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1 **Effects of conservation agriculture maize-based cropping systems on soil health and crop performance in**
2 **New Caledonia**

3

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19 **Abstract**

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

39

40 **Keywords** Cover crop; Living mulch; Magnesian fluvisol; No tillage; Soil functions; Systemic approach

41 1. Introduction

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

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

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

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

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

91 **2. Materials and methods**

92 2.1. Site description

93 The study site is located at the Adecap Technopole Ouenghi experimental station in Boulouparis, South province,
94 New Caledonia (21°53'50" S, 166°06'45" E). The west coast of New Caledonia is characterised by a semi-arid
95 subtropical climate with a cool, dry season from May to September, and a warm, wet season from December to
96 April. Intense rainfall associated with thunderstorms peaking in austral summer are usually followed by recurrent
97 drought periods from October to November. Data from the Ouenghi Meteo-France station (21°55'42"S,
98 166°05'00"E; 3.5 km from the study site) were used to characterise the meteorological conditions. Mean annual
99 precipitation between 2011 and 2018 was 909 mm with most of the rainfall occurring from February to April. In
100 the same period, the monthly average minimum and maximum temperatures were 17 °C and 29 °C, respectively.

101 Soil is classified as a silty loam soil according to the USDA classification with 33.6% sand, 51.6% silt and
102 14.8% clay (Euro-analyse laboratory soil analysis, 2011). It is a magnesian alkaline soil ($\text{pH}_{\text{water}} = 8.1$) with high
103 concentrations of Mg^{2+} (exchangeable magnesium accounts for 76% of cation exchange capacity) and $\text{Ca/Mg} =$
104 0.3 ($\text{K/Mg} = 0.01$). The average bulk density (in the 0-10 cm layer) was $1.01 \pm 0.08 \text{ g cm}^{-3}$ and soil organic
105 carbon (0-20 cm depth) was $28.1 \pm 1.1 \text{ g kg}^{-1}$ (LAMA laboratory soil analysis, 2017).

106 2.2. Experimental design

107 The experiment was set up in 2011 to study contrasted cropping systems representative of cereal production
108 along the west coast of New Caledonia characterised by short rotations and maize (*Zea mays* L.) grain as main
109 crop production. Two main periods characterize the experiment (Supplementary information, Table A.1). From
110 2011-2016, the cropping sequence was based on a succession cowpea-maize and cowpea-maize-sorghum under
111 two type of management: (i) conventional plough-based management (CT), and (ii) CA management based on
112 dead mulch. Cowpea (*Vigna unguiculata* L.) was used as a cover crop before maize in all treatments. The second
113 period started in 2017, when the cropping pattern was updated with a maize-based cropping system under three
114 different managements: (i) maize under CT, which is the main practice in the region, which represented a
115 continuation of the CT management of the first period, (ii) maize under CA with direct seeding in a dead mulch
116 (CA-DM), and (iii) maize under CA with direct seeding in a living mulch (CA-LM). CA-DM and CA-LM
117 represented the continuation of the plots under CA management in the first period. Crop residues were not
118 exported in all the cropping systems, and under CT, the soil was ploughed once a year to a depth of 25-30 cm
119 with a mouldboard plough. A randomised block design experiment was used consisting in the three treatments
120 with three replicates of plots measuring 1200 m^2 (50 m x 24 m) for each system (Supplementary information,
121 Fig. A.1).

122 In 2018, all cover crops were sown on the 24th of January with a no-till seeder (Semeato PD 17) (Supplementary
123 information, Table A.2). The cover crop used under CA-DM consisted of a mix of four species: sorghum
124 (*Sorghum bicolor* L. Moench, cv. sweet jumbo; sowing density 15 kg ha^{-1}), sunnhemp (*Crotalaria juncea* L., cv.
125 crescent sunn; 10 kg ha^{-1}), cowpea (*Vigna unguiculata* L. Walp., cv. ebony; 10 kg ha^{-1}), and lablab (*Lablab*
126 *purpureus* L. Sweet, cv. highworth; 15 kg ha^{-1}). The cover crop used under CA-LM was stylo (*Stylosanthes*
127 *guianensis* Aubl. Sw.; 10 kg ha^{-1}). Under CT, the mouldboard plough was used on the 19th of March 2018 to a
128 depth of 25-30 cm, and the rotary cultivator on the 27th of April 2018 to a depth of 5-10 cm, before maize
129 sowing. Under CA-DM, the cover crop was terminated by rolling combined with herbicide spraying on the 20th
130 of April 2018, 15 days before the maize was sown. Under CA-LM, the maize was sown directly in standing

131 green stylo. The aboveground biomass of the cover crops was assessed before maize was sown and ranged from
132 22.6 ± 8.8 t_{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%
133 of the soil surface was covered by mulch at sowing and about 80% under CA-LM.

