agricultural intensification has also had detrimental impacts on soil and water resources, including significant soil erosion (Dugain, 1953; Losfeld et al., 2015), especially in New Caledonia, a hotspot of biodiversity (Myers et al., 2000).

Conservation agriculture (CA) is a farming system that promotes minimum soil disturbance (*i.e.*, no tillage), maintenance of a permanent soil cover, and diversification of plant species (FAO, 2014). Through the application of these three principles, the maintenance and improvement of soil functioning is driven by (i) high and continuous production of above and belowground biomass, (ii) a permanent soil cover which supports a continuous flow of nutrients and organic compounds and improves the water balance, and (iii) enhanced soil biological activity which regulates carbon transformation, soil structure maintenance, and improved nutrient cycling (FAO, 2014; Hobbs et al., 2008; Scopel et al., 2013). CA is being promoted to improve the resilience of cropping systems and reduce their negative externalities (Hobbs et al., 2008; Lal, 2015a; Séguy et al., 2006). CA can help reduce physical, chemical and biological soil depletion and production costs (Palm et al., 2014; Scopel et al., 2013; Sithole et al., 2016; Thierfelder and Wall, 2012). CA practices could thus be a promising way to reduce the negative impacts of agriculture, especially on soil, while conserving production and ecosystem services (Pittelkow et al., 2015; Verhulst et al., 2010).

The relationships among soil and crop management practices, soil health, crop performance and ecosystem services under CA practices are poorly described in the literature (Palm et al., 2014; Ranaivoson et al., 2017; Verhulst et al., 2010). Appropriate and sensitive indicators should be selected to assess agrosystem multifunctionality. Soil health is defined as "the capacity of a soil to produce a good quantity and quality food and fibre together with the delivery of other ecosystem services" (Kibblewhite et al., 2008). Although many approaches are available to assess soil health, Thoumazeau et al. (2019b) proposed an integrative, multifunctional, and easily transferable approach, named Biofunctool®. Biofunctool® makes it possible to assess the three main soil functions linked to soil biological activities identified by Kibblewhite et al. (2008): (i) carbon transformation, (ii) nutrient cycling, and (iii) soil structure maintenance with a core set of ten in-field and low-tech indicators. Weeds and crop development are key aspects to assess cropping system performance. Weeds are indeed a major factor affecting yields (Teasdale et al., 2007) and weed control is one of the farmer's main concerns in agricultural systems (Hobbs, 2007; Nichols et al., 2015; van Heemst, 1985). On the other hand, grain yield is the main indicator used by farmers to assess the performance of their system. Combining these measurements should help understand the synergies and trade-offs between the components that may affect cropping system performance.

We hypothesise that CA practices have both direct and indirect effects on weeds and crop productivity by influencing soil health, thereby increasing the performance of CA compared to that of CT. The overall objective of the study was to conduct an integrative and quantified assessment of the relationships between contrasted maize-based cropping management (*i.e.*, conventional plough-based tillage (CT), and CA with a diversity of cover crops and managements), soil health and cropping system performance in New Caledonia.

2. Materials and methods

2.1. Site description

The study site is located at the Adecal Technopole Ouenghi experimental station in Boulouparis, South province, New Caledonia (21°53'50" S, 166°06'45" E). The west coast of New Caledonia is characterised by a semi-arid subtropical climate with a cool, dry season from May to September, and a warm, wet season from December to April. Intense rainfall associated with thunderstorms peaking in austral summer are usually followed by recurrent drought periods from October to November. Data from the Ouenghi Meteo-France station (21°55'42"S, 166°05'00"E; 3.5 km from the study site) were used to characterise the meteorological conditions. Mean annual precipitation between 2011 and 2018 was 909 mm with most of the rainfall occurring from February to April. In the same period, the monthly average minimum and maximum temperatures were 17 °C and 29 °C, respectively.

Soil is classified as a silty loam soil according to the USDA classification with 33.6% sand, 51.6% silt and 14.8% clay (Euro-analyse laboratory soil analysis, 2011). It is a magnesic alkaline soil (pH_{water} = 8.1) with high concentrations of Mg^{2+} (exchangeable magnesium accounts for 76% of cation exchange capacity) and Ca/Mg = 0.3 (K/Mg = 0.01). The average bulk density (in the 0-10 cm layer) was 1.01 ± 0.08 g cm^{-3} and soil organic carbon (0-20 cm depth) was 28.1 ± 1.1 g kg^{-1} (LAMA laboratory soil analysis, 2017).

2.2. Experimental design

The experiment was set up in 2011 to study contrasted cropping systems representative of cereal production along the west coast of New Caledonia characterised by short rotations and maize (*Zea mays* L.) grain as main crop production. Two main periods characterize the experiment (Supplementary information, Table A.1). From 2011-2016, the cropping sequence was based on a succession cowpea-maize and cowpea-maize-sorghum under two type of management: (i) conventional plough-based management (CT), and (ii) CA management based on dead mulch. Cowpea (*Vigna unguiculata* L.) was used as a cover crop before maize in all treatments. The second period started in 2017, when the cropping pattern was updated with a maize-based cropping system under three different managements: (i) maize under CT, which is the main practice in the region, which represented a continuation of the CT management of the first period, (ii) maize under CA with direct seeding in a dead mulch (CA-DM), and (iii) maize under CA with direct seeding in a living mulch (CA-LM). CA-DM and CA-LM represented the continuation of the plots under CA management in the first period. Crop residues were not exported in all the cropping systems, and under CT, the soil was ploughed once a year to a depth of 25-30 cm with a mouldboard plough. A randomised block design experiment was used consisting in the three treatments with three replicates of plots measuring 1200 m² (50 m x 24 m) for each system (Supplementary information, Fig. A.1).

