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1 **INTEGRATING NO-TILLAGE WITH AGROFORESTRY AUGMENTS SOIL QUALITY INDICATORS**
2 **IN KENYA’S DRY-LAND AGROECOSYSTEMS**

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16 **Abstract**

17 Conservation agriculture with trees (CAWT) is one of the best-bet strategies for enhanced soil quality under
18 extensive and intensive smallholder farming. CAWT is an agroforestry system that integrates legume trees and
19 shrubs into cropping fields under minimum soil disturbance and tillage. This study identified principal soil quality
20 indicators (SQI) under CAWT system. The study further assessed the effects of CAWT components; i.e. tillage
21 (convention or no-tillage), leguminous trees/shrubs (*Calliandra calothyrsus*, *Gliricidia sepium* and *Cajanus cajan*),
22 and their inter-row spacing (1.5 m, 3.0 m or 4.5 m) on the SQI in the dry-land agroecosystems of eastern Kenya. We
23 finally reported on the suitability of the SQI under CAWT intervention towards maize production. The experimental
24 trials were both researcher (Mother-trials; MTs) and farmer (Baby-trials; BTs) hosted and managed. Principal
25 Component Analyses (PCAs) identified soil fertility and textural components as the main factors explaining soil
26 quality under the CAWT system. In particular, the exchangeable bases (ExBas) such as ExCa, ExK, and ExMg),
27 Cation-Exchange-Capacity (CEC), total soil nitrogen (TSN), soil organic Carbon (SOC), pH, available
28 Phosphorus(P), electrical conductivity (EC), clay and bulk density (BD) were identified as the principal soil quality

29 indicators under the CAWT system. Tree species and varied inter-row spacing, significantly affected available P,
30 BD, pH, ExBas, CEC, SOC, and TSN. The tillage systems significantly ($P < 0.05$) influenced soil pH, ExBas, CEC,
31 SOC and TSN. A high concentration of TSN was recorded in no-tillage (NT) blocks integrated with *C.calothyrsus*
32 (41.9 and 41.6 Mg N ha⁻¹) and *G. sepium* (35.7 and 32.3 Mg N ha⁻¹) both spaced at 1.5 m at the MTs and BTs,
33 respectively. Combining NT with *C.calothyrsus* spaced at 1.5 m or Pigeon pea at 3.0 m significantly increases
34 available P (from 22.9 to 28.8 mg kg⁻¹ and 23.4 to 26.0 mg kg⁻¹) at the MTs, respectively. Significant rise in ExK
35 (1.91 to 2.25 cmol_c kg⁻¹), ExCa (6.86 to 8.17 cmol_c kg⁻¹), and ExMg (2.35 to 2.78 cmol_c kg⁻¹) were observed in NT
36 block's sub-plots with *G. sepium* spaced at 3.0 m at the MTs. Conclusively, a shift towards CAWT showed evidence
37 of improving soil quality, nutrient availability and increasing soil nutrient thresholds that can potentially support
38 maize production. By establishing the minimum datasets for soil quality determination through this study, key
39 stakeholders in agroforestry and conservation agriculture (CA) have an efficient cost-effective and rapid tool for soil
40 quality assessment, especially in dry-land agro-ecosystems.

41

42 **Key words:** Agroforestry; CAWT; *Gliricidia sepium*; Luvisols; minimum-dataset selection; soil quality indicators;
43 Soil Organic Carbon
44

45 **Highlights**

- 46 ❖ soil fertility & texture constitute soil quality indicators under CAWT
- 47 ❖ CAWT stabilizes soil pH
- 48 ❖ CAWT increases available-Phosphorus, exchangeable-bases and CEC
- 49 ❖ CAWT with *C.calothyrsus* & *G.sepium* increases total-N stocks (>40 Mg N ha⁻¹)
- 50 ❖ CAWT with *C.cajan* increases SOC stocks (>36 Mg C ha⁻¹)

51

52 **Graphical Abstract Here**

53

54 **1. Introduction**

55 Kenya's dry-land agro-ecosystems in the eastern region are characterized by low and declining maize and legume
56 crop productivity, high rainfall variability, sparse vegetation and animal life, low soil fertility and high vulnerability
57 to land degradation (Mcheru-Muna *et al.*, 2010, Ngetich *et al.*, 2014, Kisaka *et al.*, 2016). Maize or the legume
58 crops are grown continuously with shorter fallows, often devoid of intercropping or rotations. These practices have
59 contributed to net nutrient mining jeopardizing the soil's capacity to rejuvenate (Nyiraneza *et al.*, 2015; Gitari *et al.*,
60 2018; Nyawade *et al.*, 2019a). Besides, the heterogeneity of physicochemical soil properties and declines in soil-
61 nutrient base and fertility are widespread, contributing to declines in crop yields (Lipiec, 2017; Gitari *et al.*, 2019a).
62 Persistent exponential human population growth and decrease in land resource in the region has pushed smallholder
63 annual crop producers to expand into marginal areas seeking cultivation fields (Gitari *et al.*, 2018). This invasion
64 further compounds the above-mentioned food production constraints, such as loss of soil fertility and quality (Elias,
65 2017; Nyawade *et al.*, 2019b). Farmers occasionally utilize assorted *in situ* soil management strategies to increase
66 overall farm productivity including use of manure, inorganic and organic fertilizers, mulching and agroforestry
67 practices among others (Bationo *et al.*, 2007, Mugendi *et al.*, 2003, Mcheru-Muna, *et al.*, 2010). Nonetheless, these
68 efforts are constrained by inadequacies in access to optimal quantities and guidelines on how such technologies
69 ought to be co-implemented (Akponikpè, 2008; Mugwe *et al.*, 2009). Thus, a succinct spatial understanding of soil
70 physicochemical properties and their heterogeneity is vital in determining optimal soil management practices for
71 improved soil nutrient base, quality and its indicators, as well as crop productivity under different farming systems.

72 Intensification has been suggested as one the key strategies to enhancing total farm productivity but it destabilizes
73 and degrades soil quality (Takoutsing *et al.*, 2017). Soil quality can broadly be defined as “*the capacity of a specific*
74 *kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity,*
75 *maintain or enhance water and air quality, and support human health and habitation*” (USDA NRCS, 2022).
76 During our study, this definition was modified with specific reference to maize-legumes intercropping
77 agroecosystems. Specifically, soil quality was defined as the capacity of farm soils to function within natural and
78 managed agroecosystems to sustain maize and legume cover crops as well as animal production, soil fertility and
79 functioning. Under the intensive mixed farming systems, restoration of depleted soil nutrients is often managed
80 using chemical fertilizers (Mugwe *et al.*, 2009; Gitari *et al.*, 2018). Among most smallholder farmers in sub-Saharan
81 Africa (SSA), optimal implementation of this strategy is constrained by the high costs of chemical fertilizers (Gitari
82 *et al.*, 2019b). The high costs often lead to the compromised application of fertilizers at inadvisable rates that cannot
83 support improved crop production but rather contribute towards soil deterioration (Muthoni *et al.*, 2013; Sharma *et*
84 *al.*, 2017; Gitari *et al.*, 2018). In Kenya’s eastern region, cases of imbalanced use of chemical fertilizers can
85 potentially be stabilized by the use of green residues and manure such as *Glycine max*, *Tithonia diversifolia*, *Lablab*
86 *purpureus*, and *Mucuna pruriens* with positive effects on yield production, soil structure, soil organic matter and
87 fertility (Mugwe *et al.*, 2009; Mucheru-Muna, 2010; Kisaka *et al.*, 2016). However, this strategy’s efficacy can be
88 constrained under intensive farming systems predisposed to extended dry spells and erratic rainfall, which limits the
89 availability of the residues. Besides, in the dry-land agro-ecosystems, the best-bet mitigation options should be
90 aimed at integrated farming systems that can enhance the soils’ capacity to build up soil nutrient base, conserve soil
91 water, optimize total land productivity and land-resource utilization in the long term (Muthoni *et al.*, 2013; Sharma
92 *et al.*, 2008). CAWT has been suggested as a better bet for both extensive and intensive smallholder farmers in the
93 dry-land regions (UNDP, 2014; ICRAF, 2015).

94 CAWT is an agroforestry system that integrates legume trees and shrubs into cropping fields under minimum soil
95 disturbance and tillage (ICRAF, 2015). The leguminous crops and shrubs have been reported to promote soil cover,
96 nutrient and residue supply, fodder for livestock feeding while no-tillage conserves these benefits within the soils
97 (ICRAF, 2015). Traditional agroforestry leguminous species suitable for intercrop with annual crops
98 include *Calliandra calothyrsus* (*C.calothyrsus*), *Gliricidia sepium* (*G.sepium*), *Leucaena leucocephala*
99 (*L.leucocephala*) and *Cajanus cajan* (*C.cajan*) (Gitari *et al.*, 2018). *C.calothyrsus* has been reported to thrive well in

100 a wide range of soil types and biophysical environments, including nutrient-deficient soils due to its capacity to host
101 beneficial fungi (*Vesicular arbuscular* (VA-mycorrhiza), and ability to nodulate fast (ICRAF,
102 2015). *C.calothyrsus* also reduces soil erosion, promotes nutrient retrieval (using its extensive rooting systems of
103 1.5m), improves soil physical properties, and increases topsoil organic matter with minimal shading effects to
104 annual crops (Wiersum and Rika 1992, Sitienei *et al.*, 2017). Kabi and Bareeba (2008) showed
105 that *C.calothyrsus* could yield up to 45.9 Mg ha⁻¹ yr⁻¹ on quarterly harvests with crude protein content of 492.8 g kg⁻¹
106 ¹
107 dry-matter within two months. Consequently, this makes them ideal for livestock fodder and green residue.
108 Makumba *et al.* (2006) established that the use of *G.sepium* as green residue in maize cropping fields influenced
109 production of an average yield of 3.8 Mg ha⁻¹yr⁻¹ of maize grain and 5 Mg ha⁻¹ yr⁻¹ leafy dry matter
110 of *G.sepium* twigs without use of inorganic fertilizer amendment. A study by Ojiem *et al.* (2007) further reported
111 that *Dolichos* (*Lablab purpureus*) could potentially raise soil nitrogen content through atmospheric fixation by up to
112 42 kg N ha⁻¹. According to Albrecht and Kandji (2003), no-tillage in agroforestry systems can stock more SOC
113 without compromising farm-food productivity. These examples indicate that legume plants can fix atmospheric N
114 and contribute to nutrient recycling through residue incorporation; hence a source of soil nutrient build-up and
115 availability thus enhance soil quality.
116 Nonetheless, studies on the precise integration of leguminous shrubs into cropping fields and incorporating their
117 residues into the soils under minimum soil disturbance to boost soil productivity are scarce, especially in highly
118 heterogeneous environments. A few studies on maize-tree intercrop mainly focus on the intercropping strategy in
119 isolation overlooking no-tillage (NT) potentials or are just focused on dry-matter production capacity. Besides, most
120 of the studies are carried out under highly advanced technologies and research management systems whose results
121 cannot easily be scaled out and contextualized to the rural on-farm settings for adoption (Chang *et al.*, 2016). Others
122 (Ojiem *et al.*, 2007; Mucheru-Muna *et al.*, 2010; Gitari *et al.*, 2018) have studied intercropping systems either
123 without tree components or by the external acquisition of the green residues grown on different farms. There is
124 further limited information on how such an intensive farming system impacts soil quality and its indicators as a
125 response to different tree-shrub species and intensive legume-maize intercrop with maximized green residues'
126 retention in the cropping fields. To fully and precisely establish CAWT benefits, there is a need to identify key
127 indicator candidates of overall soil quality and establish critical (threshold) levels using measurable soil attributes
that influence soil capacity to deliver ecosystem services over time and space. With this backdrop, this study

128 identified principal soil quality indicators under CAWT. The study further assessed the effects of
129 CAWT components; i.e. tillage systems (convention (CT) or no-tillage (NT)), leguminous
130 trees/shrubs (*C.calothyrsus*, *G.sepium*) and *C.cajan*), and their varied inter-row spacing on the
131 soil quality indicators in the dry-land agroecosystems of eastern Kenya. We finally reported on
132 the suitability of the SQI under CAWT intervention towards maize production. The findings of this study were
133 envisioned to provide contextualized information for relevant stakeholders championing the adoption of intensive
134 ever-green farming.

135 **2. Materials and Methods**

136 **2.1 The study area**

137 The study was carried out in the expansive sub-humid and semi-arid eastern region of Kenya, spanning across an
138 estimated area of about 6,281.4 km², covering three administrative sub-counties (Machakos, Kangundo and Mwala)
139 of Machakos County (Figure 1).
140

141 **Figure 1: A map of the study area showing the distribution of the experimental sites across the administrative sub**
142 **counties.**

143 **Here**

144
145
146 Machakos County stretches from latitudes 0° 4' to 1° 31' in the South and longitudes 36° 45' to 37° 45' to the east.
147 The region lies within three agro-ecological zones, generally clustered as sub-humid, transitional, and semi-arid
148 regions, representing low to medium potential agricultural production areas (Jaetzold *et al.*, 2006). The region
149 receives an average of 700 mm of annual rainfall, which is normally bimodal, erratic and poorly distributed with
150 high peaks in April and November (Recha *et al.*, 2017). Seasonal rainfall occurs between the months of mid-March
151 to mid-May (as Long-rains (LRs)) and mid-October to early-January (as short-rains (SRs)). The average seasonal
152 rainfall amount varies between 250 mm and 400 mm. Seasonal rainstorms are highly variable recording coefficient
153 of variations (CVs) ranging from 45% to 58% (Kisaka *et al.*, 2015). The remainder of the year is emblematic of
154 extended dry periods. There are frequent crop failure cases among rain-fed cropping farmers, rendering over 50% of

155 the local populace food insecure (Abbas, 2009; Anon, 2010). In terms of agricultural productivity, high potential
156 areas span across Kangundo sub-county with moderate temperate climates but highly unpredictable rainfall
157 averaging 1250 mm per annum. Low potential production regions cover Mwala sub-county with less than 550 mm
158 of annual rainfall. Machakos sub-county is considered a medium potential agricultural production region. Kangundo
159 lies in the Upper Midlands agro-ecological zone 4 (UM4) while Mwala falls within Lower-Midlands agro-ecological
160 zone 4 (LM4) (Jaetzold *et al.*, 2006). The average annual temperature ranges between 17°C and 25°C, with highs of
161 over 30°C (Recha *et al.*, 2017; Sennhenn *et al.*, 2015). Machakos County is generally hilly with altitudes ranging
162 from 1000 to 1600 m above sea level. Luvisols are the dominant soil type, characteristic of deficiency in plant-
163 available P and Nitrogen as well as low soil organic carbon content (0.5 – 1.0%) and a slight acid reaction (pH 5.7–
164 6.9 in water) (Gicheru, 2004; FAOSTAT, 2017). Due to variations in the region's anthropogenic geological nature,
165 other soil types include patches of Vertisols, Acrisols, and Cambisols. Maize, beans, and cowpeas are dominant
166 annual crops grown by the smallholder farmers in the semi-humid and transitional zone, while sorghum and millets
167 cropping predominate the semi-arid areas (Aruma *et al.*, 2014). Major cash crops include coffee, horticultural crops,
168 and fruit trees in the semi-humid zone, while cotton, sunflower and fruit trees are typical in the transitional zone
169 (Recha *et al.*, 2017). Fruit trees are grown across the agro-ecological zones, including mangoes, banana, citrus,
170 papaws, and avocado.

171

172 **2.2 Research and Experimental Design**

173 This study utilized primary field measurements collected from experimental trials on CAWT installed in the study
174 area. The trials (described below) were either researcher (Mother-Trials) or farmer (Baby-Trials) hosted and
175 managed.