134 In all cropping systems, maize was grown during the dry, cool season (May-September) with 223 mm
135 cumulative precipitation during the crop cycle. Maize (cv. CS Frontal) was sown at 108000 kernels ha⁻¹ in 76-cm
136 rows on the 7th of May 2018, using a no-till seeder (Jumil JM3090 PD). A hose reel irrigation system was used
137 on 13 occasions to supply 290 mm of water. The water balance method was used to determine water amounts,
138 and irrigation uniformity was controlled by rain gauges. The nitrogen (N) fertilisation during the maize cycle
139 included 350 kg ha⁻¹ of urea (46% N) and 300 kg ha⁻¹ of ammonium sulphate (21% N) applied 17 and 51 days
140 after sowing (DAS), respectively. Herbicide treatments included pre- and post-emergence herbicides. Pre-
141 emergence herbicides were applied immediately after sowing, while post-emergence herbicides were applied at
142 10 and 31 DAS.

143 2.3. Soil monitoring and analysis

144 Biofunctool® consists in a set of ten functional indicators that assess three main soil functions with (i) carbon
145 transformation, (ii) soil structure maintenance and (iii) nutrient cycling (Thoumazeau et al., 2019b). Four
146 indicators were used to assess the changes of the carbon transformation including the labile fraction of the soil
147 organic carbon (permanganate oxidizable carbon (POXC)) (Weil et al., 2003); the basal soil respiration
148 (SituResp®) (Thoumazeau et al., 2017); and the soil biological activity using the bait lamina test (scored from 0
149 [no degradation] to 1 [complete degradation]) (Törne, 1990; van Gestel et al., 2003) and the green tea bag (GTB)
150 score (adapted from Keuskamp et al. (2013)). The bait lamina consists of a plastic strip, comprising 16 small
151 holes, that was filled with an organic standard substrate, made of cellulose powder, bran flakes and active carbon
152 (70:27:3). Bait laminas were vertically inserted in the soil for seven days. For the analysis, we used the average
153 of lamina holes number 1 to 4 (0-2 cm) only, as it was the only depth that allowed us to significantly distinguish
154 the treatments (Supplementary information, Fig. A.2). The GTB indicator consisted in the decomposed fraction
155 of green tea after a burial period of 30 days.

156 We then used three indicators to study the impact of each cropping system on soil structure maintenance function
157 by assessing soil aggregate water stability (AggSoil) at a depth of 0-10 cm (scored from 1 [poor] to 6 [high
158 stability]) (Herrick et al., 2001), water infiltration (Beerkan) (Thoumazeau et al., 2019b), and soil structure
159 (visual evaluation of soil structure (VESS)) in the 0-30 cm layer (scored from 1 [good] to 5 [poor soil structure])
160 (Guimarães et al., 2011). The VESS consists of visually assessing the size and porosity of aggregates, the

161 strength of aggregates, the presence of roots and the colour of the soil. Finally, we used three indicators to study
162 the impact of each cropping system on soil nutrient cycling function. We quantified available ammonium (N-
163 NH_4^+) and nitrate (N- NO_3^-) in the soil after extraction with 1M KCl (Maynard et al., 1993; Thoumazeau et al.,
164 2019b). Soil nitrate dynamics were evaluated using anion exchange membrane (AEM- NO_3^-) placed horizontally
165 at a depth of 8 cm for a 10 days burial period (Qian and Schoenau, 2002; Thoumazeau et al., 2019b).
166 Except for the VESS, soil samples were collected in June 2018 in the 0-10 cm soil layer. This soil layer was
167 selected to fit with Biofunctool® approach that aims at integrating soil biological activities (Thoumazeau et al.,
168 2019b). Also, early changes under CA mostly occur at the soil surface, making the top soil assessment highly
169 relevant (de Moraes Sa and Lal, 2009). Three sampling points (internal replicates) were collected per plot giving
170 a total of 27 soil samples for Biofunctool® analysis (except for available nitrogen (N- NH_4^+ , N- NO_3^-) for which
171 only one replicate per plot was analysed).

172 2.4. Agronomic data collection

173 Weed biomass was assessed using a quadrat sampling method at four maize stages: sowing, 6-leaf (25 DAS),
174 flowering (80 DAS), and post-harvest. In each repetition (three repetitions per treatment), three quadrats of 0.25
175 m^2 were delimited to count weeds. Weed aboveground biomass was then determined for each sampling period
176 after drying at 80 °C until constant mass was reached. Cumulative weed biomass per treatment was determined
177 by adding the dry matter of the four sampling periods.

178 Maize density was monitored weekly in three subplots per repetition (three repetitions per treatment) on two
179 contiguous maize rows two meters in length (3.04 m^2) from emergence to the 8-leaf (35 DAS) stage. Maize
180 density per treatment was the average of the maize counted during the successive sampling periods.