In 2018, all cover crops were sown on the 24th of January with a no-till seeder (Semeato PD 17) (Supplementary information, Table A.2). The cover crop used under CA-DM consisted of a mix of four species: sorghum (*Sorghum bicolor* L. Moench, cv. sweet jumbo; sowing density 15 kg ha^{-1}), sunnhemp (*Crotalaria juncea* L., cv. crescent sunn; 10 kg ha^{-1}), cowpea (*Vigna unguiculata* L. Walp., cv. ebony; 10 kg ha^{-1}), and lablab (*Lablab purpureus* L. Sweet, cv. highworth; 15 kg ha^{-1}). The cover crop used under CA-LM was stylo (*Stylosanthes guianensis* Aubl. Sw.; 10 kg ha^{-1}). Under CT, the mouldboard plough was used on the 19th of March 2018 to a depth of 25-30 cm, and the rotary cultivator on the 27th of April 2018 to a depth of 5-10 cm, before maize sowing. Under CA-DM, the cover crop was terminated by rolling combined with herbicide spraying on the 20th of April 2018, 15 days before the maize was sown. Under CA-LM, the maize was sown directly in standing green stylo. The aboveground biomass of the cover crops was assessed before maize was sown and ranged from 22.6 ± 8.8 $t_{\text{dry matter (DM)}}$ ha^{-1} to 2.5 ± 0.8 t_{DM} ha^{-1} under CA-DM and CA-LM, respectively. Under CA-DM, 100% of the soil surface was covered by mulch at sowing and about 80% under CA-LM.

In all cropping systems, maize was grown during the dry, cool season (May-September) with 223 mm cumulative precipitation during the crop cycle. Maize (cv. CS Frontal) was sown at 108000 kernels ha^{-1} in 76-cm rows on the 7th of May 2018, using a no-till seeder (Jumil JM3090 PD). A hose reel irrigation system was used on 13 occasions to supply 290 mm of water. The water balance method was used to determine water amounts, and irrigation uniformity was controlled by rain gauges. The nitrogen (N) fertilisation during the maize cycle included 350 kg ha^{-1} of urea (46% N) and 300 kg ha^{-1} of ammonium sulphate (21% N) applied 17 and 51 days after sowing (DAS), respectively. Herbicide treatments included pre- and post-emergence herbicides. Pre-emergence herbicides were applied immediately after sowing, while post-emergence herbicides were applied at 10 and 31 DAS.

2.3. Soil monitoring and analysis

Biofunctool® consists in a set of ten functional indicators that assess three main soil functions with (i) carbon transformation, (ii) soil structure maintenance and (iii) nutrient cycling (Thoumazeau et al., 2019b). Four indicators were used to assess the changes of the carbon transformation including the labile fraction of the soil organic carbon (permanganate oxidizable carbon (POXC)) (Weil et al., 2003); the basal soil respiration (SituResp®) (Thoumazeau et al., 2017); and the soil biological activity using the bait lamina test (scored from 0 [no degradation] to 1 [complete degradation]) (Törne, 1990; van Gestel et al., 2003) and the green tea bag (GTB) score (adapted from Keuskamp et al. (2013)). The bait lamina consists of a plastic strip, comprising 16 small holes, that was filled with an organic standard substrate, made of cellulose powder, bran flakes and active carbon (70:27:3). Bait laminas were vertically inserted in the soil for seven days. For the analysis, we used the average of lamina holes number 1 to 4 (0-2 cm) only, as it was the only depth that allowed us to significantly distinguish the treatments (Supplementary information, Fig. A.2). The GTB indicator consisted in the decomposed fraction of green tea after a burial period of 30 days.

We then used three indicators to study the impact of each cropping system on soil structure maintenance function by assessing soil aggregate water stability (AggSoil) at a depth of 0-10 cm (scored from 1 [poor] to 6 [high stability]) (Herrick et al., 2001), water infiltration (Beerkan) (Thoumazeau et al., 2019b), and soil structure (visual evaluation of soil structure (VESS)) in the 0-30 cm layer (scored from 1 [good] to 5 [poor soil structure]) (Guimarães et al., 2011). The VESS consists of visually assessing the size and porosity of aggregates, the strength of aggregates, the presence of roots and the colour of the soil. Finally, we used three indicators to study the impact of each cropping system on soil nutrient cycling function. We quantified available ammonium (N-NH_4^+) and nitrate (N-NO_3^-) in the soil after extraction with 1*M* KCl (Maynard et al., 1993; Thoumazeau et al., 2019b). Soil nitrate dynamics were evaluated using anion exchange membrane (AEM-NO_3^-) placed horizontally at a depth of 8 cm for a 10 days burial period (Qian and Schoenau, 2002; Thoumazeau et al., 2019b).

Except for the VESS, soil samples were collected in June 2018 in the 0-10 cm soil layer. This soil layer was selected to fit with Biofunctool® approach that aims at integrating soil biological activities (Thoumazeau et al., 2019b). Also, early changes under CA mostly occur at the soil surface, making the top soil assessment highly relevant (de Moraes Sa and Lal, 2009). Three sampling points (internal replicates) were collected per plot giving a total of 27 soil samples for Biofunctool® analysis (except for available nitrogen (N-NH_4^+, N-NO_3^-) for which only one replicate per plot was analysed).

2.4. Agronomic data collection

Weed biomass was assessed using a quadrat sampling method at four maize stages: sowing, 6-leaf (25 DAS), flowering (80 DAS), and post-harvest. In each repetition (three repetitions per treatment), three quadrats of 0.25 m² were delimited to count weeds. Weed aboveground biomass was then determined for each sampling period after drying at 80 °C until constant mass was reached. Cumulative weed biomass per treatment was determined by adding the dry matter of the four sampling periods.

Maize density was monitored weekly in three subplots per repetition (three repetitions per treatment) on two contiguous maize rows two meters in length (3.04 m²) from emergence to the 8-leaf (35 DAS) stage. Maize density per treatment was the average of the maize counted during the successive sampling periods.

At harvest on the same subplots, thousand kernel weight (TKW) was measured at random from the grain lot of five maize plants per repetition (three repetitions per treatment). Three subsamples per repetition of one hundred kernels were dried at 80 °C until constant mass was reached and weighed. TKW was then standardized to 13% moisture content.

The yield was recorded from five plants randomly selected from three sub-plots per repetition (three repetitions per treatment) following methodologies from Echarte et al. (2006) and Daei et al. (2009). The ears were counted, and hand-shelled. The kernels of each ear were dried, and weighed. The grain yield was calculated as follows and standardized to 13% moisture content:

$$\text{Maize yield } (\text{t ha}^{-1}) = \text{Maize density } (\text{plants m}^{2}) * \text{Number of ears per plant } (\text{ear plant}^{-1}) * \text{Kernel weight per ear } (\text{g ear}^{-1}) * 10^{-2}$$

2.5. Statistical analysis

All statistical analyses were performed using R software 3.6.0 (R Development Core Team, 2008).

