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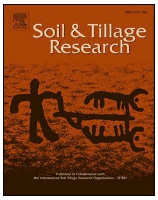

Integrating no-tillage with agroforestry augments soil quality indicators in Kenya’s dry-land agroecosystems

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ABSTRACT

Conservation agriculture with trees (CAWT) is one of the best-bet strategies for enhanced soil quality under extensive and intensive smallholder farming. CAWT is an agroforestry system that integrates legume trees and shrubs into cropping fields under minimum soil disturbance and tillage. This study identified principal soil quality indicators (SQI) under CAWT system. The study further assessed the effects of CAWT components; i.e. tillage (convention or no-tillage), leguminous trees/shrubs (*Calliandra calothyrsus, Gliricidia sepium and Cajanus cajan)*, 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 finally reported on the suitability of the SQI under CAWT intervention towards maize production. The experimental trials were both researcher (Mother-trials; MTs) and farmer (Baby-trials; BTs) hosted and managed. Principal Component Analyses (PCAs) identified soil fertility and textural components as the main factors explaining soil quality under the CAWT system. In particular, the exchangeable bases (ExBas) such as ExCa, ExK, and ExMg), Cation-Exchange-Capacity (CEC), total soil nitrogen (TSN), soil organic Carbon (SOC), pH, available Phosphorus(P), electrical conductivity (EC), clay and bulk density (BD) were identified as the principal soil quality indicators under the CAWT system. Tree species and varied inter-row spacing, significantly affected available P, BD, pH, ExBas, CEC, SOC, and TSN. The tillage systems significantly ($P < 0.05$) influenced soil pH, ExBas, CEC, SOC and TSN. A high concentration of TSN was recorded in no-tillage (NT) blocks integrated with *C. calothyrsus* (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, respectively. Combining NT with *C.calothyrsus* spaced at 1.5 m or Pigeon pea at 3.0 m significantly increases available P (from 22.9 to 28.8 mg kg^{-1} and 23.4–26.0 mg kg^{-1}) at the MTs, respectively. Significant rise in ExK (1.91–2.25 cmol$_c$ kg^{-1}), ExCa (6.86–8.17 cmol$_c$ kg^{-1}), and ExMg (2.35–2.78 cmol$_c$ kg^{-1}) were observed in NT block’s sub-plots with *G. sepium* spaced at 3.0 m at the MTs. Conclusively, a shift towards CAWT showed evidence of improving soil quality, nutrient availability and increasing soil nutrient thresholds that can potentially support maize production. By establishing the minimum datasets for soil quality determination through this study, key stakeholders in agroforestry and conservation agriculture (CA) have an efficient cost-effective and rapid tool for soil quality assessment, especially in dry-land agro-ecosystems.

1. Introduction

Kenya’s dry-land agro-ecosystems in the eastern region are characterized by low and declining maize and legume crop productivity, high rainfall variability, sparse vegetation and animal life, low soil fertility and high vulnerability to land degradation (Mucheru-Muna et al., 2010; Ngetich et al., 2014; Kisaka et al., 2016). Maize or the legume crops are grown continuously with shorter fallows, often devoid of intercropping or rotations. These practices have contributed to net nutrient mining jeopardizing the soil’s capacity to rejuvenate (Nyiraneza et al., 2015;

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Gitari et al., 2018; Nyawade et al., 2019a). Besides, the heterogeneity of physicochemical soil properties and declines in soil-nutrient base and fertility are widespread, contributing to declines in crop yields (Lipiec, 2017; Gitari et al., 2019a). Persistent exponential human population growth and decrease in land resource in the region has pushed smallholder annual crop producers to expand into marginal areas seeking cultivation fields (Gitari et al., 2018). This invasion further compounds the above-mentioned food production constraints, such as loss of soil fertility and quality (Elias, 2017; Nyawade et al., 2019b). Farmers occasionally utilize assorted in situ soil management strategies to increase overall farm productivity including use of manure, inorganic and organic fertilizers, mulching and agroforestry practices among others (Bationo et al., 2007; Mugendi et al., 2003; Mucheru-Muna et al., 2010). Nonetheless, these efforts are constrained by inadequacies in access to optimal quantities and guidelines on how such technologies ought to be co-implemented (Akponikpè, 2008; Mugwe et al., 2009). Thus, a succinct spatial understanding of soil physicochemical properties and their heterogeneity is vital in determining optimal soil management practices for improved soil nutrient base, quality and its indicators, as well as crop productivity under different farming systems.