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

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

189 $\text{Maize yield (t ha}^{-1}\text{)} = \text{Maize density (plants m}^2\text{)} * \text{Number of ears per plant (ear plant}^{-1}\text{)} *$

190 $\text{Kernel weight per ear (g ear}^{-1}\text{)} * 10^{-2}$

191 2.5. Statistical analysis

192 All statistical analyses were performed using R software 3.6.0 (R Development Core Team, 2008).
193 First, each Biofunctool® indicator was analysed separately using a linear-mixed effects model (package lme4,
194 (Bates et al., 2015)). Treatment was defined as fixed factor and replicates (plots and internal replicates) as
195 random factors. After checking the normality of the model residuals and the homoscedasticity of the variance
196 residuals, ANOVAs were run using the car package (Fox and Weisberg, 2011). This was followed by a post-hoc
197 mean comparison, using Tukey's test with Bonferroni adjustment (Hothorn et al., 2008).
198 After analysing each indicator separately, indicators were computed within a principal component analysis
199 (PCA) (FactoMineR package, (Lê et al., 2008)). The last step of analysis consisted in calculating the
200 Biofunctool® soil health index (SHI), according to the methodology defined by Obriot et al. (2016) and
201 Thoumazeau et al. (2019a). First, a weight was applied to the PCA variable to give the same weight to each soil
202 function. The scoring function of the indicators was based on the "more is better" response curve, except for the
203 VESS indicator where the "less is better" was used (Obriot et al., 2016). The SHI finally ranged from 0 (low) to
204 1 (high soil health). After calculation of the index, a variance analysis of the contribution of each soil function to
205 the final score was run using one-way ANOVA.
206 Next, we used SEM (Grace et al., 2012, 2007) to explicit relationships from a web of possible causal pathways,
207 including direct and indirect effects between practices (CT and CA systems), soil health and cropping systems
208 performance. CA-DM and CA-LM were grouped into a single cropping system modality (CA). A combination
209 of the aboveground biomass of the cover crops at maize sowing and the soil management practices (qualitative
210 data) was used to characterize cropping system practices for the SEM. The three Biofunctool® aggregated
211 functions (*i.e.*, structure maintenance, nutrient cycling, and carbon transformation) were used as soil health
212 indicators. Cumulative weed aboveground biomass during the maize cycle, maize thousand kernel weight
213 (TKW) and grain yield were used as cropping system performance parameters for the SEM. Weeds are a major
214 factor that affects yields (Teasdale et al., 2007). TKW was used to assess maize growth performance, providing
215 insight into the strength of late competition (Meynard and David, 1992). Grain yield expresses the overall
216 conditions of the crop cycle, and is the main indicator used to assess system productivity. Strength and
217 directionality (positive or negative) of the relationship between variables are indicated through the path
218 coefficients. The SEM was performed using the piecewiseSEM package (Lefcheck, 2016).

219 3. Results

220 3.1. Effects of the cropping systems on soil health

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

225 Concerning structure maintenance, the same trend was recorded for the three indicators (Table 2). Mean VESS
226 scores were significantly lower for soils under CA (1.45 ± 0.3 and 1.28 ± 0.3 for CA-DM and CA-LM,
227 respectively) indicating a better soil structure than under CT soil (2.11 ± 0.4). Mean AggSoil scores were
228 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,
229 respectively). Finally, water infiltration was two-fold lower in soil under CT ($93.4 \pm 20.5 \text{ mL min}^{-1}$) than in soil
230 under CA (176.5 ± 71.5 and $226.0 \pm 117.3 \text{ mL min}^{-1}$ for CA-DM and CA-LM, respectively). No significant
231 differences were found in VESS, AggSoil, and Beerkan scores between CA-DM and CA-LM.

232 For nutrient cycling, the mean AEM-NO₃⁻ score was two-fold higher under CT than under CA (20.4 ± 6.4 vs.
233 10.5 ± 4.0 and $9.8 \pm 5.0 \mu\text{g cm}^{-2} \text{ d}^{-1}$ for CA-DM and CA-LM, respectively) (Table 3). In contrast, the
234 concentration of N-NH₄⁺ was two-fold higher under CA-DM than under CT ($6.1 \pm 0.2 \text{ mg kg}^{-1}$ vs. $2.6 \pm 0.3 \text{ mg}$
235 kg^{-1}). The concentration of N-NO₃⁻ tended to be higher under CA than under CT but the differences were not
236 statistically significant.

237 The PCA performed on the 10 functional indicators allowed to separate the treatments (Fig. 1). The differences
238 between Biofunctool® indicators appeared mainly between the CT and CA cropping systems. Total variability
239 was represented at 45.7% on the first axis and at 14.2% on the second axis. The difference in soil health between
240 the two CA cropping systems and CT was mainly based on indicators linked with the first axis: AEM-NO₃⁻ and
241 N-NH₄⁺ (nutrient cycling), VESS and AggSoil (structure maintenance), and POXC (carbon transformation).

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

247 3.2. Performance of the cropping systems

248 The cumulative aboveground weed biomass differed significantly among the three treatments with higher weed
249 biomass under CT (mean value of $1.4 \pm 0.7 \text{ t}_{\text{DM}} \text{ ha}^{-1}$) than under CA-LM ($0.2 \pm 0.3 \text{ t}_{\text{DM}} \text{ ha}^{-1}$) and CA-DM ($0.7 \pm$
250 $0.3 \text{ t}_{\text{DM}} \text{ ha}^{-1}$) (Table 4).