First, each Biofunctool® indicator was analysed separately using a linear-mixed effects model (package lme4, (Bates et al., 2015)). Treatment was defined as fixed factor and replicates (plots and internal replicates) as random factors. After checking the normality of the model residuals and the homoscedasticity of the variance residuals, ANOVAs were run using the car package (Fox and Weisberg, 2011). This was followed by a post-hoc mean comparison, using Tukey's test with Bonferroni adjustment (Hothorn et al., 2008).

After analysing each indicator separately, indicators were computed within a principal component analysis (PCA) (FactoMineR package, (Lê et al., 2008)). The last step of analysis consisted in calculating the Biofunctool® soil health index (SHI), according to the methodology defined by Obriot et al. (2016) and Thoumazeau et al. (2019a). First, a weight was applied to the PCA variable to give the same weight to each soil function. The scoring function of the indicators was based on the "more is better" response curve, except for the VESS indicator where the "less is better" was used (Obriot et al., 2016). The SHI finally ranged from 0 (low) to 1 (high soil health). After calculation of the index, a variance analysis of the contribution of each soil function to the final score was run using one-way ANOVA.

Next, we used SEM (Grace et al., 2012, 2007) to explicit relationships from a web of possible causal pathways, including direct and indirect effects between practices (CT and CA systems), soil health and cropping systems performance. CA-DM and CA-LM were grouped into a single cropping system modality (CA). A combination of the aboveground biomass of the cover crops at maize sowing and the soil management practices (qualitative data) was used to characterize cropping system practices for the SEM. The three Biofunctool® aggregated functions (*i.e.*, structure maintenance, nutrient cycling, and carbon transformation) were used as soil health indicators. Cumulative weed aboveground biomass during the maize cycle, maize thousand kernel weight (TKW) and grain yield were used as cropping system performance parameters for the SEM. Weeds are a major factor that affects yields (Teasdale et al., 2007). TKW was used to assess maize growth performance, providing insight into the strength of late competition (Meynard and David, 1992). Grain yield expresses the overall conditions of the crop cycle, and is the main indicator used to assess system productivity. Strength and directionality (positive or negative) of the relationship between variables are indicated through the path coefficients. The SEM was performed using the piecewiseSEM package (Lefcheck, 2016).

3. Results

3.1. Effects of the cropping systems on soil health

For carbon transformation, labile fraction of the soil organic carbon (POXC), basal soil respiration (SituResp®) values as well as bait lamina scores were significantly higher under the two CA cropping systems than under CT (Table 1). The GTB score was significantly higher under CA-DM (0.46 ± 0.03) than under CT (0.43 ± 0.02) but did not significantly differ from CA-LM (0.45 ± 0.02).

Concerning structure maintenance, the same trend was recorded for the three indicators (Table 2). Mean VESS scores were significantly lower for soils under CA (1.45 ± 0.3 and 1.28 ± 0.3 for CA-DM and CA-LM, respectively) indicating a better soil structure than under CT soil (2.11 ± 0.4). Mean AggSoil scores were significantly lower under CT soil (1.22 ± 0.4) than CA soils (2.00 ± 0.8 and 2.15 ± 0.9 for CA-DM and CA-LM, respectively). Finally, water infiltration was two-fold lower in soil under CT (93.4 ± 20.5 mL min^{-1}) than in soil under CA (176.5 ± 71.5 and 226.0 ± 117.3 mL min^{-1} for CA-DM and CA-LM, respectively). No significant differences were found in VESS, AggSoil, and Beerkan scores between CA-DM and CA-LM.

For nutrient cycling, the mean AEM-NO_3^- score was two-fold higher under CT than under CA (20.4 ± 6.4 *vs.* 10.5 ± 4.0 and 9.8 ± 5.0 µg cm^{-2} d^{-1} for CA-DM and CA-LM, respectively) (Table 3). In contrast, the concentration of N-NH_4^+ was two-fold higher under CA-DM than under CT (6.1 ± 0.2 mg kg^{-1} *vs.* 2.6 ± 0.3 mg kg^{-1}). The concentration of N-NO_3^- tended to be higher under CA than under CT but the differences were not statistically significant.

The PCA performed on the 10 functional indicators allowed to separate the treatments (Fig. 1). The differences between Biofunctool® indicators appeared mainly between the CT and CA cropping systems. Total variability was represented at 45.7% on the first axis and at 14.2% on the second axis. The difference in soil health between the two CA cropping systems and CT was mainly based on indicators linked with the first axis: AEM-NO_3^- and N-NH_4^+ (nutrient cycling), VESS and AggSoil (structure maintenance), and POXC (carbon transformation).

Biofunctool® SHI values for CA treatments were about 1.3-fold higher than under CT (mean value of 0.7 *vs.* 0.5) (Fig. 2). For the nutrient cycling and the structure maintenance functions, the main differences were observed between CT and CA with mean CA scores (CA-DM and CA-LM) 20% and 46% higher than under CT, respectively. Concerning soil carbon transformation function, only the CA-DM score was significantly higher than CA-LM and CT, representing an increase of 12%.

3.2. Performance of the cropping systems

The cumulative aboveground weed biomass differed significantly among the three treatments with higher weed biomass under CT (mean value of 1.4 ± 0.7 t_{DM} ha^{-1}) than under CA-LM (0.2 ± 0.3 t_{DM} ha^{-1}) and CA-DM (0.7 ± 0.3 t_{DM} ha^{-1}) (Table 4).

Maize density differed significantly among the treatments: the maize plant population was higher under CA-LM (10.3 ± 0.5 plants m^{-2}) than under CT (9.0 ± 0.4 plants m^{-2}) and CA-DM (8.0 ± 1.1 plants m^{-2}), with a decrease at emergence under CA-DM.

There was one ear per plant for all the maize plants sampled. The kernel weight per ear was significantly higher under CA-DM (158.6 ± 25.5 g) than under CA-LM and CT (125.8 ± 18.2 g and 107.8 ± 21.0 g, respectively). The TKW followed the same trend and was significantly higher under CA-DM (388.2 ± 7.5 g) than under both CA-LM and CT (364.2 ± 12.9 g and 355.1 ± 16.3 g, respectively).

Maize grain yields ranged from 9.7 ± 2.0 t ha^{-1} under CT to 12.7 ± 2.9 t ha^{-1} and 12.9 ± 1.8 t ha^{-1} under CA-DM and CA-LM, respectively, and were significantly higher under the two CA treatments than under CT.