176

177 **2.2.1 Mother Trials (MTs)**

178 The MTs were solely researcher designed, hosted and managed. They (MTs) were established on 3rd October 2012
179 during the SRs of 2012 (SR2012) at Agricultural Training Centre (ATC) in Machakos county and were monitored
180 for six consecutive cropping seasons up to the LR of 2015 (LR2015), on 10th July 2015. The trials adopted a split-
181 plot design with a factorial combination of two tillage systems (as the main blocks) and three spatial agroforestry
182 patterns plus control treatment (as the sub-plot treatments). The two tillage systems were Conventional tillage (CT)

183 and no-tillage (NT) as the main splitting blocks. The CT block was subjected to complete soil turnover (of
184 approximately 30 cm depth) using manual hand-held hoes while minimum tillage was done on the NT block. The
185 three spatial agroforestry patterns were the integration of three leguminous shrubs
186 (*G.sepium*, *C.calothyrsus*, and Pigeon peas (Ppeas)) at three inter-row spacing of 1.5 m, 3.0 m or 4.5 m and a
187 standard intra-row spacing of 1 m between the individual shrubs, culminating to 2708, 4514 and 8125 trees per
188 hectare, respectively; into a maize-legume cover crop intercrop to constitute the sub-plot treatments. In summary,
189 the sub-plot treatments were *G.sepium* spaced at 1.5, 3.0 or 4.5 m, *C.calothyrsus* at 1.5, 3.0 or 4.5 m, and Pigeon
190 peas at 1.5., 3.0 or 4.5 m plus the control (sole maize-legume cover crop intercrop) translating to 10 treatments per
191 replication in each of the two main blocks and a total of 60 sub-plots at the MTs. These treatments were arranged in
192 a randomized complete block design (RCBD), on sub-plot measuring 12 m by 12 m, separated by a path of 0.5 m
193 and replicated three times. Figure 2 (two) shows a pictorial sketch of the arrangement of these sub-plot treatments
194 within a single replication of the LR2014, SR2014 and SR2015 cropping seasons when common beans were planted
195 under NT block. This arrangement was applied in a similar way to the other cover crops (cowpeas and dolichos)
196 during the specific seasons they were intercropped with maize. Maize intercropped with legume crops (cowpeas,
197 common beans, and dolichos) were the test crops during the experimental period. Maize was planted at 0.9 m inter-
198 row and 0.3 m intra-row spacing, and intercropped with different leguminous cover crops (LCC) varied seasonally
199 as follows: cowpeas (*Vigna unguiculata*) in SR2012 and LR2013, Dolichos (*Lablab purpureus*) in SR2013 and
200 common beans (*Phaseolus vulgaris*) in LR2014, SR2014 and SR2015. The subplots in each tillage block with sole
201 maize-legume crops (without trees) were treated as control plots during our study. The legume crops were
202 intercropped between maize rows at intra-row spacing of 0.07 m. The choice of LCC to other cover crops was
203 guided by their proven effective sustainability of soil fertility as was reported by and the frequency by which they
204 are cropped in the region (Cheer *et al.*, 2006).

205

206 **Figure 2:** Pictorial sketch of the replicate 1 sub-plot treatments in a CA main block at the Mother trials (MTs) and
207 in Baby trials (BTs) sites. This arrangement was applied in a similar way to the other cover crops during the
208 specific seasons they were intercropped with maize.

209 **Key:** M+B=Maize+beans, Grl=*Grilicidia sepium*, Cal=*Calliandra calothyrsus*, Pp= Pigeon peas. The subplots in
210 each tillage block with only maize-legume crops (without trees) were treated as control plots during our study

211 **Here**

212

213 2.2.2 Baby Trials (BTs)

214 To foster evidence-based adoption of the CAWT technology, and enhance regionalization of the study findings, nine
215 volunteer farmers, three from each host sub-county (Machakos, Mwala and Kangundo), were identified to host a
216 sub-set of the mother trial treatments on their farms to constitute the BTs. Besides volunteering, selection of the host
217 farmers was based on the availability of land and willingness to host a specific replica of the experimental trials at
218 the MTs on their farms. The three farmers in each sub-county had to identify one specific leguminous shrub species
219 of their preference (translating to 3 tree species per sub-county), which was subsequently established on their farms.
220 The design adopted on each host farm was a split-plot layout with two tillage systems as main blocks and inter-row
221 spatial spacing (4.5 m, 3.0 m, and 1.5 m) of the specific legume shrubs into a maize-legume intercrop as sub-plots.
222 Thus, the sub-counties acted as replicates of the treatments distributed in the entire county arranged in a randomized
223 complete block design. Each sub-plot measured 12 m by 12 m, separated by a path of 0.5 m. Similar to the
224 establishment at the MTs, maize intercropped with legume cover crops (cowpeas, common beans, or dolichos varied
225 seasonally) were the test crops. Maize was planted at 0.9 m inter-row and 0.3 m intra-row spacing, and intercropped
226 with different leguminous cover crops (LCC) seasonally as follows: cowpeas (*Vigna unguiculata*) in SR2012 and
227 LR2013, Dolichos (*Lablab purpureus*) in SR2013 and common beans (*Phaseolus vulgaris*) in LR2014, SR2014 and
228 SR2015. The legume crops were intercropped between maize rows at an intra-spacing of 0.07 m. The BTs were
229 solely farmer-managed. However, all the farm inputs and occasional training were provided by the researcher.

230

231 **2.2.3 Common Experimental Management at the MTs and BTs**

232 Both the Mother and Baby trials were established during the SR2012. Preparation of the cropping fields started on
233 3rd October 2012 while the first sowing was on 17th October 2012. During the first season of establishment,
234 Roundup herbicide (360 g/l glyphosate) was applied in the NT blocks 14 days before planting (3rd October 2012) to
235 kill the perennial and annual weeds. However, after the tree establishment and maize planting, and the remainder of
236 the experimental period, weed control in the NT blocks was carried out using weed scrapers.

237 Two maize and legume crops seeds were planted per hill at an approximate sowing depth of 15 cm. The test crop
238 varieties were DH04 (maize), KVVU-419 (cowpeas), KATX69 (common beans) and KAT/PP60/8 (Pigeon peas).

239 Two weeks after planting, maize thinning was done to ensure the recommended population density of 37,037 plants
240 ha⁻¹ for this study area (Kisaka *et al.*, 2016). Mineral fertilizer was spot-applied as NPK 23:23:0 and Di-Ammonium
241 Phosphate (DAP) at a rate of 60 kg N ha⁻¹ and 90 kg P ha⁻¹, respectively. In the CT block, land preparation and weed

242 control were done manually using hand-held hoes. Two seasons after establishment (one week to the SR2013 maize
243 planting season), first tree harvesting was done through coppicing to a height of 0.3m to harvest tree leaves, twigs
244 and wood stem for biomass estimation, laboratory analyses (5% of total weight per sub-plot) as well as utilization as
245 a green residue (95% of total weight per sub-plot). For the remainder of the experimental period, tree coppicing was
246 done seasonally, during maize-legume crop sowing date whereby the green residue was retained within the specific
247 sub-plots as organic fertilizers. The woody stalks were removed from the cropping fields and used by the host
248 farmers as firewood. Maize and cover crop grain, stover and haulms were harvested at physiological maturity from
249 a net area of 129.9 m² (out of the total area of 144 m²). The net area was computed after leaving out one row on each
250 side of the sub-plot and the first and last maize and cover crop plants in each row to minimize the edge effect. Maize
251 and cover crop grains, stover and haulms were dried and their weight expressed in terms of dry matter content. Dry
252 matter yields were extrapolated to a hectare basis using plant populations corrected for the emergence rate and
253 moisture content. Plant emergence rates were not affected by treatments. No diseases were observed during the
254 experimental period. All other standard agronomic practices were followed for optimal crop production.

255

256 **2.4 Soil sampling framework**

257 Soil sampling was carried out at the end of the LR2015 season from the 20th of July 2015 to the 6th of August 2015.
258 A total of 132 sub-plots (i.e., 60 at the MTs and 72 from the BTs) were sampled. Of the 60 sub-plots at the MTs, 54
259 (27 in each tillage block and 9 per replication) were integrated with leguminous shrubs/trees while 6 (3 in each
260 tillage block and 1 per replication) acted as control plots. Similarly, at the BTs, 54 sub-plots (18 per sub-county) had
261 leguminous trees/shrubs while 18 (6 per sub-county) acted as the controls. On each sub-plot, five sampling spots
262 were randomly selected following a W-design with particular reference to tree spatial locations (i.e., very close to
263 the tree roots (Close-to-Tree), mid-way the intra-row tree spaces (Away-from-Tree in sub-plots integrated with
264 trees) or where there were no trees (No-Tree) in the control plots. Sampling was done at depths of 0-30 cm using
265 soil augers and 5 cm long steel core-rings for disturbed and undisturbed samples, respectively, as guided by Pennock
266 and Yates (2008). The disturbed samples were thoroughly mixed to constitute net composite sub-plot samples. Two
267 composite soil samples (“Close-to-tree” and “Away-from-tree”) were collected in each sub-plot integrated with
268 leguminous trees/shrubs while only one composite sample (No-Tree) was collected in the control sub-plots. In this
269 regard, a total of 240 (i.e. (54+54)*2=216 samples in sub-plots with trees *plus* (6+18=24 control samples) composite

270 soil samples were taken for laboratory analyses. Precautionary measures were taken, including exposure of samples
271 to direct sunlight before laboratory analyses at the World Agroforestry Centre (ICRAF) soil laboratories in Nairobi
272 Headquarters, Kenya.

273

274 **2.5 Laboratory and spectral analyses of Soil samples**

275 The soil samples (n=240) were then air-dried, and ground using a wooden rolling pin and sieved through a 2 mm
276 sieve. They were then finely ground to powder and loaded into micro-cups for Mid Infrared (MIR) analysis.
277 Reference samples (n = 38 (i.e., (9+9)*2=36 under sub-plots with trees *plus* (1+1=2) under control sub-plots)
278 collected from sub-plots in the first replication at the MTs were selected based on the Kennard-Stone method and
279 analyzed for fifteen chemical properties using the conventional wet chemistry methods. Soil pH (soil: water ratio of
280 1: 2.5) was measured using a pH meter (Ryan *et al.*, 2001), total N by modified micro-Kjeldahl method (Bremner,
281 1996) and organic Carbon (OC) by modified Walkley and Black method (Nelson and Sommers, 1996). Phosphorus
282 was extracted by the Mehlich-1 method (Mehlich, 1978) then measured using a UV-vis spectrophotometer (Murphy
283 and Riley, 1962). Cation exchange capacity was analyzed following procedures provided by Rhoades and Polemio
284 (1977). The flame photometry method was used to analyze K and Na while Atomic Absorption Spectrophotometry
285 was used for Ca and Mg analyses (Jackson, 1967). Soil texture was measured using the hydrometer method (Gee
286 and Bauder, 1979). Undisturbed soil samples were also collected in core rings for bulk density determination as
287 described by Doran and Mielke (1984). The other properties analyzed were nitrogen (N) and Carbon (both total and
288 Organic), clay, silt, sand, electric conductivity (EC), exchangeable bases (ExBas), calcium (ExCa), potassium
289 (ExK), magnesium (ExMg), phosphorus (m3.P), CEC, Bulk Density (BD) and pH. A soil-MIR spectral library
290 consisting of the 240 composite samples was used, which included 38 reference soil samples that had analytical data
291 on soil properties obtained using the wet soil analytical methods described above. The MIR spectra were
292 preprocessed using Savitzky-Golay's first derivative with a smoothing interval of 21 points (Terhoeven-Urselmans
293 *et al.*, 2010). Using Radom Forest (RF) regression method and soil properties data from the conventional wet
294 chemistry methods for the reference samples were used to train the preprocessed spectra. The fitted regression
295 models were used to predict soil values for the rest of the samples, including the calibration samples that had not
296 been subjected to reference analyses (Hengl *et al.*, 2015).

297 **2.6: Data Analyses**

298 Descriptive statistics (means, standard deviation (SD) and coefficient of variation (CV) were used to summarize and
299 describe the general soil properties after CAWT intervention. Pearson correlation coefficients were used to assess
300 the relationships among pairs of the soil properties. Principal Component Analyses were used to identify properties
301 that elucidate the most variability in soil properties and select principal indicators of soil quality. Analyses
302 of variance (ANOVA) tested the effects of the tillage system, tree species, and spatial spacing on the soil
303 quality indicators. ANOVA was conducted by fitting Linear Mixed-Effects Models with a restricted maximum
304 likelihood estimation (lmer) method using the *lme4* package in R. Tillage system, tree species, and tree spatial-
305 spacing were treated as fixed while replication as random sources of variations in the model. Split-plot level means
306 comparisons (with observed significant interactions) were tested using the least-square-means (*lsmeans*) package
307 with Tukey's Honest Significant Difference (HSD) adjustment at a 5% level of significance for separation of
308 means. All the statistical analyses were implemented in the open-source R software version 3.5.3 (R Core Team,
309 2018).

310

311 **3. Results and Discussion**

312 **3.1 Descriptive statistics of the overall soil properties after CAWT interventions**

313 The coefficients of variations (CV) were used to test intra-dataset variations in all experimental plots, both at the
314 mother and baby trials (MTs & BTs). In all plots across the different experimental sites, a large degree of variability
315 in soil properties was observed in TSN (CV=0.31), ExK (CV=0.31), ExBas (CV=0.25), and P (CV=0.29) (Table
316 1). The least variability was observed in the soil pH (CV=0.03). Similar trends were observed in datasets at the
317 mother and baby trials, with high variability recorded in TSN (CV=0.29 and CV=0.31) at the Mother and baby
318 trials, respectively (Table 1).

319

T

320 **Table 1: General descriptive statistics of the soil properties after CAWT intervention**

321 **Here**

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323 A large degree of variability in available P and ExBas across the region (“all plots”) could be attributed to the
324 different sites’ natural characteristics, land use and management. Soils in Machakos are generally deficient in
325 available P (Willy *et al.*, 2019). These deficiencies can be attributed to the highly weathered gneisses rocks in the
region (Willy *et al.*, 2019). The distribution and types of gneiss rocks in the region are highly variable across the

326 agro-ecological zones. Soils in the Kangundo area are dominated by banded and biotite gneisses and tuff while those
327 in Machakos are dominantly Haplic Ferrasols, developed on banded gneisses (Willy *et al.*, 2019). Besides, plant
328 available soil P, ExBas, CEC, SOC, and TN have been reported to be influenced by the soil parent material (Willy *et*
329 *al.*, 2019), soil management and farming practices (Takoutsing *et al.*, 2017), climatic and agro-ecological conditions
330 (FAO, 2015) among others. Most of these characteristics are highly variable spatially but closely associated with
331 different soil nutrients (such as extractable bases (ExBas) and changes in the organic matter build-up brought about
332 by the intensive retention of crop and green residues within the soils (Momtaz *et al.*, 2009; Waswa *et al.*, 2013).
333 Conversely, different land-use systems, history and high variations in the soil types with reported patches of
334 Vertisols, Acrisols, and Cambisol, as well as responsiveness to fertility interventions, could explain the observed
335 high coefficient of variation (CV) values in exchangeable bases, CEC and TSN (Jiang and Thelen, 2004; FAO,
336 2015).

337

338 **3.2 Identification of soil quality indicators under the CAWT farming system**

339 The use of principal component analyses (PCA) for selecting soil quality indicators from large datasets has been
340 successfully studied and documented (Andrews *et al.*, 2002; Takoutsing *et al.*, 2017; Stefanoski *et al.*, 2016). During
341 our study, significant correlations (Table 2) were observed between the soil properties, hence the need for
342 establishing a minimum dataset (MDS) of soil quality indicators as critical targets for soil amendment and
343 amelioration with CAWT.

344

345 **Table 2: Pearson product moment correlations between soil properties under the CAWT system in the study**

346 **area (n= 331)**

347 **Here**

348

349 During our study, the PCA and the correlation level were applied to identify the critical soil quality indicators under
350 the CAWT system. In applying the PC tool, variables with high factor loadings in each dimension were retained as
351 leading soil quality indicators (Takoutsing *et al.*, 2017). In cases where more than one variable is retained under a
352 single PC, a multivariate correlation statistic tested the variables' redundancy for subsequent elimination.
353 Conversely, in circumstances where the highly loaded factors were found not to be correlated, each was considered

354 essential and thus retained as part of the quality indicator sets. For the well-correlated factors, one with the highest
355 absolute factor loading value was chosen as an indicator. At both the MTs and BTs, we established that in the PC1,
356 the highly weighted soil properties were ExBas (ExCa, ExMg, and ExK) and CEC (**Table 3**). Consequently, these
357 properties were selected to constitute the minimum dataset under PC1.