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

CAWT is an agroforestry system that integrates legume trees and shrubs into cropping fields under minimum soil disturbance and tillage (ICRAF, 2015). The leguminous crops and shrubs have been reported to promote soil cover, nutrient and residue supply, fodder for livestock feeding while no-tillage conserves these benefits within the soils (ICRAF, 2015). Traditional agroforestry leguminous species suitable for intercrop with annual crops include *Calliandra calothyrsus (C.calothyrsus), Gliricidia sepium (G.sepium), Leucaena leucocephala (L.leucocephala) and Cajanus cajan (C.cajan)* (Gitari et al., 2018). *C.calothyrsus* has been reported to thrive well in a wide range of soil types and biophysical environments, including nutrient-deficient soils due to its capacity to host beneficial fungi (*Vesicular arbuscular* (VA-mycorrhiza), and ability to nodulate fast (ICRAF, 2015). *C.calothyrsus* also reduces soil erosion, promotes nutrient retrieval (using its extensive rooting systems of 1.5 m), improves soil physical properties, and increases topsoil organic matter with minimal shading effects to annual crops (Wiersum and Rika, 1992; Sitienei et al., 2017). Kabi and Bareeba (2008) showed 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} dry-matter within two months. Consequently, this makes them ideal for livestock fodder and green residue. Makumba et al. (2006) established that the use of *G. sepium* as green residue in maize cropping fields influenced production of an average yield of 3.8 Mg $ha^{-1}yr^{-1}$ of maize grain and 5 Mg ha^{-1} yr-1 leafy dry matter of *G.sepium* twigs without use of inorganic fertilizer amendment. A study by Ojiem et al. (2007) further reported that Dolichos (*Lablab purpureus*) could potentially raise soil nitrogen content through atmospheric fixation by up to 42 kg N ha^{-1}. According to Albrecht and Kandji (2003), no-tillage in agroforestry systems can stock more SOC without compromising farm-food productivity. These examples indicate that legume plants can fix atmospheric N and contribute to nutrient recycling through residue incorporation; hence a source of soil nutrient build-up and availability thus enhance soil quality.

Nonetheless, studies on the precise integration of leguminous shrubs into cropping fields and incorporating their residues into the soils under minimum soil disturbance to boost soil productivity are scarce, especially in highly heterogeneous environments. A few studies on maize-tree intercrop mainly focus on the intercropping strategy in isolation overlooking no-tillage (NT) potentials or are just focused on dry-matter production capacity. Besides, most of the studies are carried out under highly advanced technologies and research management systems whose results cannot easily be scaled out and contextualized to the rural on-farm settings for adoption (Chang et al., 2016). Others (Ojiem et al., 2007; Mucheru-Muna et al., 2010; Gitari et al., 2018) have studied intercropping systems either without tree components or by the external acquisition of the green residues grown on different farms. There is further limited information on how such an intensive farming system impacts soil quality and its indicators as a response to different tree-shrub species and intensive legume-maize intercrop with maximized green residues' retention in the cropping fields. To fully and precisely establish CAWT benefits, there is a need to identify key 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 identified principal soil quality indicators under CAWT. The study further assessed the effects of CAWT components; i.e. tillage systems (convention (CT) or no-tillage (NT)), leguminous trees/shrubs (*C.calothyrsus, G.sepium) and C.cajan*), and their varied inter-row spacing on the soil quality indicators in the dry-land agroecosystems of eastern Kenya. We finally reported on the suitability of the SQI under CAWT intervention towards maize production. The findings of this study were envisioned to provide contextualized information for relevant stakeholders championing the adoption of intensive ever-green farming.