3.3. Links between practices, soil health, and cropping system performance

The SEM fitness index was significant (Fisher's test P = 0.255), and six of the 21 relationships tested were significant (Fig. 3). SEM revealed significant links between agricultural practices and soil health: CT had a negative influence on soil structure maintenance (path coefficient = -0.55) while CA had positive effects on carbon transformation and nutrient cycling (path coefficient = 0.38 and 0.33, respectively). SEM also confirmed significant links between agricultural practices and cropping system performance: CT had a positive impact on weed development with higher biomass collected (path coefficient = 0.40) whereas CA had a positive influence on TKW (path coefficient = 0.46). Finally, SEM highlighted significant links between soil functions and cropping system performance with a positive correlation between nutrient cycling and weed development (path coefficient = 0.36). However, no significant indirect effects of soil health on maize crop performance emerged.

4. Discussion

It is worth noting that the results are based on the cumulative effects of the two distinct periods linked to changes in the experiment management strategy. The results of CT compared to CA are linked to a relatively long-term change (2011-2018), whereas the results that compare CA practices are linked to short-term changes (2017-2018).

4.1. Effects of CA cropping systems on soil functions

First, higher POXC and SituResp® scores were measured under CA treatments than under CT. POXC is sensitive to management practices, and mainly depends on the amount of residues returned to the soil (Bongiorno et al., 2019; Chan et al., 2002). Plant material including above- and below-ground biomass and living organisms mainly contribute to the labile carbon fraction. The higher basal soil respiration observed in soils under CA can be explained by the increased labile carbon fraction, which stimulated microbial pools and activity (Balota et al., 2004; Bongiorno et al., 2019). Bait laminas and GTB bioindicators showed greater biological activity in CA cropping systems than under CT. Concerning laminas, feeding activity was mainly observed in the 0-2 cm layer. This vertical feeding pattern has already been reported in the literature and the 0-2 cm layer was mentioned as a key layer (Gongalsky et al., 2004; Hamel et al., 2007; Rożen et al., 2010). In our system, the vertical pattern can be explained by the effects of cover crop residues on the soil surface and root systems of dead and living mulches that may affect specific organisms such as earthworms (van Gestel et al., 2003) and soil mesofauna (Helling et al., 1998), and then reflected in the bait lamina score. Concerning the GTB indicator, only CA-DM had a higher score than CT. CA-DM thus enhanced decomposition of the green tea at a depth of 8 cm thanks to soil biological activity (Tóth et al., 2018). The larger quantity of mulch under CA-DM (22.6 t_{DM} ha^{-1}) than under CA-LM (2.5 t_{DM} ha^{-1}) may have had a short term positive effect on the environmental variables (*e.g.*, soil moisture) resulting in differences in soil biological activity (Arroita et al., 2013). The difference in mulch quality (N contents: 1.14% and 2.82% of DM for CA-DM and CA-LM, respectively) is also an important factor that may have influenced the activity under CA-DM compared with CA-LM (Lienhard et al., 2013; Nemergut et al., 2010; Pascault et al., 2010).

The VESS, Beerkan and AggSoil indicators were significantly improved by CA management. The absence of tillage combined with the presence of plant residues on the soil surface, and living or dead cover crop root systems globally improved the structure maintenance function (Indoria et al., 2017; Tivet et al., 2013). The addition of residues and mulches stimulated microbial activity, which, along with root exudates, enhanced aggregate stability (Lal, 2015b; Zuber et al., 2017). In contrast, tillage destroyed soil aggregates, thereby increasing slaking and pore clogging, which could reduce porosity and infiltration rates (Mitchell et al., 2017; Rosolem et al., 2016).

A higher concentration of NH_4^+ and a trend (although not significant) of higher concentration of NO_3^- were observed under CA. These results were linked to a better soil structure (AggSoil) enabling diversified pH-redox (Eh) niches, and consequently diversified microbial communities (Husson et al., 2018). The soil nitrogen should have therefore operated in a variety of forms from nitrate to ammonium in the 0-10 cm layer. The better soil structure (AggSoil) explains the better water infiltration but also the fact that concentrations of both nitrate and ammonium were higher under CA. In their study on a Red Oxisol in Cambodia, Pheap et al. (2019) also reported higher concentrations of NO_3^- (although not significant) and NH_4^+ under CA compared with CT. As ion exchange membranes aim at mimicking plant-rooting systems, measurement of the AEM-NO_3^- indicator provided information on plant nutrient absorption and dynamics based on soil and crop management (Le Cadre et al., 2018; Qian and Schoenau, 2002). Compared to other measurements such as nitrate and ammonium extracted from the soil, the quantity of nitrate adsorbed on the membrane was two-fold higher under CT than CA. Tillage may expose previously protected organic matter which may then serve as a substrate for microbial growth (Rovira and Greacen, 1957), stimulating mineralisation and nitrification under an oxidized environment (Calderón et al., 2001; Muruganandam et al., 2010), explaining higher nitrate dynamics under CT. However, this tillage-induced nitrogen dynamics can lead to N losses through denitrification and nitrate leaching especially under soil with poor soil structure, which could explain the smaller amounts of available N-NH_4^+ and N-NO_3^- from soil extraction measured under CT (Boulakia et al., 2019; Calderón et al., 2001; Chatskikh and Olesen, 2007; Ruan and Robertson, 2013). In addition, the results of AEM-NO_3^- can be analysed in accordance with a previous study conducted by Husson et al. (2018) who observed a reversed soil profile for the redox potential when comparing CA to CT for four soil types in France. The authors observed lower redox potential on the soil surface under CA which is likely to lead to a higher concentration of NH_4^+, while limiting N leaching. Under CT, they observed a higher redox potential on the soil surface (0-5 cm) and a strong decrease with depth creating an electrical force which pushes the negative charges from the soil surface to depth. The higher oxidation on the top soil under CT and the trend of Eh from the soil surface to depth may increase NO_3^- leaching. We can also note that the NH_4^+:NO_3^- ratio is 27-73% under CA (average of CA-DM and CA-LM) and 20-80% under CT which can lead to a physiological imbalance in the plant, alkalinize the rhizosphere, promoting fungi, viruses, bacteria and insects (Husson et al., 2018). Considering these results and the key role of Eh to characterize soil health (Cottes et al., 2020; Husson, 2013), it would appear judicious to consider the assessment of the redox potential within the framework of Biofunctool®.