358

359 **Table 3: Rotated factor loadings for the five principal components (PC) for the topsoil (0–30 cm) properties**

360 **under CAWT system at the Mother and Baby trials used for minimum data selection (MDS)**

361 **Here**

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363 The exchangeable bases and CEC principally constitute critical soil fertility properties, and thus, PC1 could be
364 interpreted as a soil fertility component (Takoutsing *et al.*, 2017). Clay, silt, and sand recorded relatively high
365 eigenvalues under PC2 at both the MTs and BTs (**Table 2**). However, they were highly correlated, and thus, only
366 clay (having recorded the highest absolute eigenvalues) was retained as a soil quality indicator under PC2 (Table 3).
367 The rest were dropped due to redundancy. On the other hand, Soil pH was selected in this component (PC2) for
368 having the least significant correlation (**Table 2**) with the other soil properties that had recorded relatively high
369 factor loadings. High factor loadings in PC3 were observed in TSN and SOC from both MTs and BTs. Available
370 soil P and EC were selected as the soil quality indicators under PC4. Bulk Density (BD) was selected as the only
371 highly loaded soil property on PC5 at the MTs while compensating for the highly loaded sand in PC1 at the BTs to
372 constitute the final minimum dataset for soil quality indicators (**Table 3**). According to Andrews *et al.* (2002) and
373 Takoutsing *et al.* (2017), once the MDS has been established, there is no underpinning need to tests a broad array of
374 other indicators to assess soil fertility or quality over time.

375

376 Thus, the following properties were identified as the most appropriate soil quality indicators under the CAWT
377 system in the region: ExBas, CEC, TSN, SOC, pH, P, EC, clay, and BD. These properties have been reported to be
378 highly (positive or negatively) correlated with soil quality (Yao *et al.*, 2013; Takoutsing *et al.*, 2013). However, an
379 assessment of these properties within agroforestry systems under CA remains consistently low. Thus, it is essential
380 to report these indicators' appositeness under agroforestry systems that integrate maize and legume crops with
381 seasonal leguminous trees and shrubs under conservational management (Figure 3).

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Figure 3: The Variable factor loading map (above) between Dimension 1 and 2 (PC1 and PC2) showing soil properties responsible for maximum variance and in the CAWT system (Below): Arrows (in above) represent the directions of maximum variation

Here

The first component is dominated by the positive loading of exchangeable bases and the CEC at the MTs and BTs (Figure 3). These properties have been reported to have a common variance that is attributed to the soil organic matter content that influences soil nutrients (Takoutsing *et al.*, 2017). These positive loadings on the PC1 component principally represent the soil fertility status and nutrient availability (Takoutsing *et al.*, 2015). On the other hand, the high factor negative loadings of clay, silt, and sand (PC2) represent the textural properties, which are often used to explain soils' capacity to store or release nutrients, and available soil pores (Waswa *et al.*, 2013). By extension, the third component (PC3) is dominated by total soil nitrogen and SOC (often reported in PC1), an indicator that CAWT systems could shift variations in soil fertility components with the transition from CT towards NT systems (Figure 3). It is evident that most properties have a strong relationship and are defined by the NT block (Figure 3). For instance, at the MTs (Figure 3), there was a strong association of all soil properties from the NT block when compared to those under the CT block. This influence could either be positive or negative depending on the soil surface management strategies employed, such as presence or absence of minimal soil tillage, crop and green residue retention, and type of leguminous shrubs integrated (Ngetich *et al.*, 2014) as discussed in **section 3.3 (below)** of our current study. Generally, soil quality indicators form a significant basis as decision support tools for understanding soil functioning, management, and quality assessment over time (Ghaemi *et al.*, 2014). However, the remaining soil properties, not selected during this study, could still be monitored to build on site-system-specific minimum dataset (MDS) development.

3.3 Effects of CAWT on soil quality indicators in the study area

The selected soil quality indicators differed significantly in response to tillage systems (CT and NT), compounded species' effects, inter-row spacing, and selected interactions/combined effects (Table 4 supplementary materials).

410 The tillage systems (CT and NT) significantly ($P < 0.05$) influenced soil pH, ExBas, CEC, SOC, and TSN while tree
411 species and varied inter-row spacing, significantly affected soil available P and BD in addition to pH, ExBas, CEC,
412 SOC, and TSN (Table 4). It was further observed that the association of the tillage systems with the different tree
413 species under varied spatial spacing had significant effects on some soil properties. At both the MTs and BTs, inter-
414 row tree spacing variations showed a significant effect on ExBas, CEC, SOC, and BD.

415 The existence of significant interactive effects showed evidence of a combined or associated influence of the tillage
416 system and variations in inter-row tree spacing (Ayuke *et al.*, 2011). Lack of significant interactive effects on soil
417 properties would indicate that the independent variables had sole but similar effects across the experiment's response
418 variable (Takoutsing *et al.*, 2015). It was observed that some influences were significant at the MTs but not among
419 the BTs. These variations in response to the CAWT intervention could be explained by the experimental host sites
420 diverse spatial characteristics and changes in temporal variables and management skills during the experimental
421 period (Jiang and Thelen, 2004). For instance, available plant P, ExBas, CEC, SOC, and TSN have been reported to
422 be influenced by the soil parent material (Willy *et al.*, 2019), soil management and farming practices (Takoutsing *et*
423 *al.*, 2017), climatic and agro-ecological conditions (FAO, 2015) among others. Our findings of significant effects of
424 tillage systems are corroborated by studies such as Momtaz *et al.*, 2009; Waswa *et al.*, 2013; which reported changes
425 in organic matter build-up (evident with SOC and TSN accumulation during our study) and increased base
426 saturation due to intensive retention of crop and green residue as well as minimum soil disturbance. The efficiency
427 of plot management could equally explain possible variations among the observed effects of different interventions
428 at the MTs and BTs (Naab *et al.*, 2017). With reference to bolstering the adoption of CAWT technologies among
429 farmers, the duration of change and nutrient buildup plays an integral part (Mugwe *et al.*, 2009). The changes in
430 nutrient build-up depend on the rate and nature of the residue applied, soil type, and climatic variables, among others
431 (Albiach *et al.*, 2001; Tejada and Gonzalez, 2003). The duration for significant changes in the above soil quality
432 indicators to be noted is often varied (Luo *et al.*, 2010). For instance, studies suggest that an increase in SOC content
433 happens immediately but proportionally after adopting CA, including NT strategies (Larney *et al.*, 2012). In the CT
434 systems, faster residue decomposition may lead to declining SOC content after residue application (Haynes *et al.*,
435 1998). The CT systems may lead to approximately 18% decline in SOC content at an average rate of $0.3 \text{ Mg ha}^{-1}\text{y}^{-1}$
436 in the dry-land regions (Xu *et al.*, 2015). Luo *et al.* (2010) showed that conventional soil cultivation for more than
437 five years resulted in soil Carbon loss of more than 20 Mg C ha^{-1} . However, adopting a no-till system led to an

438 increase of $3.15 \pm 2.42 \text{ Mg ha}^{-1}$ of SOC in the top 10cm of the soil layer within five years (Luo *et al.*, (2010).
439 Another study by Spiegel *et al.* (2015) reported a 37% increase in SOC content within ten years of CA with NT
440 implementation. Xu *et al.* (2015) reported significant but gradual changes in soil pH, BD, and plant-available N, P,
441 and K and SOC after 7 years of CA adoption. Generally, persistent annual no-till enhances soil quality in the long
442 term (Luo *et al.*, 2010; Busari *et al.*, 2015). These durations indubitably have an impact on farmers' decision to
443 adopt CA. Generally, setting up strategically located and managed experimental sites, comparing NT versus CT
444 systems under varied soil-climate types, and on-farm management would enhance predictive, but hands-on
445 understanding of their (tillage systems) effects on soil quality and assess their feasibility in different socio-economic
446 and biophysical settings to enhance adoption (Palm *et al.*, 2014).

447

448 3.3.1 Effects of CAWT on Soil Nitrogen, Soil Organic Carbon and Phosphorus

449 Results showed that interacting tillage systems with different tree species under varied spatial spacing significantly
450 influenced TSN and SOC quantities (Table 4A). It appears that shifting from the CT towards the NT system
451 significantly increased quantities of both TSN and SOC regardless of the variations in inter-row tree spacing (Table
452 4A). However, larger TSN and SOC quantities were recorded in the NT systems in sub-plots integrated
453 with *G.sepium* or *C.calothyrsus* spaced at either 3 m or 4.5 m (Table 4A). Conversely, the closer spacing of pigeon
454 peas (at 1.5 m) showed evidence of stocking higher TSN and SOC quantities under the NT system both at the MTs
455 and BTs (Table 4A).

456

457 **Table 4A: Least Square Means for available P, Soil organic carbon (SOC), total soil nitrogen (TSN) in**
458 **different Tillage system, tree species and spacing**

459 **Here**

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461 Regardless of recording a non-significant change in available P across the two tillage systems, there was evidence of
462 consistently high quantities of plant-available P in sub-plots under the NT system compared to those under the CT
463 system. Higher quantities of P were observed in NT sub-plots with *C.calothyrsus* at the MTs, especially under the
464 inter-row spacing of 1.5 m. At the BTs, the high quantities of P were recorded in no-tillage (NT) sub-plots
465 with *C.calothyrsus* and pigeon peas spaced at 1.5 and 3.0 m, respectively (Table 4A).

466 The NT system combined with the leguminous trees increased TSN and SOC with positive trends of accumulating
467 plant-available P quantities. The consistently high TSN and SOC content in the NT sub-plots could be attributed in
468 part to the crop residues and agroforestry litter/twigs that were retained in the NT block throughout the
469 experimentation period. The crop residues and green tree matter have been reported to be among essential factors
470 that contribute to N-mineralization (Naab *et al.*, 2017). Even though both farming systems were supplied with
471 mineral fertilizer to complement crop production, the CT system recorded lower quantities of TSN, which some
472 studies attribute to rapid nitrification (Yuan *et al.*, 2017). However, on the assumption that the mineral N applied
473 would have similar effects in both tillage systems, higher quantities of TSN in the NT block could be linked to the
474 minimum soil disturbance ensured throughout the experimental period. The effects of minimum soil disturbance
475 compounded with residue cover (as mulch) within inter-crop rows and shading from the integrated leguminous trees
476 played a significant role in Nitrogen accumulation through reduced leaching, gradual nutrient release and nitrogen
477 fixation (Duwig *et al.*, 2000). In general, intensive CT contributes towards declines in SOC and TSN concentration,
478 a situation ascribed to destroyed soil structure, aggravated SOM decomposition, and exposed soil aggregates (Xue *et*
479 *al.*, 2015). Adopting NT systems minimizes the risks of SOC and TSN depletion. The concentration of SOC and
480 TSN increases in the topsoil horizons under NT block but may not significantly differ with concentrations in the
481 deeper layers compared to CT (Baker *et al.*, 2007). No-tillage systems can also increase the soil C-N ratio in the
482 surface horizon (Baker *et al.*, 2007). The tillage system impacts TSN accumulation or depletion. For instance, soil
483 structure deterioration and aggregate disruption following CT may lead to higher organic matter mineralization and
484 leaching, resulting in lower soil N and C content (Halvorson *et al.*, 2002; West and Post 2002, and Ali *et al.*, 2006).
485 Ali *et al.* (2006) further suggested that CT contributes to the inversion of the topsoil with less fertile sub-soils during
486 ploughing leading to increased leaching and low SOM/SOC, N, and P concentrations in the inversed topsoil. Other
487 studies reported that NT enhances TSN and SOC stratification ascribed to minimal soil disturbance and residue
488 retention (Xue *et al.*, 2015). However, NT may contribute towards heterogeneous nutrient distribution due to
489 inadequate incorporation of residues and fertilizers within the topsoil layers (Xue *et al.*, 2015). In addition, surface
490 placement of the organic residue under the NT system offers a suboptimal decomposition environment, which may
491 lead to the accumulation of SOM at the soil surface (Franzluebbers 2007). TSN is an essential component of SOC
492 and significantly affects SOC humification and decomposition rates (Zhang *et al.*, 2016).

493 Palm *et al.* (2014) reported that crop residues are vital components of CA in terms of increasing soil carbon and
494 fertility, water relations, and biological properties. However, these benefits depend on the amount the residue
495 retained in the fields, residue quality and type alongside the N placement method (Naab *et al.*, 20017). During our
496 study, an estimated 3 to 6 Mg ha⁻¹ of crop residue was retained into the cropping plots under the NT block. This
497 amount of residue has been reported to significantly increase TSN and SOC quantities under NT (Gicheru *et al.*,
498 2004; Mupangwa *et al.*, 2007, Kisaka *et al.*, 2016). On the other hand, studies by Lal (1976), Agboola (1981),
499 Govaerts *et al.* (2006), Verhulst *et al.* (2011), Muchabi *et al.* (2014) and Naab *et al.* (2017) attributed low SOC and
500 N build-up in the CT systems to increased residue decomposition and mineralization of the organic matter
501 occasioning losses in carbon and nitrogen brought about by reduced mineral stabilization. Other studies attributed
502 NT with residue retention benefits to rhizospheric priming. Rhizosphere priming changes the rate and quantity of
503 SOM decomposition brought about by root activity and is crucial for soil C and N biogeochemical cycling (Dijkstra
504 *et al.*, 2013). Even though rhizosphere priming is affected by nutrient availability, it significantly affects plants'
505 nutrient supply. A study by Fontaine *et al.* (2011) showed that increased rhizosphere priming enhances the release of
506 nitrogen through the decomposition of larger fractions of SOM. In soils with limited plant available P, such as those
507 under our study; Rhizo-deposition is used for P mobilization, while rhizosphere priming enhances C sequestration in
508 N poor than in P poor soils under increased atmospheric CO₂ concentrations (Dijkstra *et al.*, 2013). Despite the
509 observed evidence that NT systems enhance SOC, TSN, and P build-up, during our study, cropping fields in tropical
510 African soils are highly deficient in soil N and P, partly, due to the removal of crop residues from the fields for
511 multiple purposes (Valbuena *et al.*, 2012; Takoutsing *et al.*, 2015). For instance, crop residues are dependable
512 sources of animal feeds and household fuel thus practicing CAWT would be undermined due to the unavailability of
513 sufficient crop residues for mulch (Bationo *et al.*, 2007). In more marginal environments, where CA confers even
514 more ecological benefits, crop productivity is lower, and therefore volumes of crop residues are lower, making
515 competition for them even higher. As a result, achieving optimum CA benefits is difficult, as evidenced by the lower
516 TSN and SOC quantities in the farmer-managed BTs during the current study (**Table 4A**). Generally, a focus on
517 strategies that maximize rain-water retention within the soils' root zone conserves soil nutrients status and provides
518 sustainable alternatives for the farm's fodder, feed, food, and fuel requirements are required to enhance promotion,
519 adoption and implementation of CAWT (Naab *et al.*, 2017). It has been suggested that soil quality (soil organic
520 carbon, nitrogen, and P build-up) and productivity can be achieved by combining trees and crops in agroforestry

521 systems, assuming that the trees can exploit resources currently under-utilized by crops and confer more household
522 benefits (Cannell *et al.*, 1996).

523 It should however be acknowledged that managing simultaneous agroforestry in the drylands comes with a
524 formidable problem on how to retain the positive effects of tree roots and canopy on soil properties while reducing
525 negative effects of below-ground competition for soil production (Leakey, 1999). Generally, most studies
526 acknowledge the need for a better understanding of below-ground spatial and temporal interactions between crops
527 and trees before the real benefits of agroforestry can be optimally exploited (Sanchez, 1995; Gregory, 1996; Rao,
528 1998). During our study, soil nitrogen and SOC were observed to be high in closely spaced legume
529 trees. *C.calothyrsus*, *G.sepium* and *C.cajan* are nitrogen-fixing tree species in a symbiotic relationship
530 with *Rhizobium* bacteria and *mycorrhizas* that contributes to Nitrogen build-up in the soil (Palmer *et al.*, 1994;
531 Simons *et al.*, 2005). With reference to the higher quantities of SOC and TSN observed in the closely spaced trees, it
532 has been reported that organic residues are vital components of CA in terms of increasing soil carbon and fertility,
533 water retention, and biological properties (Palm *et al.*, 2014). However, these benefits depend on the amount the
534 residue retained, which is highly dependent on the plant population in a given area (Naab *et al.*, 20017). Closer inter-
535 tree spacing constitutes a high plant population per area and, subsequently, high residue retention capacity. For
536 instance, Kartasubrata (1996) and Rabach *et al.* (2017) reported an average of 20 Mg ha⁻¹ and 8 Mg ha⁻¹
537 of *C.calothyrsus* residue per year, when spaced at (intra-row) 1 m by 1 m and at 1 m by 4.5 m, respectively.