2. Materials and methods

2.1. The study area

The study was carried out in the expansive sub-humid and semi-arid eastern region of Kenya, spanning across an estimated area of about 6281.4 km^2, covering three administrative sub-counties (Machakos, Kangundo and Mwala) of Machakos County (Fig. 1).

Machakos County stretches from latitudes 0^0 4′ to 1^0 31’ in the South and longitudes 36° 45’ to 37° 45’ to the east. The region lies within three agro-ecological zones, generally clustered as sub-humid, transitional, and semi-arid regions, representing low to medium potential agricultural production areas (Jaetzold et al., 2006). The region receives an average of 700 mm of annual rainfall, which is normally bimodal,

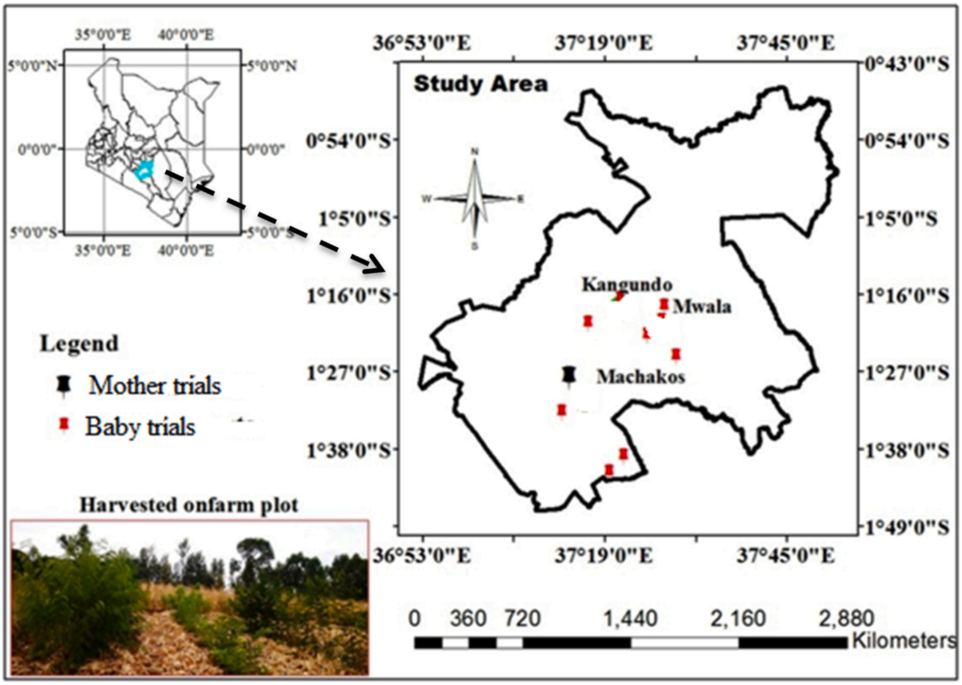

Fig. 1. A map of the study area showing the distribution of the experimental sites across the administrative sub counties.