At multivariate and Biofunctool® index analysis scales, the results generally reflect the trend observed at indicator scale, *i.e.*, the improvement in soil functioning was mainly observed between CT and the two CA systems (CA-DM and CA-LM). The Biofunctool® index showed better soil health under CA than under CT. The three soil functions also mainly reflected the difference between CT and CA. However, the carbon transformation function under CA-LM did not differ significantly from that under CT. This may be directly linked to the quality and the larger quantity of the biomass inputs under CA-DM than under CA-LM and CT, although the living root biomass may have affected soil biological activity and carbon turnover under CA-LM. Thus, no significant differences in SHI were observed between CA-DM and CA-LM probably due to the relatively recent establishment of the CA-LM cropping system (2 years).

4.2. Effects of CA cropping systems on crop performance

CA has significant and positive effects on soil functions that are likely to produce similar or even higher crop yields than CT (Thierfelder et al., 2015; Triplett and Dick, 2008). In this study, regardless of the cropping system, maize yields were generally high compared to current average farm yield of 9 t ha^{-1}. Moreover, maize yields were 1.3-fold higher under CA-DM and CA-LM than under CT. These results are consistent with those of other studies, in which the positive impact of CA on crop yield was also demonstrated (Lal, 2014; Pittelkow et al., 2015; Ranaivoson et al., 2019; Rusinamhodzi et al., 2011). At the same time, these results contrast with other studies with mixed conclusions (Erenstein et al., 2012; Pittelkow et al., 2015; Thierfelder et al., 2015) that may arise from geographical and environmental patterns of CA implementation, duration, quality and quantity of the biomass-C inputs (DeFelice et al., 2006; Fujisaki et al., 2018; Gruber et al., 2012; Thierfelder et al., 2015).

In the present experiment, the physical barrier of the high biomass input of the dead mulch under CA-DM has reduced seed-soil contact and promoted early season insect damage, decreasing final plant density. This observation is corroborated by previous studies, including those by Bezuidenhout et al. (2012) and Pantoja et al. (2015). In contrast, maize density with direct sowing in standing green stylo under CA-LM was higher than under CT because it avoids the formation of a slaking crust and provides better maize emergence conditions.

CA-DM produced higher yield as well as kernel weight and TKW. The large amount of cover crop residues under CA-DM provided better growth conditions at grain filling and enhanced available resources for maize due to less competition thanks to lower maize density and reduced weed development, increased soil water infiltration and water holding capacity (Ranaivoson et al., 2017). In comparison, higher yield was also observed under CA-LM compared with CT, while similar kernel weight and TKW values were observed for both treatments. This suggests the same late cycle crop conditions as CT with advantages in the early stages due to better weed control, reduced formation of a slaking crust (Scopel and Findeling, 2001; Sithole et al., 2016; Verhulst et al., 2010), with higher maize density and complementarity of stylo and maize during the growth period (Birteeb et al., 2011; Edye et al., 1977). Finally, the short period (2 cycles) of CA-LM practice may not be sufficient for the soil to reach a new equilibrium and thus may not provide all support and provisioning services (Gruber et al., 2012; He et al., 2011; Machado et al., 2008).

4.3. Systemic approach of CA cropping systems

SEM confirmed direct causal relationships of management practices on soil functioning revealed by Biofunctool®. In the long term, CT exhibited negative effects on soil health impacting soil structure maintenance, disrupting soil aggregation, exposing the labile carbon pool encapsulated within the aggregates to microbial oxidation and reducing water infiltration (Mitchell et al., 2017). By contrast, CA positively influenced carbon transformation and nutrient cycling functions. Several studies emphasized that CA systems contribute to an accumulation of soil organic carbon (Cheesman et al., 2016; Lal, 2015c; Powlson et al., 2016), primarily due to the continuous inputs of biomass (above and belowground), the quality of the inputs, and the protection of the labile carbon pool from microbial transformation (Fujisaki et al., 2018; Virto et al., 2012). Concomitantly, a higher soil available nitrogen concentration ($N\text{-}NO_3^-$, $N\text{-}NH_4^+$) was assessed under CA systems, promoting crop growth supported by a higher structure maintenance function, and consequently limiting nitrogen losses compared to CT (Calderón et al., 2001; Chatskikh and Olesen, 2007; Husson et al., 2018).

In the short term, management practices had direct effects on the performance of the cropping systems. During the early stages of maize growth, more weeds was recorded under CT while the physical barrier and the allelopathy effect of dead or living mulch under CA systems reduced weed pressure (Altieri et al., 2011; Burgos and Talbert, 1996; Murphy et al., 2006). On the other hand, SEM highlighted a positive effect of CA systems on TKW. The period from flowering to grain filling is highly sensitive to water stress, and the higher kernel weight was the result of better conditions under CA (Bolaños and Edmeades, 1996; NeSmith and Ritchie, 1992). Mulch was shown to be an effective way to reduce soil evaporation and to moderate the temperature at the surface of the soil, which, along with the higher infiltration rate, improved water-use efficiency notably during the maize grain filling period (Hartkamp et al., 2004).

4.4. Toward the quantification of linkages between soil health, productivity, and ecosystem services

The comprehensive links between agricultural practices, soil functions and ecosystem services (*i.e.*, productivity, weed regulation, and soil ecosystem services) were analysed with the SEM approach. In our study, the link between soil health and plant productivity was not significant and cropping system management was the main direct factor explaining differences in yield components. However, with same fertilisation and irrigation management, the CA cropping systems improved the overall crop conditions leading to a higher yield than under CT. Further understanding of the indirect effects of agricultural practices and soil health on crop productivity are needed. Long-term agronomic trial would make it possible to apply such a systemic approach and would be particularly helpful in quantifying the links between system management, soil functioning and crop productivity. Finally, we focussed on the links between soil functions, productivity, and weed regulation, but other ecosystem services also need to be tackled, for example, pest regulation, pollination, or biodiversity maintenance (Chabert and Sarthou, 2020).

5. Conclusions

The effects of three annual cropping systems (*i.e.*, CT, CA-DM and CA-LM) on soil functioning were evaluated using an integrative assessment of soil health. Higher structure maintenance (*i.e.*, soil aggregation, water infiltration, VESS) and nutrient cycling functions (*i.e.*, NO_3^-, NH_4^+) were recorded under CA-DM and CA-LM, and a higher carbon transformation function (*i.e.*, labile-C, soil respiration, baits lamina, GTB) was assessed under CA-DM. Overall, the soil health index (SHI) was 1.3-fold higher under CA systems than under CT although it did not differ between CA-DM and CA-LM, probably because the two CA management practices were recently established. By combining these results with the application of structural equation modelling (SEM), we identified relationships between soil functions and cropping system performance that are sensitive to cover crops and tillage practices. CA practices had both direct and indirect influence on soil health, thereby improving yield system performance when compared to CT. These findings indicate that CA systems are promising alternatives to the conventional plough-based system in the magnesic Fluvisol context of the west coast of New Caledonia.