538 Other studies attribute the accumulation of N in closely spaced legume trees to their specific physiological and
539 chemical composition. For instance, the observed high N quantities in closely spaced *C.calothyrsus* during our study
540 could be linked to the reduced N-mineralization due to polyphenols quantities in the *C.calothyrsus* residue materials.
541 Constantinides and Fownes (1994) noted that soluble polyphenols, whose high levels have been found in the leaves,
542 twigs, and roots of *C.calothyrsus*, prevent N-mineralization during decomposition. A study by N Schroth and
543 Lehmann (1995) showed that N release in the early weeks of legume tree intercrops was inversely related to
544 polyphenols-N ratios; a potential pointer towards its (TSN) high accumulation. As a result, *C.calothyrsus* has been
545 extensively used to restore degraded lands for agricultural production due to its physiological nature, nitrogen-fixing
546 capacity, and ability to survive in acidic soils (Sebuliba *et al.*, 2012). It was observed that Pigeon peas spaced at 1.5
547 m recorded higher TSN and SOC quantities at the BTs compared to MTs (Table 4A). This can be attributed to the
548 capacity of *C.cajan* N-fixing legume properties and the exceptional management they receive from the host

549 farmers. *C.cajana* can fix between 40 Mg N ha⁻¹ and 235 Mg N ha⁻¹ and stock 40-60 Mg N ha⁻¹ for the subsequent
550 cropping season (Valenzuela, 2011). On the other hand, farmers tend to provide optimal management to crops and
551 trees that earn them immediate benefits than long-term speculation (Mugwe *et al.*, 2009; Willy *et al.*,
552 2019). *Cajanus cajan* being a legume crop, farmers are assured of the direct grain harvest and thus tend to provide
553 the most favorable management practices to realize their immediate benefits in terms of grain yield. The consistently
554 higher amounts of P in plots with *C.cajana* can further be linked to its deep taproots that can extract P from the lower
555 horizons into the upper soil layers for crop growth and production (Valenzuela, 2011). Notably, in the CT system,
556 smaller quantities of plant-available P were recorded in closely spaced *C.cajana* compared to sparsely spaced ones.
557 Plant available P adsorption onto the soil constituents such as high soil organic matter (high SOC and TSN reported
558 in closely spaced species), clay and sesquioxides could explain its lower quantities in closely spaced *C.cajana*
559 (Hinsinger *et al.*, 2011; Hopkins *et al.*, 2014; Hill *et al.*, 2015). This could generally further influence adoption of
560 *C.cajana*, whose contribution towards plant available P can be realized within shorter periods. For instance, Xu *et al.*
561 (2015) reported significant but gradual changes in plant-available P after 7 years of NT with *C.cajana* adoption.

562

563 3.3.2 Response of Exchangeable Bases and CEC to CAWT intervention

564 The exchangeable bases and CEC showed a significant (P<0.05) response to the tillage systems (Table 4). The
565 mean differences in CEC were consistently high in the NT blocks with high CEC quantities recorded in sub-plots
566 under *C.calothyrsus*, *G.sepium*, and *C.cajana* as compared to the control sub-plots without any trees both at the MTs
567 and BTs (Table 4B). Similarly, high values of ExBas were observed in the NT block compared to those under the
568 CT block. In terms of specific bases, a significant (P<0.05) rise in ExK (from 1.91 to 2.25 cmol_c kg⁻¹) and ExCa
569 (from 6.86 to 8.17 cmol_c kg⁻¹) was observed in sub-plots under NT block with *G.sepium* spaced at 3.0 m. High
570 quantities of ExMg were recorded in *G.sepium* at 3.0 m (from 2.35 to 2.78 cmol_c kg⁻¹) and Pigeon peas at 3.0 m
571 (2.81 cmol_c kg⁻¹) and 4.5m (2.81 cmol_c kg⁻¹) at the MTs and BTs, respectively (Table 4B).

572

573 **Table 4B: The CEC and Exchangeable Bases (ExBas) response to tillage systems, tree species and spacing**

574 **Here**

575

576 Generally, these results show that integrating tree species within cropping fields under NT system significantly
577 improves the soil CEC and build-up of ExBas in the study area. The significant rise in ExBas and CEC in response
578 to the CAWT interventions could be attributed to the accumulation of crop residues, agroforestry litter and twigs, as
579 well as their high sensitivity to soil organic matter amendments (Yemefack *et al.*, 2006). This implies that fertile
580 conditions are evident in NT systems. Having observed no significant differences in texture and clay content
581 between CT and NT tillage systems (Table 4), yet SOC and TSN, which are critical indicators of soil organic matter
582 differed significantly (Table 4A); then the observed significant differences in CEC must be attributed to soil organic
583 matter accumulated (Schwab *et al.*, 2015). Soils with high clay and organic matter content have high probabilities of
584 retaining positively charged ions and consequently show high concentration of CEC (Selassie *et al.*, 2015). A host of
585 studies (such as Schwab *et al.*, 2015, Challa *et al.*, 2016 and Belayneh, 2019) reported significant differences in
586 CEC and ExBas between CT and NT cropping fields. According to Sinore *et al.* (2018) and Belayneh *et al.* (2019),
587 significantly high CEC and ExBas concentration in farming fields under CA would be as a result of improved soil
588 aggregate stability, the high biomass generated, increased organic matter, and controlled erosion. During our study,
589 the *relative abundance* in ExBas was as follows: $K^+ < Mg^{2+} < Ca^{2+}$ both at the MTs and BTs (Table 1). High values
590 of ExBas under *G.sepium* can be attributed to the total quantities of green biomass produced and retained within the
591 cropping fields. *G.sepium* has been reported to yield as high as 20 Mg ha⁻¹ of residue, which, when incorporated into
592 the soils, contributes towards ExBas concentration (Palmer *et al.*, 1994). A study by Kang *et al.* (1989) observed
593 that *G.sepium* twigs used as green residue would add up to 149 kg K ha⁻¹, 65.2 kg Ca ha⁻¹, and 16.9 kg Mg ha⁻¹ from
594 a 5 Mg ha⁻¹ of *G.sepium* residue harvested in hedgerows of 0.5 m by 4 m. This implies that closer spacing (1 m by 1
595 m) yielding 20 Mg ha⁻¹ would significantly contribute to the build-up of these nutrients in the soil as compared to
596 sparsely spaced *G.sepium*, as observed at the MTs during our study.

597 On the other hand, Palmer *et al.* (1994), reported that incorporation of *C.calothyrsus* (11.3 Mg ha⁻¹)
598 and *G.sepium* (12.6 Mg ha⁻¹) would induce positive changes of between 0.87 cmol_c kg⁻¹ and 2.39 cmol_c kg⁻¹ of CEC
599 in the soil, further corroborating our findings. An assessment of each base quantities in relation to the documented
600 threshold levels for maize production (ExMg = 0.9 cmol_c kg⁻¹, ExCa = 2.8 cmol_c kg⁻¹, and ExK = 0.16 cmol_c kg⁻¹;
601 Takoutsing *et al.*, 2017) showed that the measured quantities during our study were way above these limits. This
602 sufficiency of exchangeable bases in the soils could generally justify the dominant use of NPK (23:23:10) fertilizers
603 in our study area (Kisaka *et al.*, 2016).

604

605 3.3.3 CAWT effects on Soil pH and Electrical Conductivity (EC)

606 A transition from CT to the NT system occasioned a consistent drop in soil pH regardless of the tree spacing and
607 species factor-level interventions at both the MTs and BTs. However, these changes were statistically not significant
608 (Table 4C). In the NT blocks, high pH (7.13) was observed in plots with *C.calothyrsus* spaced at 3.0 m while the
609 lowest pH (6.89) was observed in the Pigeon peas sub-plots at an inter-row spacing of 3.0 m (Table 4C). No clear
610 trend was observed in the case of EC response to CAWT interventions. However, integrating *G.sepium* at 3.0 m
611 spacing occasioned a significant ($P = 0.004$) drop in EC quantities from CT to NT systems (Table 4C).

612

613 Table 4C: The soil pH and Electrical conductivity as affected by tillage system, tree species and spacing

614 Here

615

616 Generally, it was observed that soil pH increased with an increasing inter-row spacing of *C.calothyrsus* (in CT
617 block) and *G.sepium* (in NT block). This trend could be linked to variations in the amount of organic matter build-up
618 and decomposition environment as a response to different spacing (Limousin and Tessier 2007). Closer tree spacing
619 promotes the accumulation of organic residue in the topsoil, whose decomposition under decreased aeration and
620 oxidation, releases organic acids that contribute to the observed lower pH values (Singh *et al.*, 2015). The
621 accumulation of organic matter quantities reduces with increased tree spacing hence less release of organic acids
622 and, consequently, a rise in pH values (Limousin and Tessier 2007; Singh *et al.*, 2015). Such evidence can be drawn
623 from a study conducted in Burundi by Wong *et al.* (1995), which showed that *C.calothyrsus* mulches in a
624 conventional maize-bean intercrop decreased the aluminium concentrations and toxicity in the soil; evidence of
625 increasing soil pH under the CT system. In general, it was observed that the soil pH range (6.67 to 7.64; Table 4)
626 falls within the recommended threshold level of the pH range of 5.5 to 7.8, ideal for maize production (Lafitte, 1993;
627 Ghaemi *et al.*, 2014; Ochieng' *et al.*, 2021). Changes in soil pH have been shown to dictate the availability or
628 unavailability of soil nutrients. It limits the availability of nitrogen, SOC, phosphorus, copper, boron, manganese,
629 iron when too high, and P, Ca, Mg, and other ExBas when it is too low (Takoutsing *et al.*, 2017).

630 Results further showed that EC (whose toxicity threshold level is $>4 \text{ dS m}^{-1}$) could not limit maize cropping in the
631 current study since all the observed values were less than 1 dS m^{-1} (Table 4C). Electric conductivity has been

632 reported to affect maize yield production, soil nutrient availability, and microbial activities (Vargas Gil *et al.*, 2009).
633 Maize is susceptible to soil salinity, but its productivity can endure levels of up to 4 dS m⁻¹ without significant
634 effects on final yields (Takoutsing *et al.* 2017). These levels can be reversed and stabilized by the use of
635 *G.sepium* spaced at 3.0 m in maize and legumes' cropping fields.

636

637 **3.4 Soil quality indicators and suitability of the CAWT system for maize production**

638 The majority of the selected soil quality indicators recorded minimum values that are way above the documented
639 threshold for optimal maize production (Takoutsing *et al.* 2017). In part, this could be attributed to the CAWT
640 interventions that had been implemented in the study area. However, some of the soil quality indicators identified
641 during this study recorded minimum values below the documented thresholds for maize production (Takoutsing *et*
642 *al.* 2017). These are TSN (mean = 23.92 Mg N ha⁻¹, and minimum = 10.12 Mg N ha⁻¹), plant-available P (mean =
643 22.37 mg kg⁻¹, and minimum = 5.31 mg kg⁻¹), ExMg (mean = 2.49 cmol_c kg⁻¹, and minimum = 0.97 cmol_c kg⁻¹) and
644 CEC (mean = 12.87 cmol_c kg⁻¹, and minimum = 5.04 cmol_c kg⁻¹) (**Table 5**). These results showed that, to some
645 extent, maize production on average was constrained during the experimental period. Besides, a succinct comparison
646 of the average threshold values against those under the control treatment (**Table 5**) showed that only clay
647 (threshold=10-30% against control=74.5 %,) and TSN (threshold=40-60% against control=15.0 %,) fell out of range
648 for optimal maize production. The rest of the quality indicators (pH, P, ExCa, ExMg, ExK, ExBas, CEC, and EC)
649 were within range of the threshold requirements for optimal maize production.

650

651 **Table 5: Average threshold values vs. observed quantities of the soil quality indicators under the CAWT**
652 **system for maize production**

653 **Here**

654

655 Soil quality indicators with below or threshold values are essential drivers of maize production (Takoutsing *et al.*,
656 2017). Their interactions, availability, quantities, and management have a direct bearing on maize establishment,
657 growth, and development. In this section, we assess their dynamics under the CAWT system with reference to the
658 documented minimum thresholds suitable for maize production and report on how they can be enhanced.

659

660 3.4.1 Nitrogen

661 The total soil Nitrogen (TSN) recorded during this study ranged from 10.12 Mg N ha⁻¹ to 41.34 Mg N ha⁻¹ with a
662 coefficient of variation (CV) of 31% (Table 5). This range implies that some test plots recorded indicative TSN
663 quantities that could not fully support maize production (Takoutsing *et al.*, 2017). The recommended available N for
664 maize production in the study area is 60 Mg N ha⁻¹ (Horneck *et al.*, 2011; Willy *et al.*, 2019). However, this depends
665 on the soil type and other environmental variables, including climatic conditions and soil management. In whatever
666 case, there is an indication that the adoption of CAWT would significantly raise the base soil TSN supplement for
667 maize production to just less than 30 Mg N ha⁻¹. Through mineralization and nitrification processes, the observed
668 TSN during our study is made available for plant uptake. Due to the chemical composition of organic N, it is very
669 resistant and unavailable for plant uptake (Beegle, 1996). Through mineralization, organic N is converted into
670 mineral ammonium-N (NH₄⁺), which is further converted (through nitrification) into nitrate-N (NO₃⁻). The nitrate-N
671 is available for plants. In the soils, mineral N is highly susceptible to complex processes that involve weather and
672 soil microbes' interaction, leading to N availability losses through immobilization, denitrification, leaching and
673 volatilization (Beegle, 1996). Generally, the concentration of mineral N in the soils and the changes in its
674 availability to plants is unpredictable. Farmers need to regularly top up the deficient amounts through organic and
675 inorganic fertilizer application. In the CAWT system, lower amounts of TSN were significantly affected by soil pH
676 (**Figure 4A**). These findings are consistent with Takoutsing *et al.* (2017), who reported reduced soil nitrogen in soils
677 with lower pH values. In terms of soil fertility, EC levels of between 0.02 and 2.8 ds m⁻¹ observed during this study
678 showed evidence of negatively affecting TSN (**Figure 4B**). According to USDA (2011) and Eve *et al.* (2014), EC
679 quantities of such range (0.02 and 2.8 ds m⁻¹) could lead to increased production of nitrous oxide (N₂O) through
680 denitrification under anaerobic conditions. This can potentially contribute towards losses in TSN and emissions of
681 greenhouse gas emissions (USDA, 2011, Eve *et al.*, 2014). However, it should be acknowledged that our study area
682 is typically a rain-fed dryland region. Two main conditions necessitate the denitrification process. These conditions
683 are saturated soils and a source of energy for the microbes in the form of organic matter (Beegle, 1996). In the
684 dryland regions, rains have been reported to be poorly redistributed, with over 25% falling within a couple of
685 rainstorms spanning between two to four weeks, during which soil saturation conditions are high (Recha *et*
686 *al.*, 2012; Kisaka *et al.*, 2016). Estimating the extent of N losses through denitrification is difficult. However,
687 significant losses can occur within a week of saturated conditions, hypothetically explaining our observations in the

688 current study (Beegle, 1996). In addition, denitrification conditions are enhanced under reduced tillage systems due
689 to high organic matter concentration and soil water content (Beegle, 1996). Conditions of high organic matter and
690 soil water content are favored by the CAWT system (Rabach *et al.*, 2017).