251 Maize density differed significantly among the treatments: the maize plant population was higher under CA-LM
252 (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
253 emergence under CA-DM.

254 There was one ear per plant for all the maize plants sampled. The kernel weight per ear was significantly higher
255 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).
256 The TKW followed the same trend and was significantly higher under CA-DM (388.2 ± 7.5 g) than under both
257 CA-LM and CT (364.2 ± 12.9 g and 355.1 ± 16.3 g, respectively).

258 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
259 and CA-LM, respectively, and were significantly higher under the two CA treatments than under CT.

260 3.3. Links between practices, soil health, and cropping system performance

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

270 4. Discussion

271 It is worth noting that the results are based on the cumulative effects of the two distinct periods linked to changes
272 in the experiment management strategy. The results of CT compared to CA are linked to a relatively long-term
273 change (2011-2018), whereas the results that compare CA practices are linked to short-term changes (2017-
274 2018).

275 4.1. Effects of CA cropping systems on soil functions

276 First, higher POXC and SituResp[®] scores were measured under CA treatments than under CT. POXC is sensitive
277 to management practices, and mainly depends on the amount of residues returned to the soil (Bongiorno et al.,
278 2019; Chan et al., 2002). Plant material including above- and below-ground biomass and living organisms
279 mainly contribute to the labile carbon fraction. The higher basal soil respiration observed in soils under CA can
280 be explained by the increased labile carbon fraction, which stimulated microbial pools and activity (Balota et al.,

281 2004; Bongiorno et al., 2019). Bait laminas and GTB bioindicators showed greater biological activity in CA
282 cropping systems than under CT. Concerning laminas, feeding activity was mainly observed in the 0-2 cm layer.
283 This vertical feeding pattern has already been reported in the literature and the 0-2 cm layer was mentioned as a
284 key layer (Gongalsky et al., 2004; Hamel et al., 2007; Rozen et al., 2010). In our system, the vertical pattern can
285 be explained by the effects of cover crop residues on the soil surface and root systems of dead and living
286 mulches that may affect specific organisms such as earthworms (van Gestel et al., 2003) and soil mesofauna
287 (Helling et al., 1998), and then reflected in the bait lamina score. Concerning the GTB indicator, only CA-DM
288 had a higher score than CT. CA-DM thus enhanced decomposition of the green tea at a depth of 8 cm thanks to
289 soil biological activity (Tóth et al., 2018). The larger quantity of mulch under CA-DM ($22.6 \text{ t}_{\text{DM}} \text{ ha}^{-1}$) than under
290 CA-LM ($2.5 \text{ t}_{\text{DM}} \text{ ha}^{-1}$) may have had a short term positive effect on the environmental variables (*e.g.*, soil
291 moisture) resulting in differences in soil biological activity (Arroita et al., 2013). The difference in mulch quality
292 (N contents: 1.14% and 2.82% of DM for CA-DM and CA-LM, respectively) is also an important factor that
293 may have influenced the activity under CA-DM compared with CA-LM (Lienhard et al., 2013; Nemergut et al.,
294 2010; Pascault et al., 2010).

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

302 A higher concentration of NH_4^+ and a trend (although not significant) of higher concentration of NO_3^- were
303 observed under CA. These results were linked to a better soil structure (AggSoil) enabling diversified pH-redox
304 (Eh) niches, and consequently diversified microbial communities (Husson et al., 2018). The soil nitrogen should
305 have therefore operated in a variety of forms from nitrate to ammonium in the 0-10 cm layer. The better soil
306 structure (AggSoil) explains the better water infiltration but also the fact that concentrations of both nitrate and
307 ammonium were higher under CA. In their study on a Red Oxisol in Cambodia, Pheap et al. (2019) also reported
308 higher concentrations of NO_3^- (although not significant) and NH_4^+ under CA compared with CT. As ion
309 exchange membranes aim at mimicking plant-rooting systems, measurement of the AEM- NO_3^- indicator
310 provided information on plant nutrient absorption and dynamics based on soil and crop management (Le Cadre