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Figure captions

Fig. 1 Principal component analysis of the effects of the cropping system on soil health.

a Variables factor map. POXC: Permanganate OXidizable Carbon, SituResp®: basal soil respiration, Laminas: lamina bait degradation, GTB: fraction of Green Tea Bag decomposed, VESS: Visual Evaluation of Soil Structure, Beerkan: water infiltration, AggSoil: soil aggregate water stability, $AEMNO_3$: nitrate evaluated with anion exchange membrane, NNH_4, NNO_3: available ammonium and nitrate.

b Individual factor map. CT: Conventional Tillage, CA: Conservation Agriculture with direct seeding in Dead Mulch (CA-DM) or Living Mulch (CA-LM).

Note: AggSoil median score and 0-2cm depth laminas score were used to run the PCA.

Fig. 2 Biofunctool® Soil Health Index (SHI) per treatment. CT: Conventional Tillage, CA: Conservation Agriculture with direct seeding in Dead Mulch (CA-DM) or Living Mulch (CA-LM); n=9 for each treatment. Standard error of the index is given for each treatment. Different letters indicate significant differences at $P<0.05$ according to Tukey's test.

Fig. 3 Structural Equation Modelling (SEM) linking the cropping system, soil health, and cropping system performance (Fisher's C=14.76, df=12, $P=0.26$). CT: Conventional Tillage, CA: Conservation Agriculture systems (direct seeding in dead mulch and living mulch not differentiated): characterised by the aboveground biomass of the cover crops and the soil management practices. Weeds: Weed cumulative aboveground dry matter during the crop cycle, Maize Yield: grain yield, TKW: Maize Thousand Kernel Weight. The arrows indicate unidirectional relationships between the variables (direct effects of one variable on the others). Green arrows indicate significant positive effects, red arrows indicate significant negative effects, and grey arrows indicate non-significant relationships at $P=0.05$. Path coefficients are indicated adjacent to the corresponding arrows. Arrow widths are proportional to the path coefficients.

Table 1 Biofunctool® indicators of soil carbon transformation per treatment. CT: Conventional Tillage, CA: Conservation Agriculture with direct seeding in Dead Mulch (CA-DM) or Living Mulch (CA-LM). POXC: Permanganate OXidizable Carbon, SituResp®: basal soil respiration, Laminas: lamina bait degradation, GTB: fraction of Green Tea Bag decomposed. The analysis was conducted in the 0-10 cm layer, except for laminas (in the 0-2 cm layer) and GTB (at a depth of 8 cm); n=9 for each treatment; sd: standard deviation. Different letters indicate significant differences according to Tukey's test ($P<0.05$).

	Carbon transformation							
Treatment	POXC ($mg_C\ kg_{soil}^{-1}$)		SituResp® (Absorbance difference)		Laminas (Score)		GTB (Score)	
	mean	sd	mean	sd	mean	sd	mean	sd
CT	1071 **a**	27	0.87 **a**	0.05	4.91 **a**	4.0	0.43 **a**	0.02
CA-DM	1124 **b**	27	0.96 **b**	0.06	8.71 **b**	4.3	0.46 **b**	0.03
CA-LM	1122 **b**	34	0.95 **b**	0.06	7.17 **b**	4.0	0.45 **ab**	0.02
ANOVA	$P<0.001$		$P<0.001$		$P<0.001$		$P<0.001$	

Table 2 Biofunctool® indicators of soil structure maintenance per treatment. CT: Conventional Tillage, CA: Conservation Agriculture with direct seeding in Dead Mulch (CA-DM) or Living Mulch (CA-LM). VESS: Visual Evaluation of Soil Structure, Beerkan: water infiltration, AggSoil: soil aggregate water stability. The analysis was made in the 0-10 cm layer, except for VESS (in the 0-30 cm layer); n=9 for each treatment; sd: standard deviation. Different letters indicate significant differences according to Tukey's test.