691 **Figure 4A&4B: Influence of soil pH (4A) and Electrical Conductivity (4B) on total soil Nitrogen**

692 **Here**

693

694 **3.4.2 Phosphorus (Available P)**

695 The critical suggested available P for maize production is 8.5 mg kg⁻¹ (Olufemi and Omotoso, 2008). During our
696 study, cases of available P less than this threshold were recorded in some experimental sub-plots (Table 5). Some of
697 the potential explanatory factors of the deficiencies could be low P concentration in the parent material (Bünemann
698 *et al.*, 2004), low P fixation potential (Van der Eijk, 1997) and the dominance of highly weathered hornblende
699 gneisses (Willy *et al.*, 2019). According to Waswa *et al.* (2013), the maximum available soil P occurs within a pH
700 range of 6.5 and 7.0. Consistent with this argument, it could be observed during our study that pH values above 7.1
701 occasioned significant declines in available P (**Figure 4C.**). More iron and aluminium are available at lower pH to
702 form insoluble phosphate compounds; therefore, less phosphate is available. Soil P is generally characterized by its
703 immobility within the soil often lost through runoff or erosion (Beegle, 1996; Nyawade *et al.*, 2019b). Even though
704 little soluble Phosphate (PO₄) can be detected in soils, large quantities of P are always present, some of which are
705 part of SOM (Busari *et al.*, 2015). The availability of organic P is seasonal during warm, moist seasons with
706 heightened microbial activities. However, due to P immobility and fixation, the placement of phosphorus fertilizer
707 affects its availability to plants. Broadcasting P fertilizer under CT mixes P uniformly with large amounts of soil
708 maximizing crops' root contact for uptake (Busari *et al.*, 2015). However, it increases P contact with soils' surface,
709 which is then fixed into less available forms (Beegle, 1996). Banded application of P fertilizers limits crops' root
710 contact. Generally, loss of sediment-bound P is significantly reduced with CA implementation (Busari *et al.*, 2015).
711 However, immobile nutrients like P tend to become concentrated in the topsoil due to inadequate mixing under the
712 no-tillage (NT) system.

713 An increase in the BD was equally observed to be negatively influencing the presence of available P (Figure 4D).
714 Hypothetically, high BD negatively affects physical soil properties, thus limiting microbial and biochemical
715 activities and processes crucial for nutrients such as P, availability (Beegle, 1996). Conversely, due to high P
716

717 insolubility and immobility, its losses are expected through runoff or erosion (Beegle, 1996). High BD reduces water
718 infiltration and increases runoff and erosion, further explaining the inverse relationship between BD and P observed
719 during our study (Figure 4D).

720

721 **Figure 4C and 4D: Influence of Bulk Density (4C) and soil pH (4D) on plant-available soil Phosphorus**

722 **Here**

723

724 **3.4.3 Exchangeable Bases (ExBas) and Cation Exchange Capacity (CEC)**

725 Evidence from section one of this study suggests that the soils under our study were generally abundant in
726 exchangeable bases (ExCa, ExK, ExMg, and ExNa) and thus apt for maize production (Table 5). An assessment of
727 each base quantities in relation to the documented threshold levels (ExMg = 0.91 cmol_c kg⁻¹, ExCa = 2.8 cmol_c kg⁻¹,
728 and ExK = 0.16 cmol_c kg⁻¹; Takoutsing *et al.*, 2017) showed that the measured quantities during the current study
729 were slightly above these limits and thus ideal for maize production. However, deficiencies were observed in ExMg
730 (0.97 cmol_c kg⁻¹ against 0.91 cmol_c kg⁻¹ observed), which could be attributed to its strong negative correlation with
731 sand content (Table 2). However, the general sufficiency of ExBas in the soils could justify the dominant use of
732 NPK (23:23:10) fertilizers in the region with minimal concern on the deficiencies of the bases (Mucheru-Muna *et*
733 *al.*, 2010). Having observed relatively high clay content in the study area, it is thus necessary to select these cations
734 as essential indicators of soil quality especially in such highly weathered soils whose significant parts of the ExBas
735 components could be fixed in the clay minerals (Zhang *et al.*, 2006, Willy 2019). On the other hand, possible
736 limitations in terms of cation availability were observed in CEC (with lows of CEC = 5.04 cmol_c kg⁻¹), yet the
737 optimal threshold is proposed at a minimum of 12 cmol_c kg⁻¹ for maize production. This shows that despite the
738 availability of the exchangeable bases, the capacity to supply and exchange the bases was limited. Among the
739 observed properties, the highest CEC limiting property was BD. An increase in BD led to declines in soil CEC to
740 levels lower than the recommended threshold level in all the experimental plots (Figure 4E). This could be linked to
741 a decrease in electrical charge and reduced colloidal surfaces (Takoutsing *et al.*, 2017). Sandy soils are associated
742 with higher values of BD, low SOM and low capacity to exchange cations, rendering them susceptible to leaching
743 and nutrient mining in the long term (During, 1973).

744

745 **Figure 4E: Influence of Bulk Density on Cation Exchange Capacity (CEC)**

746 **Here**

747

748 In the cases of soil quality indicators with below threshold values for maize production, a linear regression model
749 suggest that some CAWT interventions would significantly increases their concentrations in the soil (Figure 5). For
750 instance, adopting CAWT significantly increases N concentration to bridge the below threshold values (Figure 5). In
751 addition, regardless of the tillage system, integrating either *C.calothyrsus* spaced at 1.5 m (Cal1.5m)
752 or *G.sepium* spaced at 1.5 m (Grill1.5m) into a maize-legume-crop intercropping system significantly improves soil
753 N build-up.

754

755 **Figure 5: Estimates of the linear regression model testing the relationship between explanatory variables of the soil**
756 **quality indicators with below threshold values for maize production (soil properties) against tillage systems and**
757 **spacing. Reference groups are indicated against the intercept rows.**

758 **Here**

759

760 Conversely, *C.calothyrsus* spaced at 1.5 m (Cal1.5m) and Pigeon peas spaced at 3.0 m (Ppeas3.0m) potentially
761 increases the available P concentration in the soils, regardless of the tillage systems. For the ExBas and CEC,
762 intercropping the maize-legume crop field with *C.calothyrsus* spaced at 3.0 m (Cal3.0m) significantly raises their
763 threshold concentrations within the soil (Figure 5). It is, however, established that increasing CEC concentration can
764 significantly be optimized under the NT system

765

766 **4. Conclusion and Recommendations**

767 Integration of legume trees into maize-legume intercrops under CA influences soil quality. CAWT influence on soil
768 organic carbon and TSN was found to be statistically significant. The tillage systems and the inter-row spacing of
769 the legume trees significantly influenced available soil P, exchangeable bases (K, Ca, Mg, Na), CEC, and stabilized
770 soil pH. The main properties accounting for soil quality in the region were established as ExBas, CEC, TSN, SOC,
771 pH, P, EC, clay, and BD. Despite most soil quality indicators recording values above threshold for maize cropping,
772 some components (P, TSN, ExBas, and CEC) recorded minimum values that may hamper optimum maize

773 production. To enhance soil N accumulation, use of *C.calothyrsus* or *G.sepium* both spaced at 1.5 m by 1 m is
774 recommended. However, a contextualized recommendation should consider competing trade-offs to account for
775 competitions, complementarily, and the farmers' land use preferences. In addition to *C.calothyrsus* and *G.sepium*;
776 intercropping with pigeon peas and retaining its residue on the farms can potentially complement and compensate
777 for the available P in the soil. A shift towards CAWT shows evidence of improving soil nutrient availability and
778 bridging their documented thresholds for maize farming. By establishing the minimum datasets for soil quality
779 determination through this study, farmers, policymakers, researchers, extension personnel, and all agricultural
780 stakeholders in agroforestry and CA have an efficient cost-effective and rapid tool for soil quality assessment,
781 especially in dry-land agro-ecosystems of eastern Kenya. Generally, soils under the CAWT system in the study area
782 can sustain maize production. However, this information can be used as a baseline to critically evaluate maize-
783 legume production to account for possible trade-offs on land use. A critical understanding of how this system affects
784 yield productivity, fodder, and general household needs are recommended to complement our findings.

785

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791

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Highlights

- ❖ soil fertility & texture constitute soil quality indicators under CAWT
- ❖ CAWT stabilizes soil pH
- ❖ CAWT increases available-Phosphorus, exchangeable-bases and CEC
- ❖ CAWT with *C.calothyrsus* & *G.sepium* increases total-N stocks (>40 Mg N ha⁻¹)
- ❖ CAWT with *C.cajan* increases SOC stocks (>36 Mg C ha⁻¹)

Table 1: Descriptive statistics of the soil properties at the end of the CAWT intervention

Site	All Plots (average)					Mother Trials (MTs)					Baby Trials(BTs)				
	Min	Mean	Max	SD	CV	Min	Mean	Max	SD	CV	Min	Mean	Max	SD	CV
Clay (% by vol)	37.01	73.35	85.17	8.63	0.12	72.62	75.94	84.13	2.10	0.03	37.01	68.87	85.17	12.89	0.19
Silt (% by vol)	12.69	19.39	25.84	2.33	0.12	12.84	19.17	21.21	1.14	0.06	12.69	19.89	25.84	3.43	0.17
Sand (% by vol)	12.65	18.81	53.04	7.40	0.39	12.65	16.40	19.15	1.31	0.08	12.86	23.06	53.04	10.95	0.47
BD (g cm ⁻³)	0.78	0.96	1.25	0.08	0.09	0.78	0.93	1.05	0.05	0.06	0.83	1.01	1.25	0.10	0.10
pH (H ₂ O)	6.61	7.04	7.64	0.19	0.03	6.67	7.02	7.53	0.15	0.02	6.61	7.08	7.64	0.24	0.03
EC (dSm ⁻¹)	0.03	0.06	0.16	0.01	0.25	0.04	0.06	0.16	0.01	0.23	0.03	0.06	0.11	0.02	0.28
SOC (Mg ha ⁻¹)	11.60	29.36	45.52	8.38	0.29	12.56	31.22	45.52	7.80	0.25	11.60	26.39	42.40	8.34	0.32
TSN (Mg ha ⁻¹)	10.08	23.82	39.03	7.46	0.31	11.64	25.47	39.03	7.41	0.29	10.08	21.16	36.12	6.66	0.31
P (mg kg ⁻¹)	5.31	22.39	38.44	6.23	0.28	16.10	24.84	38.44	4.38	0.18	5.31	18.24	33.15	6.76	0.37
CEC (cmol _c kg ⁻¹)	5.04	12.99	16.33	2.21	0.17	11.18	13.93	16.33	1.15	0.08	5.04	11.39	15.46	2.67	0.23
ExBas (cmol _c kg ⁻¹)	4.02	11.52	15.28	2.33	0.20	8.20	12.38	15.28	1.58	0.13	4.02	10.08	14.33	2.66	0.26
ExK (cmol _c kg ⁻¹)	0.38	1.72	3.27	0.50	0.29	1.43	1.95	3.27	0.22	0.11	0.38	1.32	2.25	0.59	0.45
ExCa (cmol _c kg ⁻¹)	3.44	7.44	10.00	1.39	0.19	5.54	7.94	10.00	0.97	0.12	3.44	6.60	9.14	1.57	0.24
ExMg (cmol _c kg ⁻¹)	0.97	2.52	3.65	0.46	0.18	2.12	2.64	3.65	0.28	0.10	0.97	2.32	3.29	0.63	0.27
ExNa (cmol _c kg ⁻¹)	0.09	0.13	0.23	0.03	0.20	0.10	0.13	0.23	0.03	0.20	0.09	0.13	0.20	0.03	0.20

KEY: Min=Minimum, Max=Maximum, SD=Standard Deviation, CV=Coefficient of Variations

Table 2: Pearson product moment correlations between soil properties under the CAWT system in the study area (n= 331).

	pH	P	ExNa	ExCa	ExMg	ExK	ExBas	EC	C.E.C	Clay	Silt	Sand	BD	TC	TOC
P	-0.38*														
ExNa	0.53**	-0.07													
ExCa	0.05	0.33**	0.42**												
ExMg	-0.03	0.05	0.28*	0.81**											
ExK	-0.19	0.52**	0.17	0.53**	0.52**										
ExBas	-0.02	0.34**	0.46**	0.94**	0.79**	0.68**									
EC	-0.01	0.15	0.15	0.03	0.22	0.51**	0.16								
C.E.C	-0.33**	0.35**	-0.07	0.31**	0.27*	0.43**	0.36*	0.01							
Clay	-0.20	0.11	0.18	0.58**	0.80**	0.73**	0.68**	0.33**	0.34**						
Silt	0.03	0.31**	-0.06	-0.26	-0.64**	-0.44**	-0.36**	-0.25	-0.17	-0.83**					
Sand	0.26	-0.27*	-0.23	-0.69**	-0.81**	-0.75**	-0.77**	-0.32**	-0.36**	-0.96**	0.66**				
BD	0.26	-0.43**	-0.11	-0.60**	-0.62**	-0.78**	-0.67**	-0.37**	-0.43**	-0.73**	0.42**	0.78**			
TC	-0.24	0.41**	0.06	0.27*	0.21**	0.29*	0.27*	0.19*	0.22	0.19	0.13	-0.32**	-0.23		
TOC	-0.24**	0.41**	0.07	0.25	0.20	0.30*	0.27*	0.19*	0.23	0.19*	0.11	-0.31**	-0.23	1.00**	
TN	-0.24	0.33**	0.05	0.18	0.18	0.33**	0.24	0.18	0.25	0.24	-0.01	-0.32**	-0.24	0.95**	0.96**
TON	-0.24	0.32**	0.05	0.16	0.18	0.32**	0.23*	0.17	0.26**	0.24	-0.01	-0.32**	-0.23	0.94**	0.96**

** Correlation is significant at $p < .01$ level (2-tailed). * Correlation is significant at $p < .05$ level (2-tailed).

Table 3: Rotated factor loadings for the five principal components (PC) for the topsoil (0–30 cm) properties under CAWT system at the Mother and Baby trials used for clustering, minimum data selection (MDS) and identifying soil quality indicators

	Mother Trials					Baby Trials					com					
	PC1	PC2	PC3	PC4	PC5	h2	u2	com	PC1	PC2		PC3	PC4	PC5	h2	u2
pH	-0.01	-0.62	-0.11	-0.27	0.10	0.48	0.52	1.5	-0.24	0.51	-0.09	-0.16	0.90	0.9	0.1	1.2
P	-0.07	0.49	0.31	-0.07	-0.55	0.65	0.35	2.6	0.20	0.02	0.09	0.93	-0.2	0.94	0.06	1.2
ExNa	0.67	-0.08	-0.14	0.07	0.27	0.55	0.45	1.5	0.37	0.11	0.22	0.07	0.82	0.86	0.14	1.6
ExCa	0.94	-0.02	0.15	-0.12	-0.08	0.93	0.07	1.1	0.88	-0.07	0.29	0.20	0.24	0.97	0.03	1.5
ExMg	0.74	0.11	0.12	-0.26	-0.24	0.70	0.30	1.6	0.86	0.23	0.21	-0.28	0.01	0.91	0.09	1.5
ExK	0.23	-0.06	-0.01	0.92	0.07	0.92	0.09	1.2	0.57	0.72	-0.04	0.17	-0.09	0.89	0.11	2.1
ExBas	0.95	-0.06	0.08	0.13	-0.01	0.93	0.07	1.1	0.93	0.11	0.18	0.17	0.13	0.96	0.04	1.2
EC	-0.17	0.02	0.03	0.91	-0.02	0.87	0.13	1.1	0.16	0.83	0.08	-0.27	0.27	0.86	0.14	1.5
CEC	0.91	-0.08	0.13	0.18	-0.1	0.89	0.11	1.2	0.93	0.25	0.2	0.10	0.03	0.99	0.01	1.3
Clay	0.05	-0.95	-0.06	0.1	0.05	0.92	0.08	1.0	0.77	0.46	0.06	-0.36	-0.17	0.96	0.04	2.2
Silt	-0.02	0.83	0.13	-0.13	-0.22	0.76	0.24	1.3	-0.48	-0.40	0.13	0.71	0.19	0.95	0.05	2.7
Sand	-0.05	0.81	-0.01	-0.05	0.3	0.75	0.25	1.3	-0.85	-0.39	-0.16	0.18	0.14	0.95	0.05	1.7
BD	-0.13	0.02	0.19	0.01	0.87	0.81	0.19	1.1	-0.73	-0.55	-0.1	-0.09	0.19	0.89	0.11	2.1
SOC	0.1	0.17	0.97	0.03	0.05	0.98	0.02	1.1	0.23	0.00	0.95	0.16	0.11	0.99	0.01	1.2
TN	0.15	0.1	0.97	0.01	0.04	0.97	0.03	1.1	0.22	0.07	0.96	-0.02	-0.03	0.97	0.04	1.1
$\bar{x}=1.3$																
$\bar{x}=1.6$																
Importance of components																
SS loadings	RC1	RC2	RC4	RC3	RC5											
Proportion Var	3.76	2.93	2.12	1.93	1.37	RC1	RC5	RC4	RC2	RC3						
Cumulative Var	0.25	0.2	0.14	0.13	0.09	6.01	2.19	2.14	1.84	1.8						
Proportion Explained	0.25	0.45	0.59	0.72	0.81	0.4	0.15	0.14	0.12	0.12						
Cumulative Proportion	0.31	0.24	0.18	0.16	0.11	0.4	0.55	0.69	0.81	0.93						
	0.31	0.55	0.73	0.89	1	0.43	0.16	0.15	0.13	0.13						
	0.31	0.55	0.73	0.89	1	0.43	0.59	0.74	0.87	1						

Key: h2=communality, u2=Uniqueness, Com=Complexity: communalities refer to shared variance with the other items, while uniqueness is variance not explained by the other items, but that could be explained by the latent variable as well as measurement error.