311 et al., 2018; Qian and Schoenau, 2002). Compared to other measurements such as nitrate and ammonium
312 extracted from the soil, the quantity of nitrate adsorbed on the membrane was two-fold higher under CT than
313 CA. Tillage may expose previously protected organic matter which may then serve as a substrate for microbial
314 growth (Rovira and Greacen, 1957), stimulating mineralisation and nitrification under an oxidized environment
315 (Calderón et al., 2001; Muruganandam et al., 2010), explaining higher nitrate dynamics under CT. However, this
316 tillage-induced nitrogen dynamics can lead to N losses through denitrification and nitrate leaching especially
317 under soil with poor soil structure, which could explain the smaller amounts of available N-NH_4^+ and N-NO_3^-
318 from soil extraction measured under CT (Boulakia et al., 2019; Calderón et al., 2001; Chatskikh and Olesen,
319 2007; Ruan and Robertson, 2013). In addition, the results of AEM- NO_3^- can be analysed in accordance with a
320 previous study conducted by Husson et al. (2018) who observed a reversed soil profile for the redox potential
321 when comparing CA to CT for four soil types in France. The authors observed lower redox potential on the soil
322 surface under CA which is likely to lead to a higher concentration of NH_4^+ , while limiting N leaching. Under CT,
323 they observed a higher redox potential on the soil surface (0-5 cm) and a strong decrease with depth creating an
324 electrical force which pushes the negative charges from the soil surface to depth. The higher oxidation on the top
325 soil under CT and the trend of Eh from the soil surface to depth may increase NO_3^- leaching. We can also note
326 that the $\text{NH}_4^+:\text{NO}_3^-$ ratio is 27-73% under CA (average of CA-DM and CA-LM) and 20-80% under CT which
327 can lead to a physiological imbalance in the plant, alkalize the rhizosphere, promoting fungi, viruses, bacteria
328 and insects (Husson et al., 2018). Considering these results and the key role of Eh to characterize soil health
329 (Cottes et al., 2020; Husson, 2013), it would appear judicious to consider the assessment of the redox potential
330 within the framework of Biofunctool®.

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

340 4.2. Effects of CA cropping systems on crop performance

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

350 In the present experiment, the physical barrier of the high biomass input of the dead mulch under CA-DM has
351 reduced seed-soil contact and promoted early season insect damage, decreasing final plant density. This
352 observation is corroborated by previous studies, including those by Bezuidenhout et al. (2012) and Pantoja et al.
353 (2015). In contrast, maize density with direct sowing in standing green stylo under CA-LM was higher than
354 under CT because it avoids the formation of a slaking crust and provides better maize emergence conditions.

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

366 4.3. Systemic approach of CA cropping systems

367 SEM confirmed direct causal relationships of management practices on soil functioning revealed by
368 Biofunctool®. In the long term, CT exhibited negative effects on soil health impacting soil structure
369 maintenance, disrupting soil aggregation, exposing the labile carbon pool encapsulated within the aggregates to
370 microbial oxidation and reducing water infiltration (Mitchell et al., 2017). By contrast, CA positively influenced

371 carbon transformation and nutrient cycling functions. Several studies emphasized that CA systems contribute to
372 an accumulation of soil organic carbon (Cheesman et al., 2016; Lal, 2015c; Powlson et al., 2016), primarily due
373 to the continuous inputs of biomass (above and belowground), the quality of the inputs, and the protection of the
374 labile carbon pool from microbial transformation (Fujisaki et al., 2018; Virto et al., 2012). Concomitantly, a
375 higher soil available nitrogen concentration (N-NO_3^- , N-NH_4^+) was assessed under CA systems, promoting crop
376 growth supported by a higher structure maintenance function, and consequently limiting nitrogen losses
377 compared to CT (Calderón et al., 2001; Chatskikh and Olesen, 2007; Husson et al., 2018).

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

387 4.4. Toward the quantification of linkages between soil health, productivity, and ecosystem services

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

399

400 5. Conclusions

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

413

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714 **Figure captions**

715

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

717 **a** Variables factor map. POXC: Permanganate OXidizable Carbon, SituResp[®]: basal soil respiration, Laminas:
718 lamina bait degradation, GTB: fraction of Green Tea Bag decomposed, VESS: Visual Evaluation of Soil
719 Structure, Beerkan: water infiltration, AggSoil: soil aggregate water stability, AEMNO₃: nitrate evaluated with
720 anion exchange membrane, NNH₄, NNO₃: available ammonium and nitrate.

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

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

724

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

729

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

739

740 **Table 1** Biofunctool® indicators of soil carbon transformation per treatment. CT: Conventional Tillage, CA:
 741 Conservation Agriculture with direct seeding in Dead Mulch (CA-DM) or Living Mulch (CA-LM). POXC:
 742 Permanganate OXidizable Carbon, SituResp®: basal soil respiration, Laminas: lamina bait degradation, GTB:
 743 fraction of Green Tea Bag decomposed. The analysis was conducted in the 0-10 cm layer, except for laminas (in
 744 the 0-2 cm layer) and GTB (at a depth of 8 cm); n=9 for each treatment; sd: standard deviation. Different letters
 745 indicate significant differences according to Tukey's test ($P<0.05$).
 746

Treatment	Carbon transformation							
	POXC		SituResp®		Laminas		GTB	
	(mg _C kg _{soil} ⁻¹)		(Absorbance difference)		(Score)		(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	$P<0.001$		$P<0.001$		$P<0.001$		$P<0.001$	