erratic and poorly distributed with high peaks in April and November (Recha et al., 2017). Seasonal rainfall occurs between the months of mid-March to mid-May (as Long-rains (LRs)) and mid-October to early-January (as short-rains (SRs)). The average seasonal rainfall amount varies between 250 mm and 400 mm. Seasonal rainstorms are highly variable recording coefficient of variations (CVs) ranging from 45% to 58% (Kisaka et al., 2015). The remainder of the year is emblematic of extended dry periods. There are frequent crop failure cases among rain-fed cropping farmers, rendering over 50% of the local populace food insecure (Abbas, 2009; Anon, 2010). In terms of agricultural productivity, high potential areas span across Kangundo sub-county with moderate temperate climates but highly unpredictable rainfall averaging 1250 mm per annum. Low potential production regions cover Mwala sub-county with less than 550 mm of annual rainfall. Machakos sub-county is considered a medium potential agricultural production region. Kangundo lies in the Upper Midlands agro-ecological zone 4 (UM4) while Mwala falls within Lower-Midlands agro-ecological zone 4 (LM4) (Jaetzold et al., 2006). The average annual temperature ranges between 17 °C and 25 °C, with highs of over 30 °C (Recha et al., 2017; Sennhenn et al., 2015). Machakos County is generally hilly with altitudes ranging from 1000 to 1600 m above sea level. Luvisols are the dominant soil type, characteristic of deficiency in plant-available P and Nitrogen as well as low soil organic carbon content (0.5 – 1.0%) and a slight acid reaction (pH 5.7–6.9 in water) (Gicheru, 2004; FAOSTAT, 2017). Due to variations in the region's anthropogenic geological nature, other soil types include patches of Vertisols, Acrisols, and Cambisols. Maize, beans, and cowpeas are dominant annual crops grown by the smallholder farmers in the semi-humid and transitional zone, while sorghum and millets cropping predominate the semi-arid areas (Aruma et al., 2014). Major cash crops include coffee, horticultural crops, and fruit trees in the semi-humid zone, while cotton, sunflower and fruit trees are typical in the transitional zone (Recha et al., 2017). Fruit trees are grown across the agro-ecological zones, including mangoes, banana, citrus, papaws, and avocado.

2.2. *Research and experimental design*

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

2.2.1. *Mother trials (MTs)*

The MTs were solely researcher designed, hosted and managed. They (MTs) were established on 3rd October 2012 during the SRs of 2012 (SR2012) at Agricultural Training Centre (ATC) in Machakos county and were monitored for six consecutive cropping seasons up to the LRs of 2015 (LR2015), on 10th July 2015. The trials adopted a split-plot design with a factorial combination of two tillage systems (as the main blocks) and three spatial agroforestry patterns plus control treatment (as the sub-plot treatments). The two tillage systems were Conventional tillage (CT) and no-tillage (NT) as the main splitting blocks. The CT block was subjected to complete soil turnover (of approximately 30 cm depth) using manual hand-held hoes while minimum tillage was done on the NT block. The three spatial agroforestry patterns were the integration of three leguminous shrubs (*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 standard intra-row spacing of 1 m between the individual shrubs, culminating to 2708, 4514 and 8125 trees per hectare, respectively; into a maize-legume cover crop intercrop to constitute the sub-plot treatments. In summary, 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 peas at 1.5., 3.0 or 4.5 m plus the control (sole maize-legume cover crop intercrop) translating to 10 treatments per replication in each of the two main blocks and a total of 60 sub-plots at the MTs. These treatments were arranged in a randomized complete block design (RCBD), on sub-plot measuring 12 m by 12 m, separated by a path of 0.5 m and replicated three times. Fig. 2 (two) shows a pictorial sketch of the arrangement of these sub-plot treatments within a single replication of the LR2014, SR2014 and SR2015cropping seasons when common beans were planted under NT block. This arrangement was applied in a similar way to the other cover crops (cowpeas and dolichos) during the specific seasons they were intercropped with maize. Maize intercropped with legume crops (cowpeas, common beans, and dolichos) were the test crops during the experimental period. Maize was planted at 0.9 m inter-row and 0.3 m intra-row spacing, and intercropped with different leguminous