Table 4A: Least Square Means for P, Soil organic carbon (SOC), total soil nitrogen (TSN) in different Tillage system, tree species and spacing

Mother Trials															
	P (mg kg ⁻¹)					SOC (Mg C ha ⁻¹)					TSN (Mg N ha ⁻¹)				
	Conventional		CA		P-value	Conventional		CA		P-value	Conventional		CA		P-value
	Mean	CA	Mean	CA		Mean	CA	Mean	CA		Mean	CA	Mean	CA	
<i>Calliandra.c</i>	24.7a	24.4a	24.4a	24.4a	0.830	28.7bcd	28.7bcd	28.7bcd	28.7bcd	<.0001	22.8bc	22.8bc	22.8bc	22.8bc	<.0001
<i>Gliricidia.s</i>	25a	26.6a	26.6a	26.6a	0.265	26.7abc	26.7abc	26.7abc	26.7abc	<.0001	20.4ab	20.4ab	20.4ab	20.4ab	<.0001
No tree	23.3a	24.8a	24.8a	24.8a	0.206	20.9ab	20.9ab	20.9ab	20.9ab	0.0001	15.8a	15.8a	15.8a	15.8a	<.0001
P-peas	23.7a	24.5a	24.5a	24.5a	0.604	22.5a	22.5a	22.5a	22.5a	<.0001	17.1a	17.1a	17.1a	17.1a	<.0001
Cal1.5m	27.2a	26a	26a	26a	0.637	34.3def	34.3def	34.3def	34.3def	0.000	27.4def	27.4def	27.4def	27.4def	<.0001
Cal3.0m	20.3a	23.5a	23.5a	23.5a	0.194	26.2bc	26.2bc	26.2bc	26.2bc	<.0001	20.9bc	20.9bc	20.9bc	20.9bc	<.0001
Cal4.5m	26.7a	23.7a	23.7a	23.7a	0.233	25.5abc	25.5abc	25.5abc	25.5abc	<.0001	20.1abc	20.1abc	20.1abc	20.1abc	<.0001
control	23.3a	27.8a	27.8a	27.8a	0.193	20.9ab	20.9ab	20.9ab	20.9ab	<.0001	15.8ab	15.8ab	15.8ab	15.8ab	<.0001
Gril1.5m	26.4a	25.3a	25.3a	25.3a	0.658	30cde	30cde	30cde	30cde	<.0001	23.4cde	23.4cde	23.4cde	23.4cde	<.0001
Gril3.0m	22.9a	28.8a	28.8a	28.8a	0.018	25.8bc	25.8bc	25.8bc	25.8bc	<.0001	19.7abc	19.7abc	19.7abc	19.7abc	<.0001
Gril4.5m	25.5a	25.6a	25.6a	25.6a	0.968	24.4abc	24.4abc	24.4abc	24.4abc	<.0001	18.2abc	18.2abc	18.2abc	18.2abc	<.0001
Ppeas1.5m	22.8a	25.1a	25.1a	25.1a	0.344	18.8a	18.8a	18.8a	18.8a	<.0001	15a	15a	15a	15a	<.0001
Ppeas3.0m	23.4a	26.0a	26.0a	26.0a	0.291	24abc	24abc	24abc	24abc	0.010	18.1abc	18.1abc	18.1abc	18.1abc	0.002
Ppeas4.5m	24.9a	22.2a	22.2a	22.2a	0.282	24.7abc	24.7abc	24.7abc	24.7abc	0.337	18.4abc	18.4abc	18.4abc	18.4abc	0.023
Baby Trials															
<i>Calliandra.c</i>	17.4ab	20.7ab	20.7ab	20.7ab	0.287	27ab	27ab	27ab	27ab	0.074	21.5ab	21.5ab	21.5ab	21.5ab	0.052
<i>Gliricidia.s</i>	17ab	14.0a	14.0a	14.0a	0.208	25.1ab	25.1ab	25.1ab	25.1ab	0.240	19.8ab	19.8ab	19.8ab	19.8ab	0.051
No tree	16ab	16.0ab	16.0ab	16.0ab	0.991	20.1ab	20.1ab	20.1ab	20.1ab	0.497	15a	15a	15a	15a	0.521
P-peas	23.6ab	24.5b	24.5b	24.5b	0.787	20.2a	20.2a	20.2a	20.2a	0.070	15.6a	15.6a	15.6a	15.6a	0.016
Cal1.5m	21.8a	25.9a	25.9a	25.9a	0.504	40.9cd	40.9cd	40.9cd	40.9cd	0.898	32.7c	32.7c	32.7c	32.7c	0.291
Cal3.0m	22.1a	25.2a	25.2a	25.2a	0.617	24.6abcd	24.6abcd	24.6abcd	24.6abcd	0.027	19.5ab	19.5ab	19.5ab	19.5ab	0.003
Cal4.5m	13.4a	16.3a	16.3a	16.3a	0.497	21.2abc	21.2abc	21.2abc	21.2abc	0.116	16.9ab	16.9ab	16.9ab	16.9ab	0.025
control	16.1a	16.0a	16.0a	16.0a	0.991	20ab	20ab	20ab	20ab	0.384	15a	15a	15a	15a	0.395
Gril1.5m	16.6a	13.5a	13.5a	13.5a	0.313	29.7abcd	29.7abcd	29.7abcd	29.7abcd	0.401	23.2abc	23.2abc	23.2abc	23.2abc	0.071
Gril3.0m	14.8a	17.9a	17.9a	17.9a	0.045	17.7a	17.7a	17.7a	17.7a	0.171	14.2a	14.2a	14.2a	14.2a	0.059
Ppeas1.5m	22.1a	22.7a	22.7a	22.7a	0.922	16.8ab	16.8ab	16.8ab	16.8ab	0.005	13.2a	13.2a	13.2a	13.2a	0.000
Ppeas3.0m	25.2a	26.6a	26.6a	26.6a	0.777	21.2abcd	21.2abcd	21.2abcd	21.2abcd	0.239	16.3ab	16.3ab	16.3ab	16.3ab	0.110
Ppeas4.5m	23.7a	24.1a	24.1a	24.1a	0.952	22.4abcd	22.4abcd	22.4abcd	22.4abcd	1.000	17abc	17abc	17abc	17abc	0.696

KEY: CA=Conservation tillage block, conventional=Conventional tillage block. Cal1.5=Calliandra calothyrsus spaced at 1.5m, Cal3.0=Calliandra calothyrsus spaced at 3m, Cal4.5=Calliandra calothyrsus at 1.5m, Gril1.5=Gliricidia sepium spaced at 1.5m, Gril3.0=Gliricidia sepium spaced at 3m, Gril4.5=Gliricidia sepium spaced at 4.5m, Ppeas1.5=Pigeon-peas spaced at 1.5m, Ppeas3.0=Pigeon-peas spaced at 3.0m, Ppeas4.5=Pigeon-peas spaced at 4.5m

Least squares means with the same letter are not significantly different ($p > 0.05$) and those with different letters are significantly different ($p < 0.05$) based on Tukey HSD test.

Table 4B: The CEC and Exchangeable bases (ExBas) response to tillage systems, tree species and spacing

Species	Mother																	
	CEC						ExCa						ExMg					
	Conventional		CA		P-value		Conventional		CA		P-value		Conventional		CA		P-value	
<i>Calliandra-c</i>	13.8abc	14.5c	0.043	12.5abc	13.2c	0.123	1.94a	1.96a	0.812	7.90abc	8.44c	0.060	2.66a	2.68a	0.799			
<i>Gliricidia-s</i>	13.6abc	14.2bc	0.098	12.1abc	12.4abc	0.478	2.03a	1.95a	0.160	7.41ab	8.24bc	0.005	2.48a	2.74b	0.003			
No tree	12.5ab	13.9abc	0.101	10.4ab	12.6abc	0.047	1.88a	1.72a	0.353	6.84abc	8.47abc	0.021	2.42a	2.96b	0.013			
Pigeon-peas	13.0a	14.6c	0.000	11.3a	13.1bc	0.000	1.89a	1.97a	0.280	7.32a	8.41c	0.000	2.53a	2.72a	0.029			
Call1.5m	13.2abc	14.3bcd	0.040	11.7abc	12.1abc	0.539	1.90ab	2.00ab	0.392	7.47abcd	7.90abcde	0.325	2.62abc	2.59abc	0.838			
Call3.0m	14.1bcd	15.0cd	0.125	12.9abc	14.3c	0.091	2.02ab	1.79a	0.051	7.90abcde	9.13c	0.005	2.59abc	2.88c	0.039			
Call4.5m	14.2bcd	14.4bcd	0.759	12.9abc	13.3bc	0.605	1.90ab	2.09ab	0.122	8.34bcde	8.31bcde	0.942	2.76abc	2.56abc	0.159			
control	12.5ab	13.9abcd	0.076	10.4ab	12.6abc	0.045	1.88ab	1.72a	0.328	6.84abcd	8.47bcde	0.009	2.42abc	2.96bc	0.008			
Grill1.5m	13.6abcd	14.4bcd	0.111	11.8abc	12.9abc	0.187	2.02ab	2.07ab	0.671	7.44abcd	8.54cde	0.012	2.55abc	2.72abc	0.223			
Grill3.0m	13.3abcd	14.3bcd	0.054	12.0abc	12.4abc	0.635	1.91ab	2.25b	0.005	6.86ab	8.17bcde	0.003	2.35ab	2.78bc	0.003			
Grill4.5m	14.0abcd	13.8abcd	0.673	12.4abc	12.0abc	0.616	1.90ab	1.88ab	0.910	7.95abcde	8.01abcde	0.883	2.53abc	2.71abc	0.189			
Ppeas1.5m	14abcd	13.8abcd	0.679	12.5abc	12.5abc	0.913	1.88ab	1.96ab	0.488	8.39bcde	7.93abcde	0.285	2.70abc	2.54abc	0.256			
Ppeas3.0m	12.1a	14.9cd	<0.001	10.2a	13.4bc	0.000	1.84ab	1.89ab	0.676	6.53a	8.62deB	<0.001	2.26a	2.81bc	0.000			
Ppeas4.5m	12.9ab	15.2d	<0.001	11.0ab	13.6bc	0.002	1.97ab	2.07ab	0.389	7.04abc	8.67deB	0.000	2.63abc	2.81bc	0.201			
BABY																		
<i>Calliandra-c</i>	11.0a	10.9a	0.9199	9.78a	9.92a	0.9151	1.221ab	1.277abc	0.813	6.62a	6.64a	0.9807	2.02a	2.03a	0.969			
<i>Gliricidia-s</i>	10.5a	10.8a	0.7784	9.18a	9.52a	0.7375	1.018a	0.999a	0.917	6.16a	6.55a	0.5349	2.27a	2.21a	0.789			
No tree	10.9a	11.4a	0.7818	9.93a	9.48a	0.7815	1.265abc	1.144abc	0.687	6.37a	6.36a	0.9924	2.38a	2.34a	0.917			
Pigeon-peas	12.1a	14.1a	0.1464	10.67a	12.71a	0.1409	1.925bc	2.041c	0.648	6.45a	7.9a	0.0935	2.32a	2.55a	0.482			
Call1.5m	11.19ab	12.38ab	0.5643	10.5abc	11.46abc	0.6479	0.514a	1.192a	0.141	7.62abc	7.64abc	0.9868	2.12abc	2.08abc	0.938			
Call3.0m	14.4ab	14.64ab	0.9075	13.59abc	13.77bc	0.9301	2.086a	1.736a	0.443	8.04abc	9.04c	0.399	2.23abc	2.67abc	0.374			
Call4.5m	9.57ab	8.6a	0.5072	7.73abc	7.46ab	0.8483	1.171a	1.119a	0.872	5.41abc	4.95ab	0.5735	1.68abc	1.5ab	0.613			
control	10.91ab	11.36ab	0.7343	9.94abc	9.49abc	0.7213	1.264a	1.143a	0.675	6.37abc	6.36abc	0.9897	2.34abc	2.29abc	0.895			
Grill1.5m	11.94ab	12.11ab	0.8692	10.46abc	10.89abc	0.6617	1.066a	1.015a	0.822	7.03abc	7.58bc	0.3521	2.71c	2.52bc	0.425			
Grill3.0m	8.15a	8.6a	0.7281	7.11a	7.28ab	0.8875	0.935a	0.967a	0.912	4.77a	4.91a	0.8541	1.39a	1.53ab	0.643			
Ppeas1.5m	13.07ab	13.68 ab	0.7678	12.09abc	12.48abc	0.8411	1.866a	2.066a	0.661	7.41abc	7.56abc	0.8945	2.42abc	2.36abc	0.910			
Ppeas3.0m	11.15ab	14.87b	0.0313	9.19abc	13.32c	0.0141	1.861a	2.031a	0.648	5.45abc	8.37c	0.0035	2abc	2.59abc	0.147			
Ppeas4.5m	13.33ab	14.07ab	0.7184	12.07abc	12.61abc	0.7866	2.151a	2.101a	0.913	7 abc	7.53abc	0.6569	2.42abc	2.41abc	0.992			

KEY: CA=Conservation tillage block, conventional=Conventional tillage block. Units of Measurements: CEC = cmol_c kg⁻¹, ExBas= cmol_c kg⁻¹, ExCa= cmol_c kg⁻¹, ExMg= cmol_c kg⁻¹, Call1.5=Calliandra calothyrsus spaced at 1.5m, Call3.0=Calliandra calothyrsus spaced at 3m, Call4.5=Calliandra calothyrsus at 1.5m, Grill1.5=Gliricidia sepium spaced at 1.5m, Grill3.0=Gliricidia sepium spaced at 3.0m, Ppeas3.0=Pigeon-peas spaced at 3.0m, Ppeas4.5=Pigeon-peas spaced at 4.5m, Ppeas1.5=Pigeon-peas spaced at 1.5m, Grill1.5=Gliricidia sepium spaced at 1.5m, Grill3.0=Gliricidia sepium spaced at 3m, Grill4.5=Gliricidia sepium spaced at 4.5m, Tukey HSD test.

Table 4C: The soil pH and electrical conductivity (EC) as affected by tillage system, tree species and spacing

	Mother Trials				Baby Trials			
	pH ($pH(H_2O)$)		EC (dSm^{-1})		pH ($pH(H_2O)$)		EC (dSm^{-1})	
	Conventional	CA	Conventional	CA	Conventional	CA	Conventional	CA
mean	P-value	mean	P-value	mean	P-value	mean	P-value	
<i>Calliandra.c</i>	7.06 ^a	0.539	0.05a	0.901	7.19a	0.901	0.052a	0.856
<i>Gliricidia.s</i>	7.03 ^a	0.445	0.06a	0.129	7.11a	0.129	0.048a	0.733
No tree	7.15 ^a	0.272	0.06a	0.755	7.05a	0.755	0.059a	0.508
Pigeon-peas	7.04 ^a	0.445	0.06a	0.799	6.95a	0.799	0.057a	0.391
Cal1.5m	6.93 ^a	0.532	0.06ab	0.248	6.9a	0.248	0.040a	0.468
Cal3.0m	7.12 ^a	0.894	0.06ab	0.108	7.18a	0.108	0.036a	0.769
Cal4.5m	7.13 ^a	0.064	0.05ab	0.487	7.34a	0.487	0.062a	0.331
Control	7.15 ^a	0.058	0.06ab	0.743	7.06a	0.743	0.059a	0.511
Gril1.5m	7.03 ^a	0.251	0.06ab	0.817	7.12a	0.817	0.052a	0.353
Gril3.0m	7.03 ^a	0.405	0.08b	0.004	7.14a	0.004	0.041a	0.528
Gril4.5m	7.04 ^a	0.713	0.06ab	0.817	-	-	-	-
Ppeas1.5m	7.12 ^a	0.372	0.05ab	0.248	7.10a	0.248	0.056a	0.472
Ppeas3.0m	7.04 ^a	0.081	0.06ab	0.355	6.93a	0.355	0.054a	0.508
Ppeas4.5m	6.96 ^a	0.968	0.06ab	0.817	6.82a	0.817	0.056a	0.946

Key: CA=Conservation tillage block, conventional=Conventional tillage block. Cal1.5=Calliandra calothyrsus spaced at 1.5m, Cal3.0=Calliandra calothyrsus spaced at 3m, Cal4.5=Calliandra calothyrsus at 1.5m, Gril1.5=Gliricidia sepium spaced at 1.5m, Gril3.0=Gliricidia sepium spaced at 3m, Gril4.5=Gliricidia sepium spaced at 4.5m, Ppeas1.5=Pigeon-peas spaced at 1.5m, Ppeas3.0=Pigeon-peas spaced at 3.0m, Ppeas4.5=Pigeon-peas spaced at 4.5m
 Least squares means with the same letter are not significantly different ($p > 0.05$) and those with different letters are significantly different ($p < 0.05$) based on Tukey HSD test.