747
 748

749 **Table 2** Biofunctool® indicators of soil structure maintenance per treatment. CT: Conventional Tillage, CA:
 750 Conservation Agriculture with direct seeding in Dead Mulch (CA-DM) or Living Mulch (CA-LM). VESS:
 751 Visual Evaluation of Soil Structure, Beerkan: water infiltration, AggSoil: soil aggregate water stability. The
 752 analysis was made in the 0-10 cm layer, except for VESS (in the 0-30 cm layer); n=9 for each treatment; sd:
 753 standard deviation. Different letters indicate significant differences according to Tukey's test.
 754

Treatment	Structure maintenance					
	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	<i>P</i> <0.001		<i>P</i> <0.001		<i>P</i> <0.001	

755
 756

757 **Table 3** Biofunctool® indicators of soil nutrient cycling per treatment. CT: Conventional Tillage, CA:
 758 Conservation Agriculture with direct seeding in Dead Mulch (CA-DM) or Living Mulch (CA-LM). AEM-NO₃⁻:
 759 nitrate evaluated with anion exchange membrane, N-NH₄⁺, N-NO₃⁻: available ammonium and nitrate. The
 760 analysis was conducted in the 0-10 cm layer, except for AEM-NO₃⁻ (at a depth of 8 cm); n=9 for each treatment
 761 except for N-NH₄⁺ and N-NO₃⁻ where n=3 per treatment (no internal replicates); sd: standard deviation. Different
 762 letters indicate significant differences according to Tukey's test.

763

Treatment	Nutrient cycling					
	AEM-NO ₃ ⁻		N-NO ₃ ⁻		N-NH ₄ ⁺	
	(μg _{N-NO₃⁻} cm ⁻² d ⁻¹)		(mg kg ⁻¹)		(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	<i>P</i> <0.001		<i>P</i> =0.4		<i>P</i> <0.001	