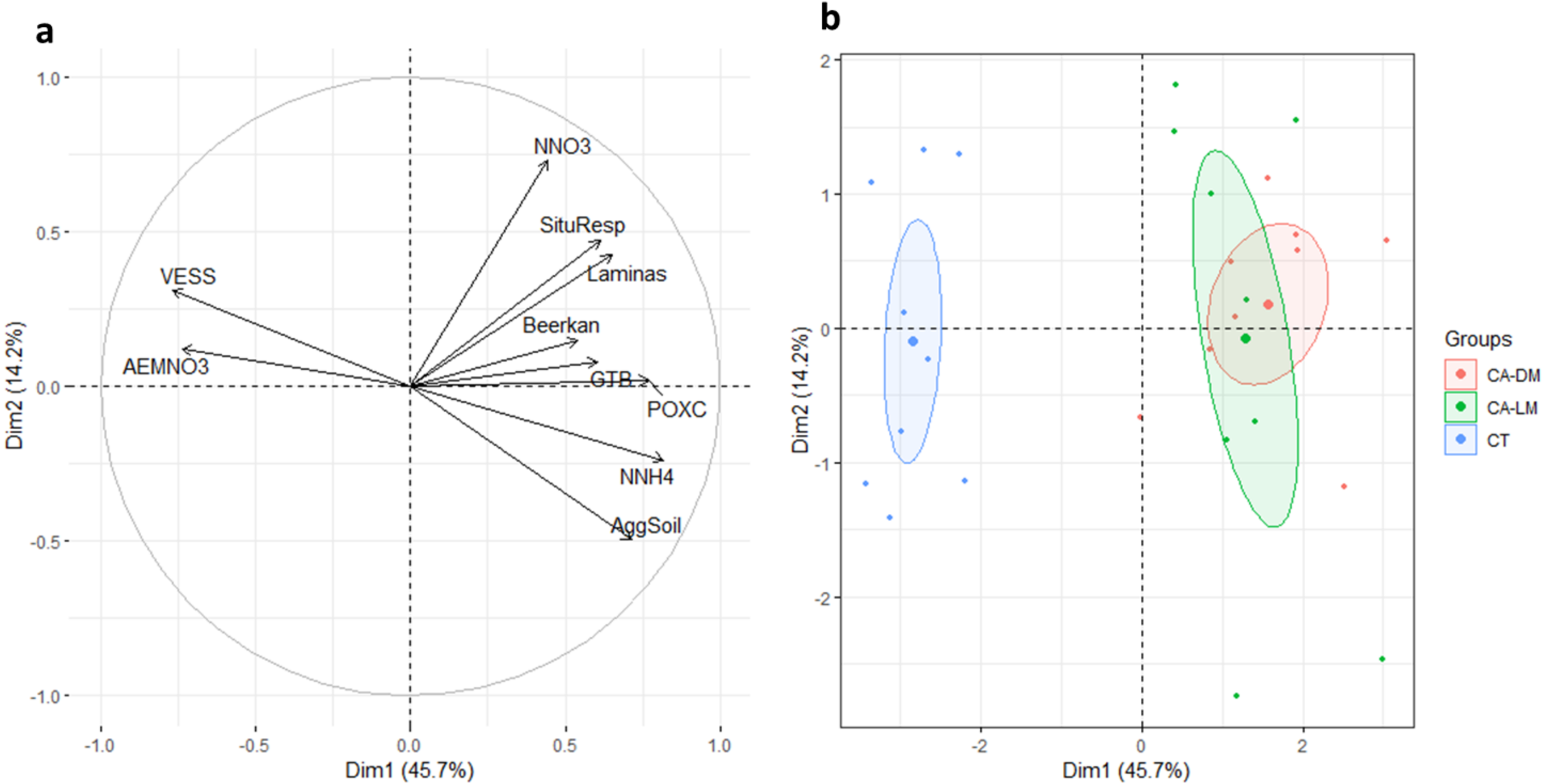
	Structure maintenance					
Treatment	VESS (Score)		Beerkan (mL min^{-1})		AggSoil (Score)	
	mean	sd	mean	sd	median	sd
CT	2.11 **b**	0.4	93.4 **a**	20.5	1.22 **a**	0.4
CA-DM	1.45 **a**	0.3	176.5 **b**	71.5	2.00 **b**	0.8
CA-LM	1.28 **a**	0.3	226.0 **b**	117.3	2.15 **b**	0.9
ANOVA	*P*<0.001		*P*<0.001		*P*<0.001	

Table 3 Biofunctool® indicators of soil nutrient cycling per treatment. CT: Conventional Tillage, CA: Conservation Agriculture with direct seeding in Dead Mulch (CA-DM) or Living Mulch (CA-LM). AEM-NO_3^-: nitrate evaluated with anion exchange membrane, N-NH_4^+, N-NO_3^-: available ammonium and nitrate. The analysis was conducted in the 0-10 cm layer, except for AEM-NO_3^- (at a depth of 8 cm); n=9 for each treatment except for N-NH_4^+ and N-NO_3^- where n=3 per treatment (no internal replicates); sd: standard deviation. Different letters indicate significant differences according to Tukey's test.

Treatment	Nutrient cycling					
	AEM-NO_3^- (μg_{N-NO3^-} cm^{-2} d^{-1})		N-NO_3^- (mg kg^{-1})		N-NH_4^+ (mg kg^{-1})	
	mean	sd	mean	sd	mean	sd
CT	20.4 **b**	6.4	10.9 **ns**	4.1	2.6 **a**	0.3
CA-DM	10.5 **a**	4.0	14.7 **ns**	2.2	6.1 **b**	0.2
CA-LM	9.8 **a**	5.0	14.7 **ns**	3.2	4.7 **ab**	1.3
ANOVA	$P<0.001$		$P=0.4$		$P<0.001$	

Table 4 Cropping system performance indicators per treatment. CT: Conventional Tillage, CA: Conservation Agriculture with direct seeding in Dead Mulch (CA-DM) or Living Mulch (CA-LM). Weeds: Weed cumulative aboveground dry matter during crop cycle, Maize density: Maize plant population, Kernel weight: Total kernel weight per maize ear, TKW: Maize Thousand Kernel Weight, Maize yield: grain yield; n=9 for each treatment; sd: standard deviation. Different letters indicate significant differences according to Tukey's test.

Treatment	Weeds ($t_{\text{cumulative DM}}$ ha^{-1})		Maize density (plants m^{-2})		Kernel weight (g ear^{-1})		TKW (g)		Yield (t ha^{-1})	
	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
CT	1.4 **c**	0.7	9.0 **b**	0.4	107.8 **a**	21.0	355.1 **a**	16.3	9.7 **a**	2.0
CA-DM	0.7 **b**	0.3	8.0 **a**	1.1	158.6 **b**	25.5	388.2 **b**	7.5	12.7 **b**	2.9
CA-LM	0.2 **a**	0.3	10.3 **c**	0.5	125.8 **a**	18.2	364.2 **a**	12.9	12.9 **b**	1.8
ANOVA	P<0.001		P<0.001		P<0.001		P<0.001		P<0.001	