Table 5: Average (all plots) threshold values vs. observed quantities of the soil quality indicators under the CAWT system for maize production

	pH(H ₂ O)	P (mg kg ⁻¹)	ExCa (cmol _c kg ⁻¹)	ExMg (cmol _c kg ⁻¹)	ExK (cmol _c kg ⁻¹)	ExBas (cmol _c kg ⁻¹)	EC (Ds m ⁻¹)	C.E.C (cmol _c kg ⁻¹)	Clay (% by vol)	BD (g cm ⁻³)	TSN (Mg ha ⁻¹)
Control treatment	7.15	23.3	23.3	2.42	1.88	10.4	0.06	12.5	74.5	0.94	15.8
Max	7.64	38.85	10.00	3.65	3.27	15.28	0.16	16.33	85.17	1.25	41.34
Mean	7.05	22.37	7.40	2.49	1.68	11.41	0.06	12.87	72.78	0.96	23.92
Min	6.67	5.31	3.44	0.97	0.38	4.02	0.03	5.04	37.01	0.78	10.12
CV	0.03	0.29	0.19	0.19	0.31	0.21	0.26	0.18	0.13	0.09	0.31
Threshold level	5.4-7.8	>8.5	>2.8	>0.91	>0.16	-	<4	<12	10-30	<1.4	40-60

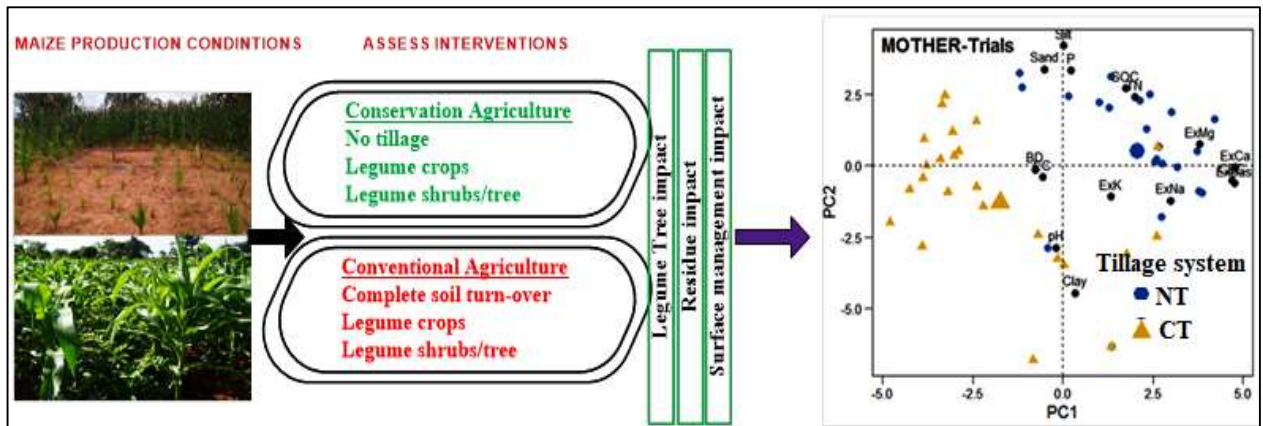
Max=maximum, Min=minimum, CV=coefficient of variation

Table 4: Analyses of variance in soil physicochemical properties in different tillage systems, Tree species and Spacing

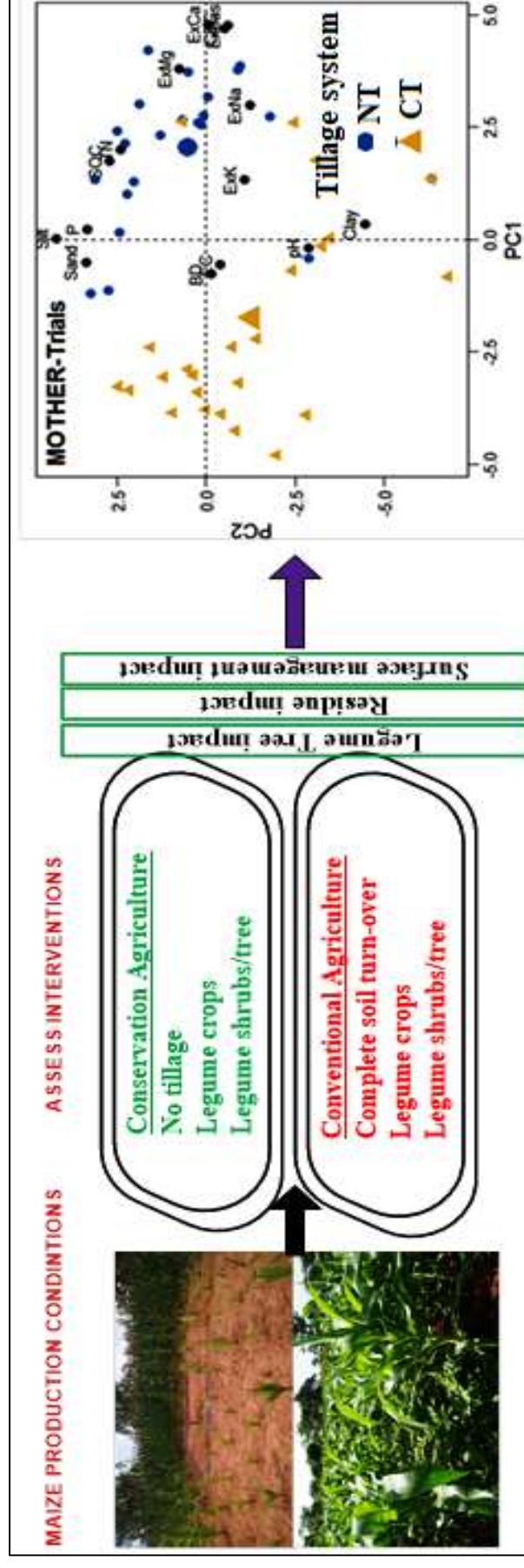
Mother	F-Stats	Tillage system			Species			Spacing			Tillage system: Spacing		
		1	3	3	3	3	3	9	9	10	10	8	8
Properties	DF	MTs	BTs	MTs	BTs	MTs	BTs	MTs	BTs	MTs	BTs	MTs	BTs
pH	F-value	5.057	4.069	0.65	4.234	0.74	0.381	1.90	2.590	0.87	0.512	0.87	0.512
	Pr(>F)	0.049*	0.794	0.582	0.048*	0.531	0.767	0.061	0.020*	0.553	0.842	0.553	0.842
P	F-value	1.78	0.179	1.01	6.520	0.67	0.945	1.28	3.580	1.45	0.359	1.45	0.359
	Pr(>F)	0.185	0.675	0.393	0.001***	0.575	0.425	0.260	0.003**	0.180	0.937	0.180	0.937
ExBas	F-value	18.30	1.497	2.35	2.547	2.21	0.574	2.17	7.725	2.18	0.755	2.18	0.755
	Pr(>F)	0.000***	0.227	0.077	0.065	0.091	0.634	0.031*	0.000***	0.031*	0.644	0.031*	0.644
EC	F-value	0.60	0.060	1.35	1.088	0.67	0.491	1.77	1.251	1.58	0.432	1.58	0.432
	Pr(>F)	0.442	0.808	0.262	0.362	0.573	0.690	0.084	0.292	0.133	0.896	0.133	0.896
CEC	F-value	31.78	1.665	2.07	2.860	2.13	0.500	1.58	6.906	3.43	0.620	3.43	0.620
	Pr(>F)	0.000***	0.203	0.108	0.045*	0.101	0.684	0.134	0.000***	0.001**	0.757	0.000***	0.757
Clay	F-value	1.03	0.137	3.03	2.386	0.03	0.068	2.90	2.970	0.92	0.367	0.92	0.367
	Pr(>F)	0.313	0.713	0.033*	0.078	0.994	0.977	0.005**	0.009**	0.514	0.933	0.009**	0.933
BD	F-value	0.32	0.000	0.33	6.114	1.61	0.162	0.52	5.824	3.01	1.173	3.01	1.173
	Pr(>F)	0.574	0.994	0.806	0.001**	0.193	0.921	0.855	0.000***	0.003**	0.335	0.000***	0.335
SOC	F-value	327.527	14.080	25.508	3.226	2.530	0.331	18.629	7.060	6.740	1.118	6.740	1.118
	Pr(>F)	<0.0001***	0.000***	0.000***	0.029*	0.061	0.803	<0.0001***	0.000***	0.000***	0.369	0.000***	0.369
TSN	F-value	455.934	22.628	31.857	4.781	4.113	0.457	21.550	8.068	6.765	2.231	6.765	2.231
	Pr(>F)	0.00001***	0.000***	0.000***	0.005**	0.008**	0.713	0.0001***	0.000***	0.000***	0.041*	0.000***	0.041*

Key: DF=Degrees of Freedom,, MTs=Mother Trials. BTs=Baby Trials,

Graphical Abstrat



Graphical Highlight



KEY: NT=no-tillage; CT=conventional tillage

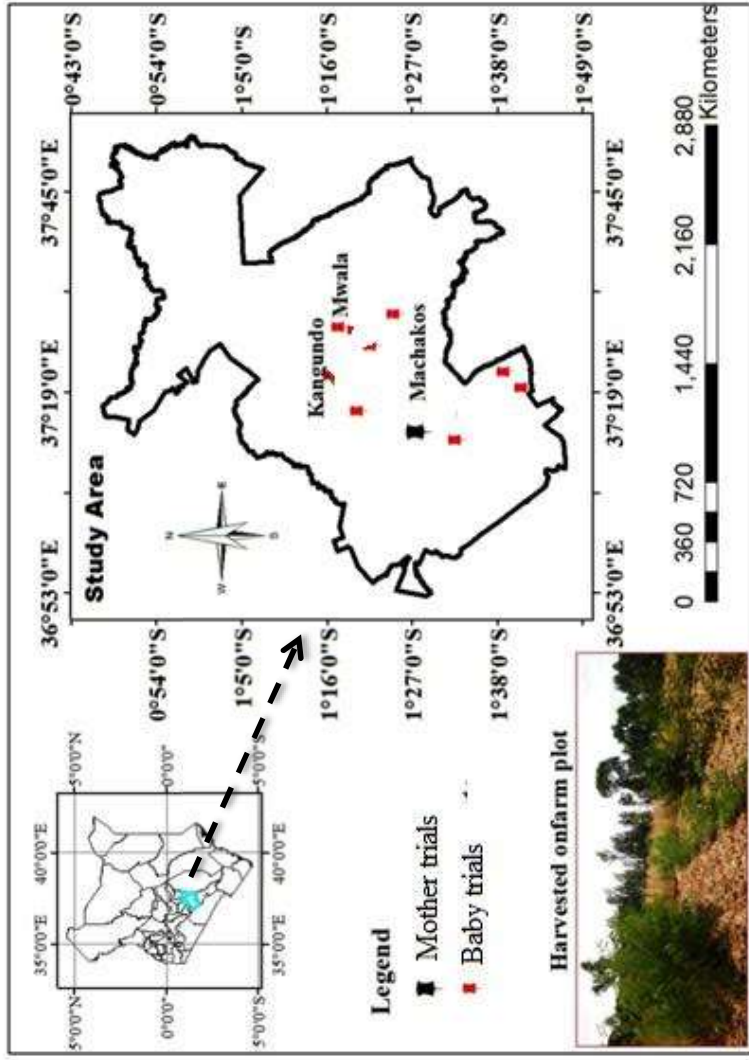


Figure 1: A map of the study area showing the distribution of the experimental sites across the administrative sub counties.

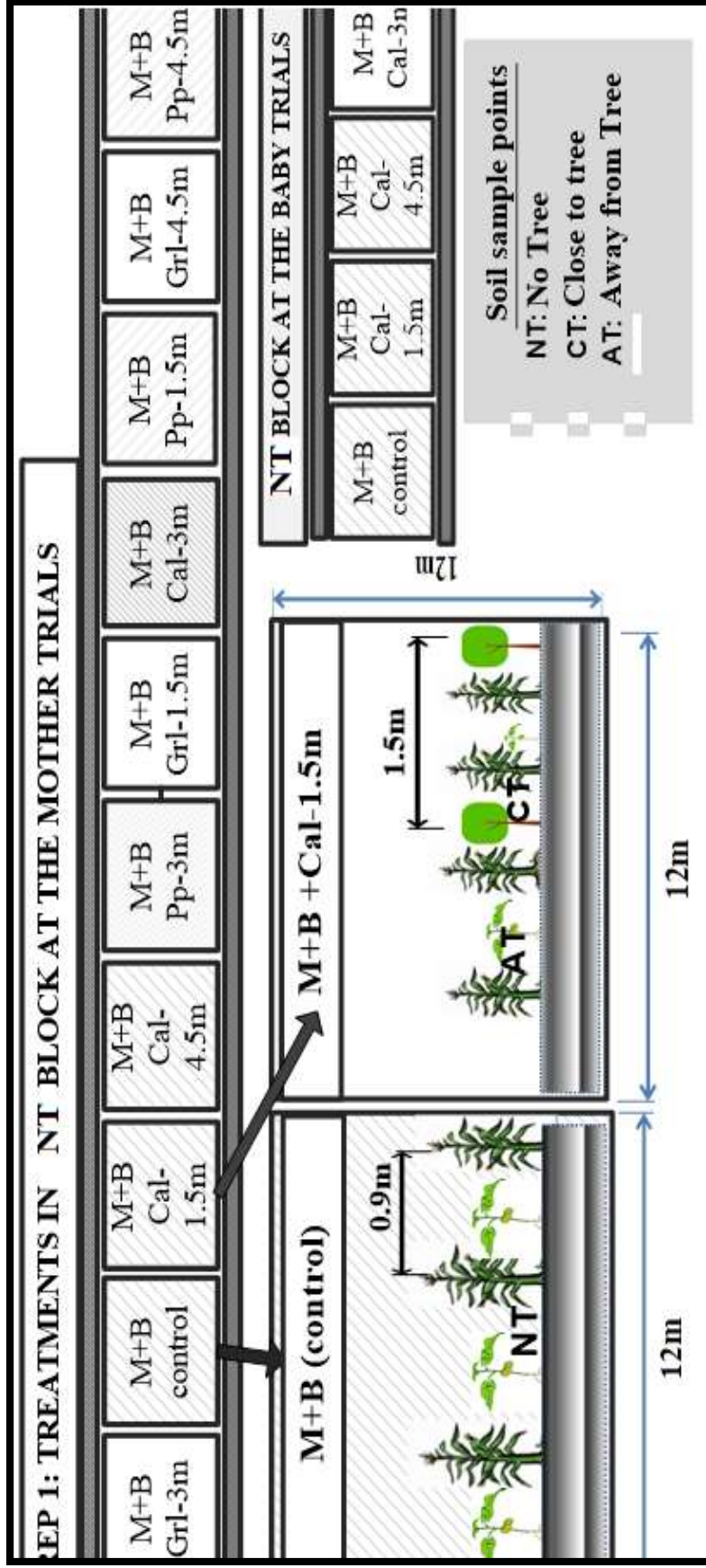


Figure 2: Pictorial sketch of the replicate 1 sub-plot treatments in a No-Tillage (NT) main block at the Mother trials (MTs) and in Baby trials (BTs) sites.
Key: M+B=Maize+beans, Grl=*Grilicidia sepium*, Cal=*Calliandra calothyrsus*, Pp= Pigeon peas. The subplots in each tillage block with only maize-legume crops (without trees) were treated as control plots during our study. This arrangement was applied in a similar way to the other cover crops during the specific seasons they were intercropped with maize.