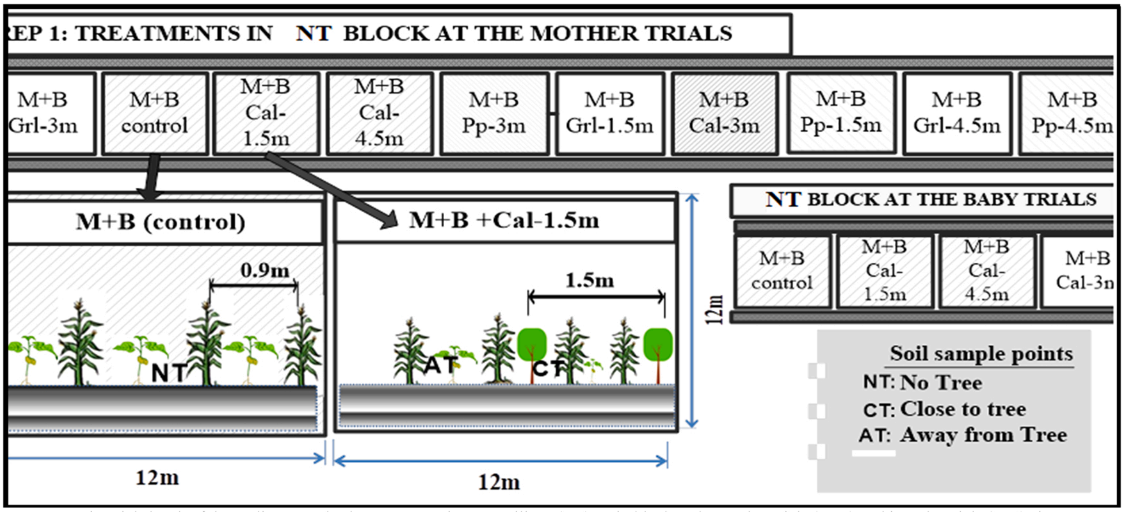

Fig. 2. Pictorial sketch of the replicate 1 sub-plot treatments in a CA main block at the Mother trials (MTs) and in Baby trials (BTs) sites. *This arrangement was applied in a similar way to the other cover crops during the specific seasons they were intercropped with maize.* ***Key:*** *M+B=Maize+beans, 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.*

cover crops (LCC) varied seasonally as follows: cowpeas (*Vigna unguiculata*) in SR2012 and LR2013, Dolichos (*Lablab purpureus*) in SR2013 and common beans (*Phaseolus vulgaris*) in LR2014, SR2014 and SR2015. The subplots in each tillage block with sole maize-legume crops (without trees) were treated as control plots during our study. The legume crops were intercropped between maize rows at intra-row spacing of 0.07 m. The choice of LCC to other cover crops was guided by their proven effective sustainability of soil fertility as was reported by and the frequency by which they are cropped in the region (Cheer et al., 2006).

2.2.2. *Baby trials (BTs)*

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

2.2.3. *Common experimental management at the MTs and BTs*

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

Two maize and legume crops seeds were planted per hill at an approximate sowing depth of 15 cm. The test crop varieties were DH04 (maize), KVU-419 (cowpeas), KATX69 (common beans) and KAT/PP60/8 (Pigeon peas). Two weeks after planting, maize thinning was done to ensure the recommended population density of 37,037 plants ha^{-1} for this study area (Kisaka et al., 2016). Mineral fertilizer was spot-applied as NPK 23:23:0 and Di-Ammonium 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 control were done manually using hand-held hoes. Two seasons after establishment (one week to the SR2013 maize planting season), first tree harvesting was done through coppicing to a height of 0.3 m to harvest tree leaves, twigs and wood stem for biomass estimation, laboratory analyses (5% of total weight per sub-plot) as well as utilization as a green residue (95% of total weight per sub-plot). For the remainder of the experimental period, tree coppicing was done seasonally, during maize-legume crop sowing date whereby the green residue was retained within the specific sub-plots as organic fertilizers. The woody stalks were removed from the cropping fields and used by the host farmers as firewood. Maize and cover crop grain, stover and haulms were harvested at physiological maturity from a net area of 129.9 m^2 (out of the total area of 144 m^2). The net area was computed after leaving out one row on each side of the sub-plot and the first and last maize and cover crop plants in each row to minimize the edge effect. Maize and cover crop grains, stover and haulms were dried and their weight expressed in terms of dry matter content. Dry matter yields were extrapolated to a hectare basis using plant populations corrected for the emergence rate and moisture content. Plant emergence rates were not affected by treatments. No diseases were observed during the experimental period. All other standard agronomic practices were followed for optimal crop production.