a
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Dim1 (45.7%)
b
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Dim2 (14.2%)
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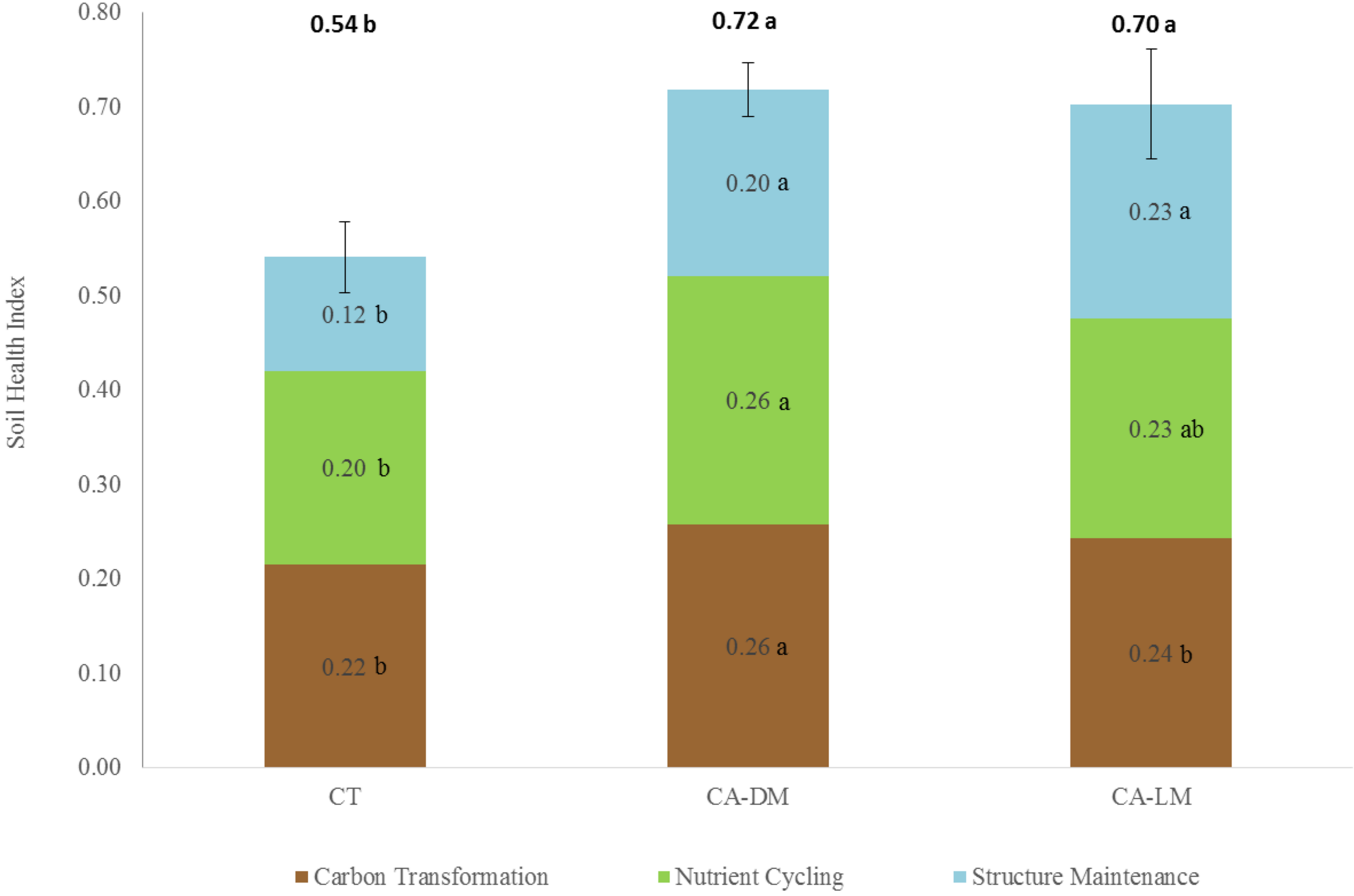
Groups
CA-DM
CA-LM
CT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Soil Health Index
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CT
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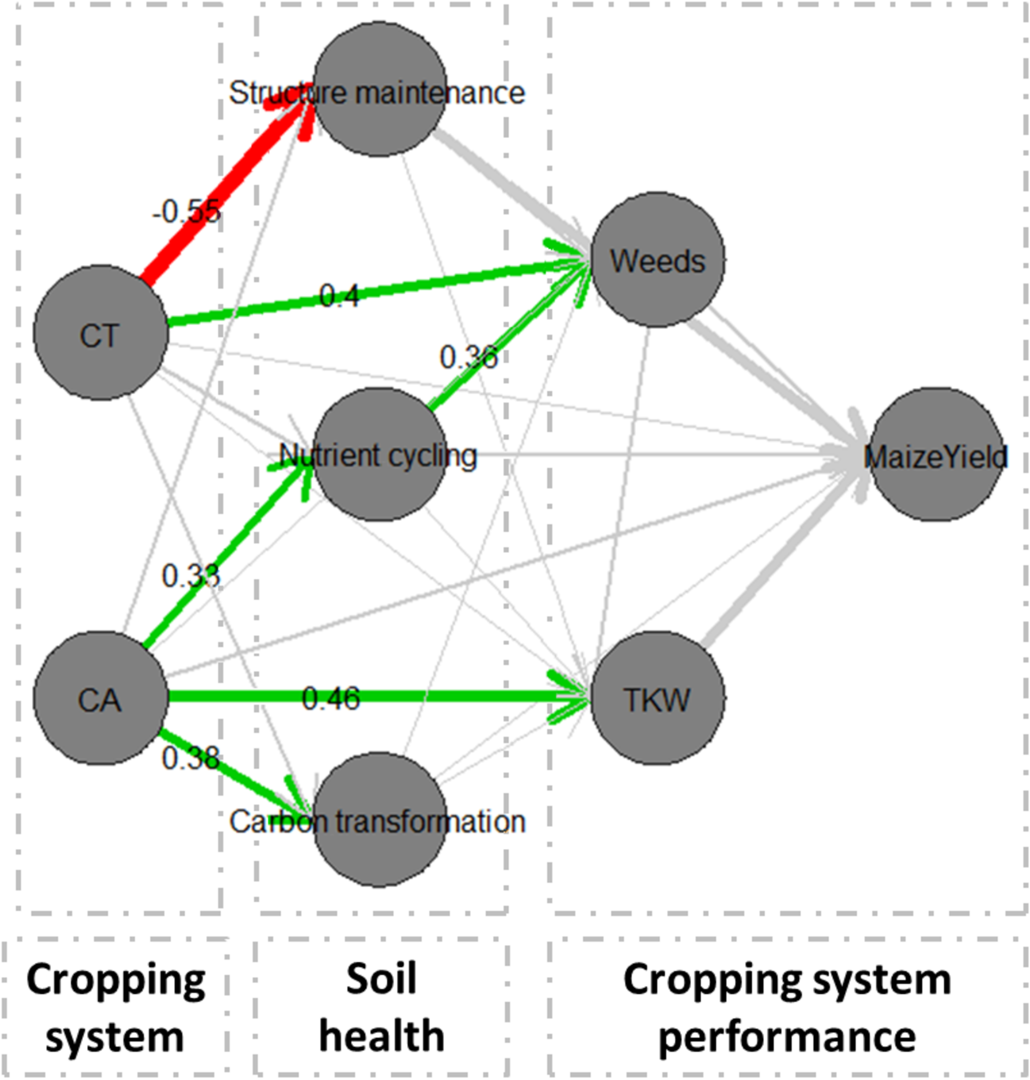
CA-LM
Carbon Transformation
Nutrient Cycling
Structure Maintenance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Carbon transformation
Cropping system
Soil health
Cropping system performance