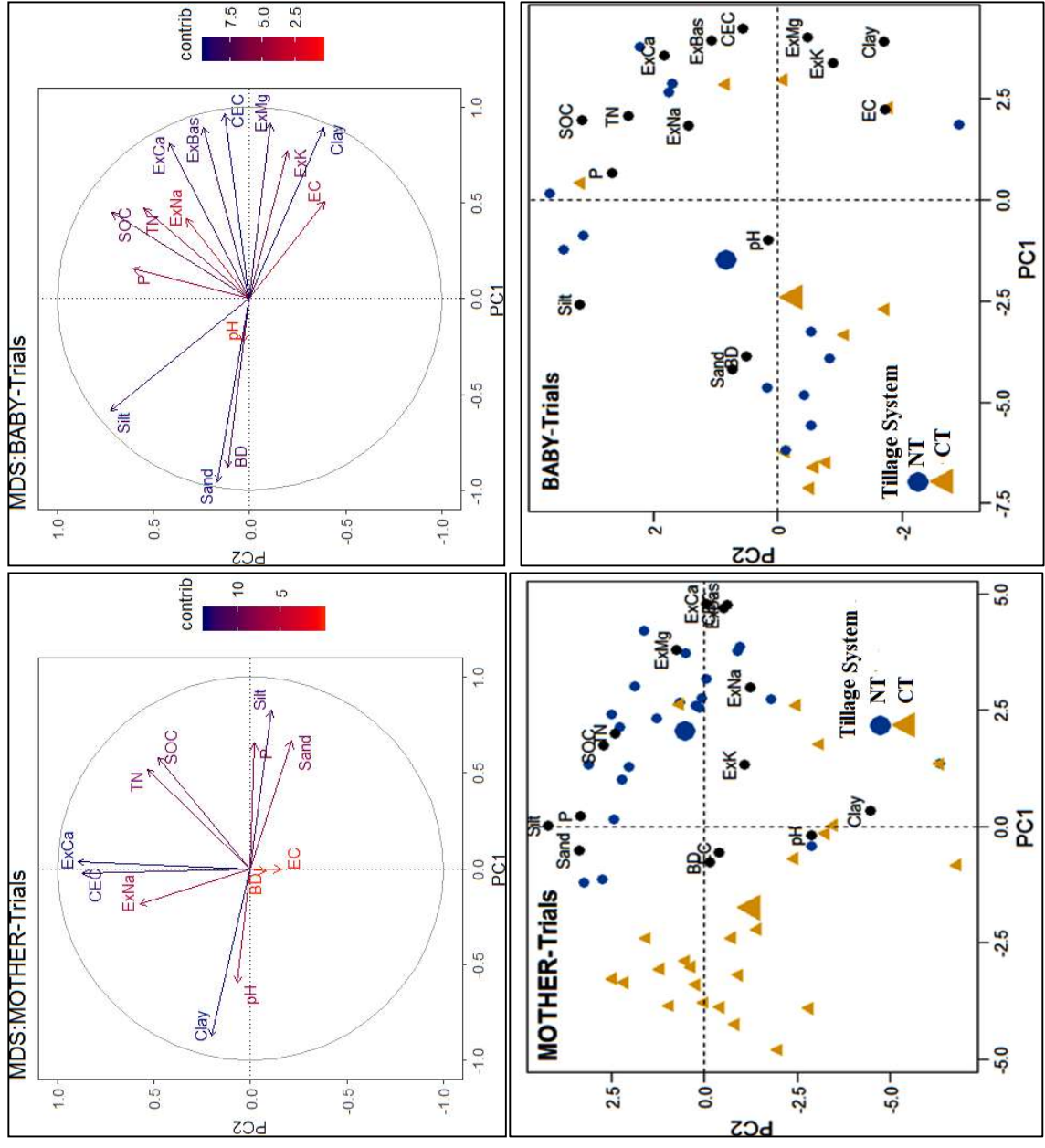


Figure 3: The Variable factor loading map (above) between Dimension 1 and 2 (PC1 and PC2) showing soil properties responsible for maximum variance (quality indicators) and in the CAWT system (Below): Arrows (in above) represent the directions of maximum variation. Key: NT= No-tillage block, CT=Conventional tillage block

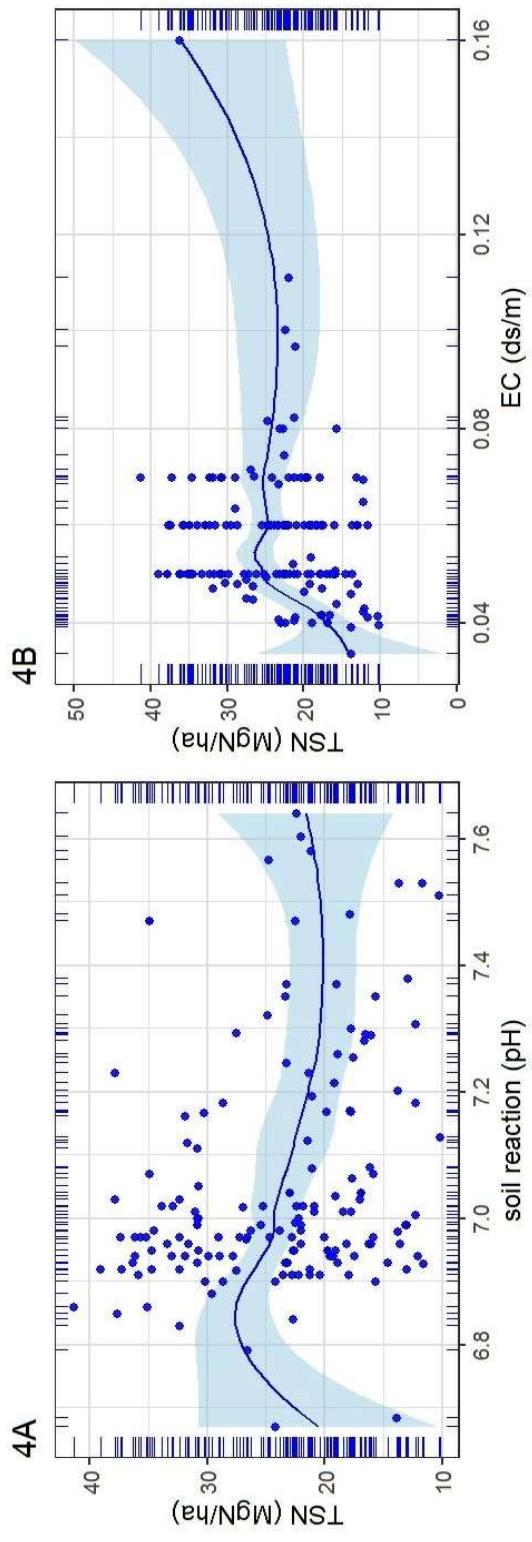


Figure 4A&4B: Influence of soil pH (4A) and Electrical Conductivity (4B) on total soil Nitrogen.

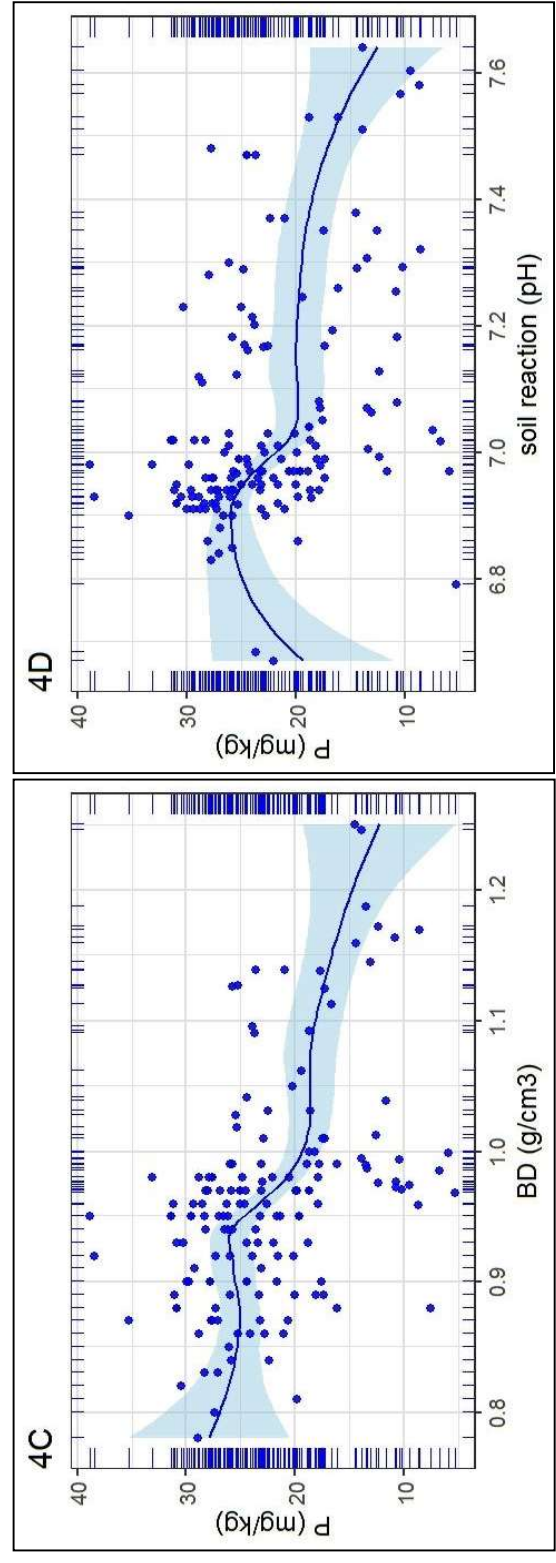


Figure 4C and 4D: Influence of Bulk Density (4C) and soil pH (4D) on plant available soil Phosphorous

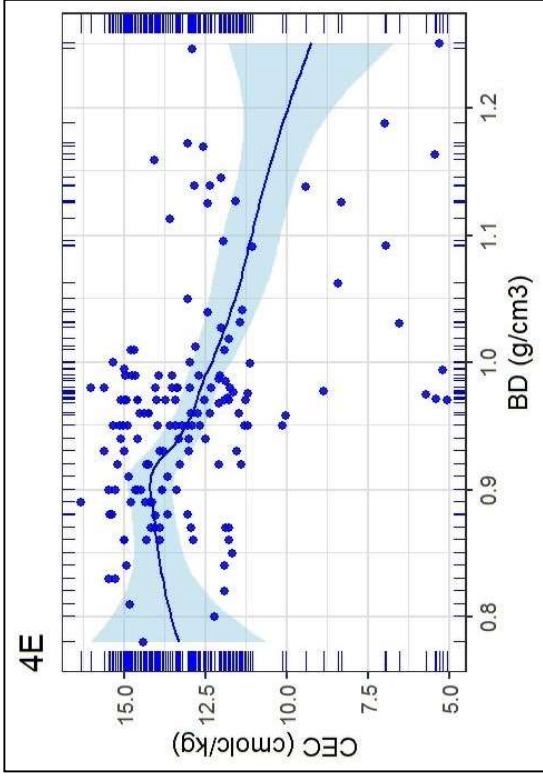


Figure 4E: Influence of Bulk Density on Cation Exchange Capacity (CEC) (**4E**)
Note: The barcode geometric-rug concentrations show intensity of influence across the properties

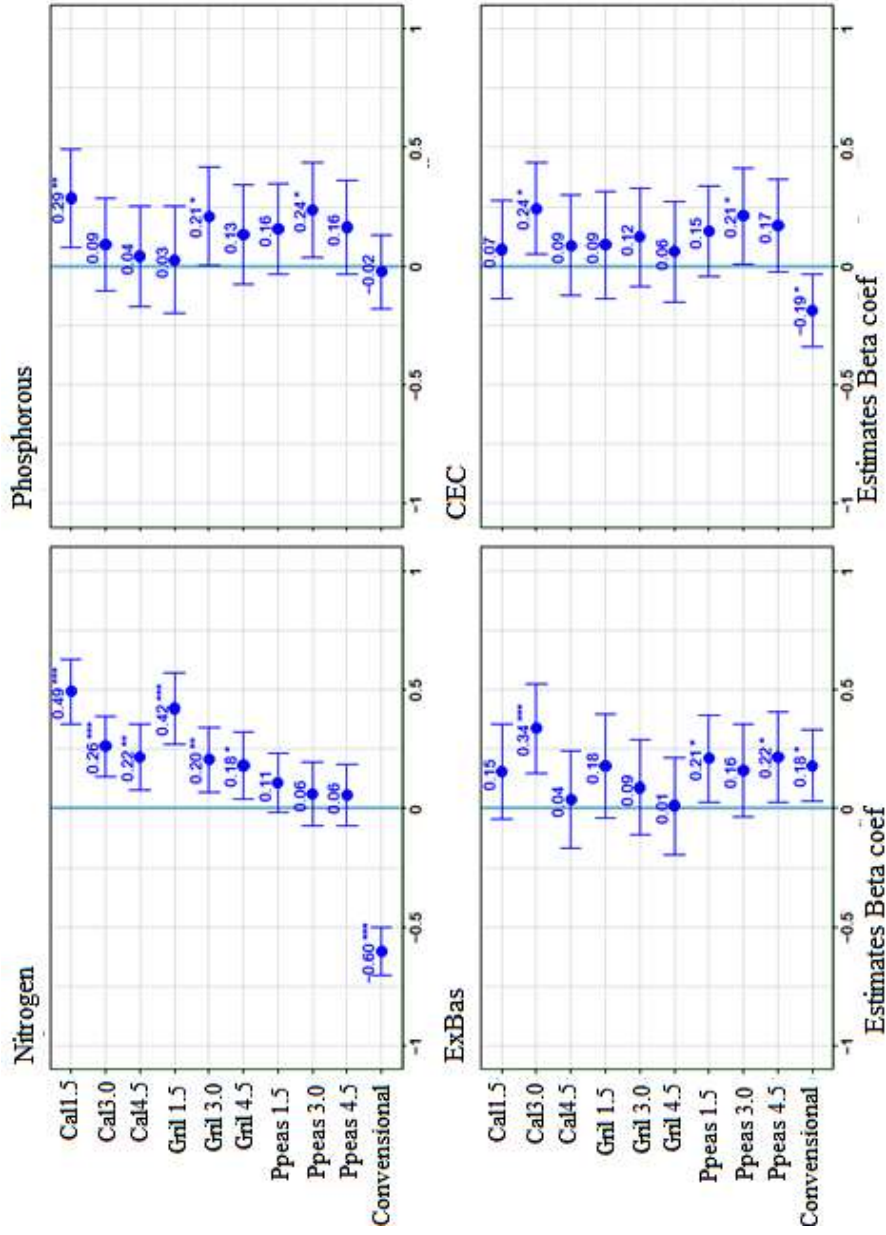


Figure 5: Estimates of the linear regression model testing the relationship between explanatory variables of the soil quality indicators with below threshold values for maize production (soil properties) against tillage systems and spacing. Reference groups are indicated against the intercept rows. **Key:** conventional=Conventional tillage block. Call.5=Calliandra calothyrsus spaced at 1.5m, Cal3.0=Calliandra calothyrsus spaced at 3m, Cal4.5=Calliandra calothyrsus at 1.5m, Gril1.5=Gliricidia sepium spaced at 1.5m, Gril3.0=Gliricidia sepium spaced at 3m, Gril4.5=Gliricidia sepium spaced at 4.5m, Ppeas1.5=Pigeon-peas spaced at 1.5m, Ppeas3.0=Pigeon-peas spaced at 3.0m, Ppeas4.5=Pigeon-peas spaced at 4.5m. Significant values codes: *P < 0.05, **P < 0.01, *** P < 0.001