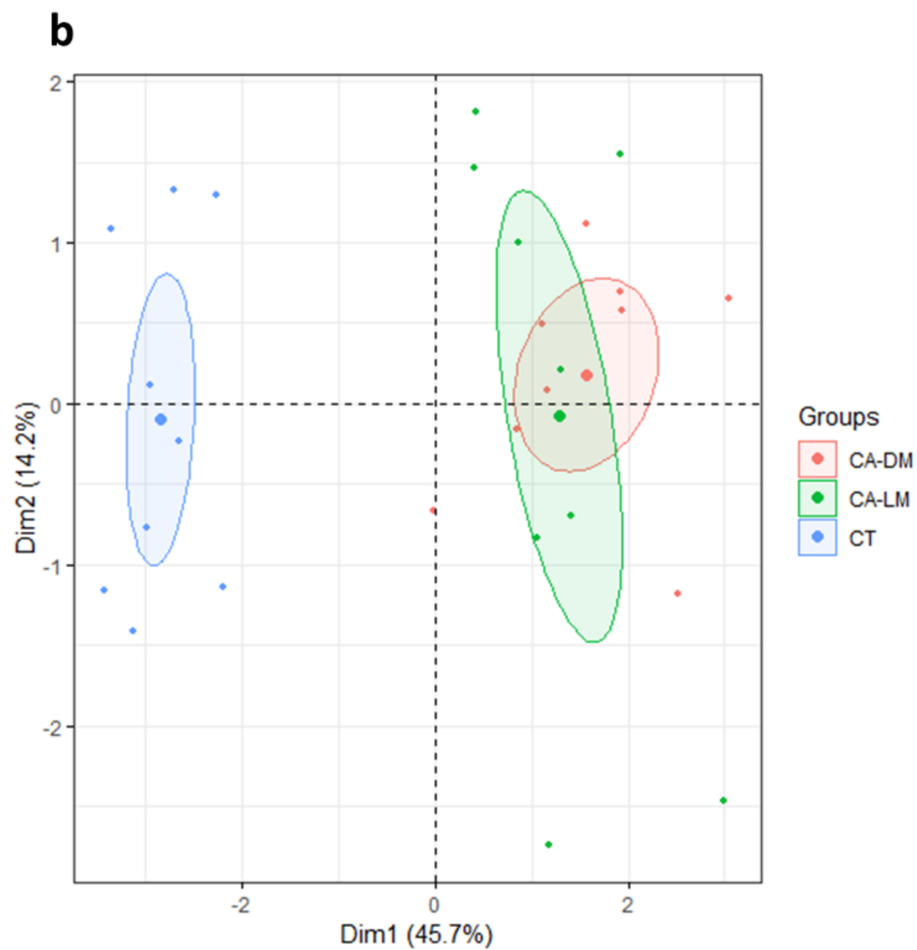
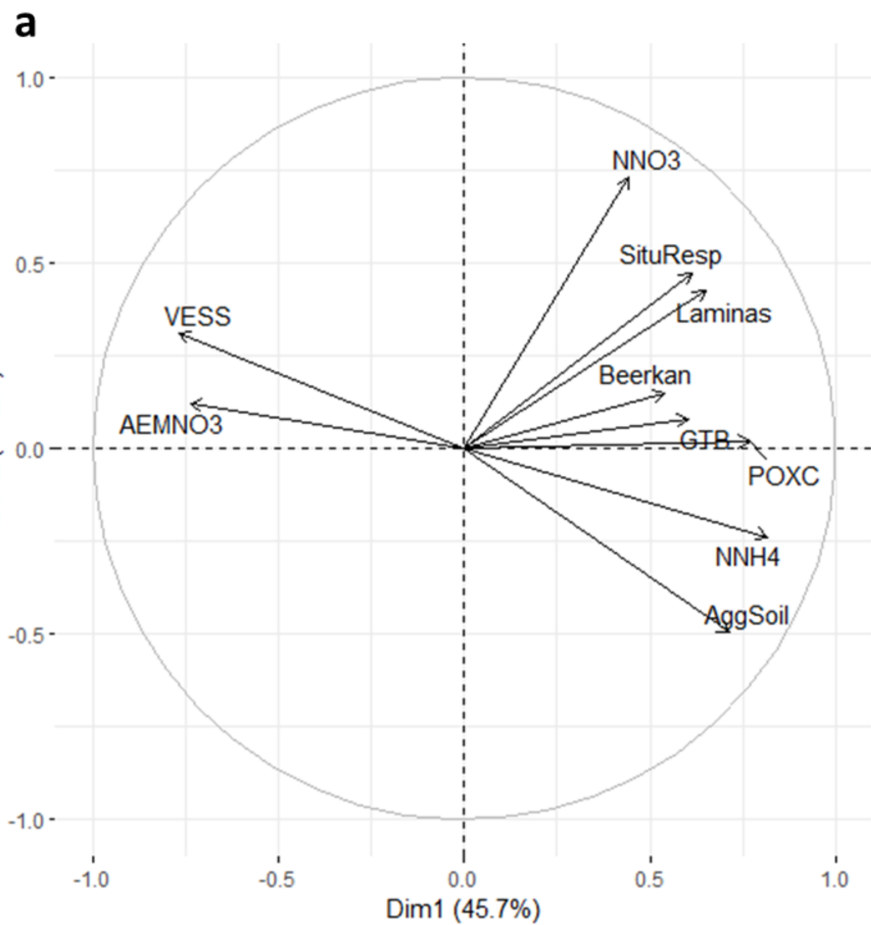
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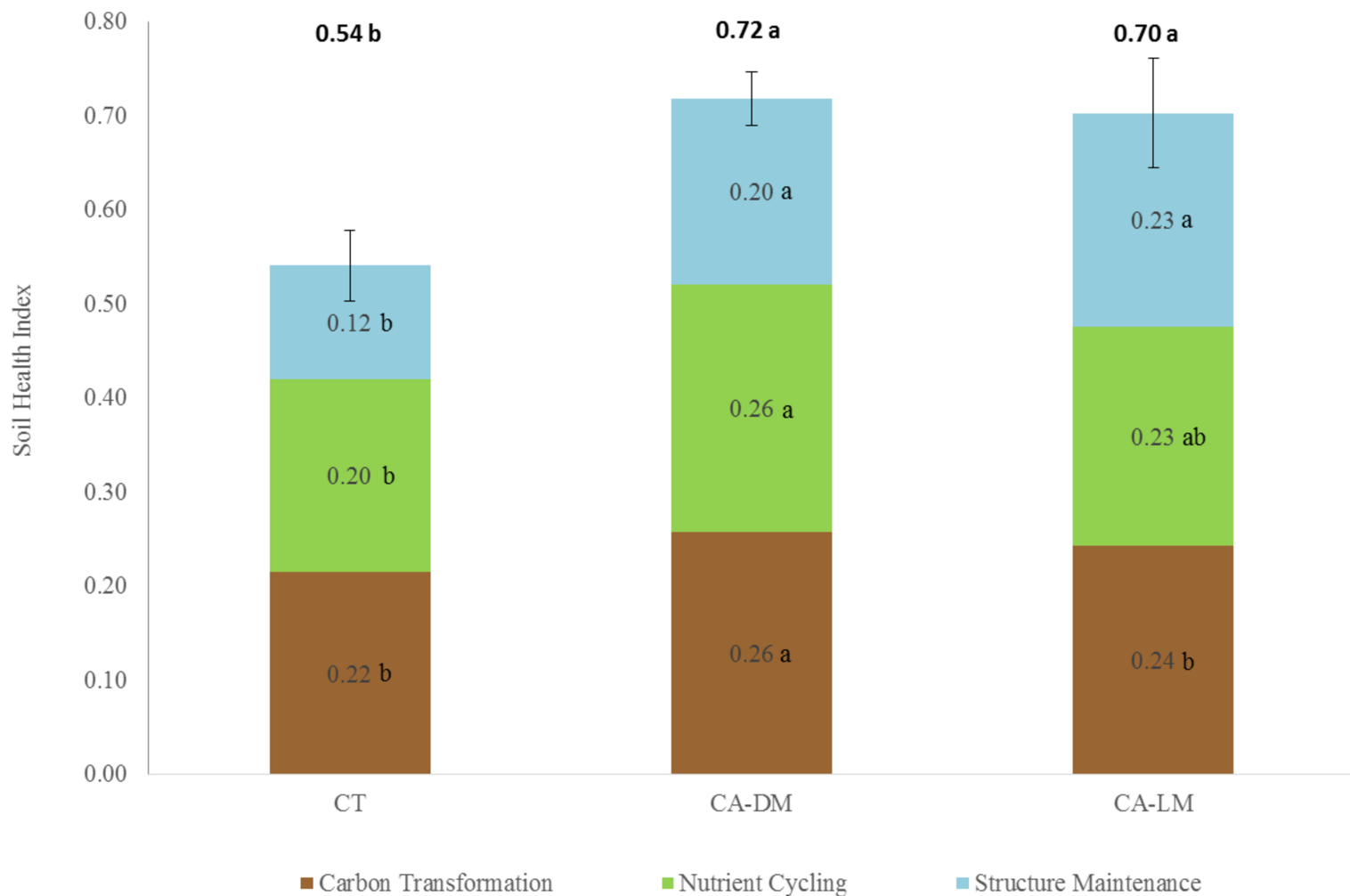
766 **Table 4** Cropping system performance indicators per treatment. CT: Conventional Tillage, CA: Conservation
 767 Agriculture with direct seeding in Dead Mulch (CA-DM) or Living Mulch (CA-LM). Weeds: Weed cumulative
 768 aboveground dry matter during crop cycle, Maize density: Maize plant population,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

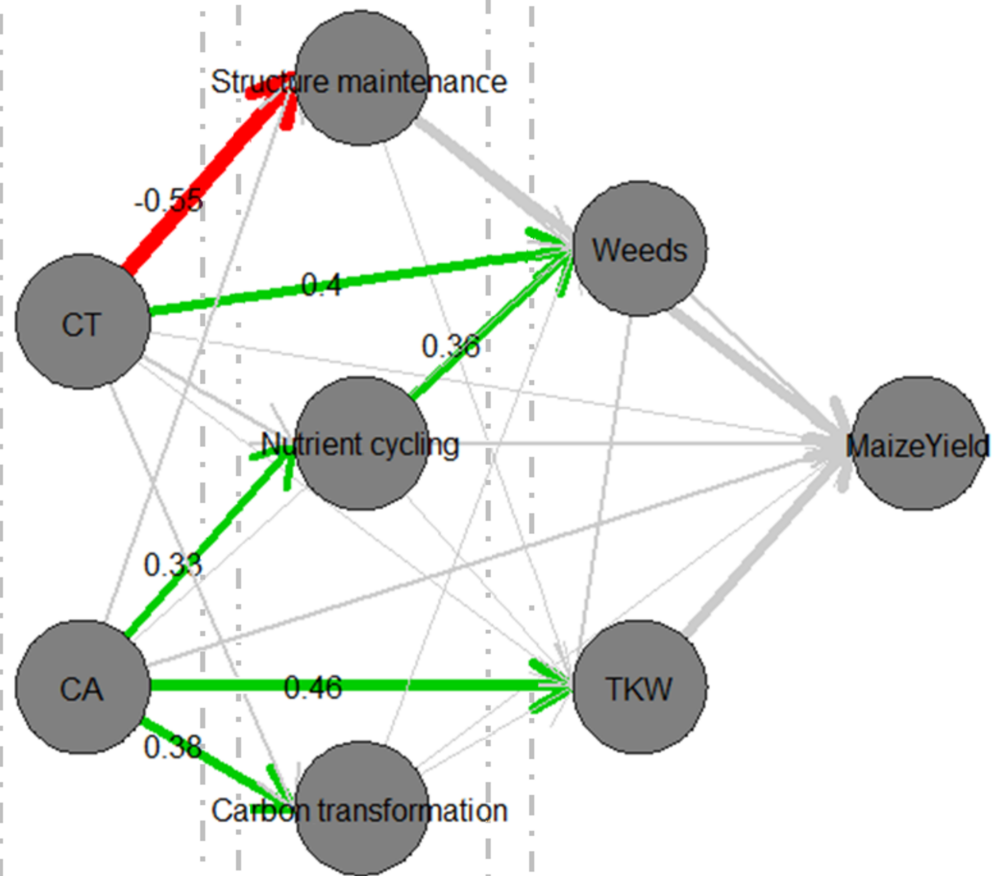
771

Treatment	Weeds		Maize density		Kernel weight		TKW		Yield	
	(t _{cumulative DM ha⁻¹})		(plants m ⁻²)		(g ear ⁻¹)		(g)		(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	<i>P</i> <0.001		<i>P</i> <0.001		<i>P</i> <0.001		<i>P</i> <0.001		<i>P</i> <0.001	

772







**Cropping
system**

**Soil
health**

**Cropping system
performance**