2.3. *Soil sampling framework*

Soil sampling was carried out at the end of the LR2015 season from the 20th of July 2015 to the 6th of August 2015.

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 (27 in each tillage block and

9 per replication) were integrated with leguminous shrubs/trees while 6 (3 in each tillage block and 1 per replication) acted as control plots. Similarly, at the BTs, 54 sub-plots (18 per sub-county) had leguminous trees/shrubs while 18 (6 per sub-county) acted as the controls. On each sub-plot, five sampling spots were randomly selected following a W-design with particular reference to tree spatial locations (i.e., very close to the tree roots (Close-to-Tree), mid-way the intra-row tree spaces (Away-from-Tree in sub-plots integrated with trees) or where there were no trees (No-Tree) in the control plots. Sampling was done at depths of 0–30 cm using soil augers and 5 cm long steel core-rings for disturbed and undisturbed samples, respectively, as guided by Pennock and Yates (2008). The disturbed samples were thoroughly mixed to constitute net composite sub-plot samples. Two composite soil samples ("Close-to--tree" and "Away-from-tree)" were collected in each sub–plot integrated with leguminous trees/shrubs while only one composite sample (No-Tree) was collected in the control sub-plots. In this regard, a total of 240 (i.e. (54 +54)* 2 = 216 samples in sub-plots with trees *plus* (6 +18 =24 control samples) composite soil samples were taken for laboratory analyses. Precautionary measures were taken, including exposure of samples to direct sunlight before laboratory analyses at the World Agroforestry Centre (ICRAF) soil laboratories in Nairobi Headquarters, Kenya.

2.4. Laboratory and spectral analyses of soil samples

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

2.5. Data analyses

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

3. Results and discussion

3.1. Descriptive statistics of the overall soil properties after CAWT interventions

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

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

3.2. Identification of soil quality indicators under the CAWT farming system

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

During our study, the PCA and the correlation level were applied to identify the critical soil quality indicators under the CAWT system. In

Table 1
General descriptive statistics of the soil properties after CAWT intervention.

Site	All Plots (average)					Mother Trials (MTs)					Baby Trials (BTs)				
Property	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_2O)	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

applying the PC tool, variables with high factor loadings in each dimension were retained as leading soil quality indicators (Takoutsing et al., 2017). In cases where more than one variable is retained under a single PC, a multivariate correlation statistic tested the variables' redundancy for subsequent elimination. Conversely, in circumstances where the highly loaded factors were found not to be correlated, each was considered essential and thus retained as part of the quality indicator sets. For the well-correlated factors, one with the highest absolute factor loading value was chosen as an indicator. At both the MTs and BTs, we established that in the PC1, the highly weighted soil properties were ExBas (ExCa, ExMg, and ExK) and CEC (Table 3). Consequently, these properties were selected to constitute the minimum dataset under PC1.

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

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

The first component is dominated by the positive loading of exchangeable bases and the CEC at the MTs and BTs (Fig. 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 (Fig. 3). It is evident that most properties have a strong relationship and are defined by the NT block (Fig. 3). For instance, at the MTs (Fig. 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). The tillage systems (CT and NT) significantly ($P < 0.05$) influenced soil pH, ExBas, CEC, SOC, and TSN while tree species and varied inter-row spacing, significantly affected soil available P and BD in addition to pH, ExBas, CEC, SOC, and TSN (Table 4). It was further observed that the association of the tillage systems with the different tree species under varied spatial spacing had significant effects on some soil properties. At both the MTs and BTs, inter-row tree spacing variations showed a significant effect on ExBas, CEC, SOC, and BD.

The existence of significant interactive effects showed evidence of a combined or associated influence of the tillage system and variations in inter-row tree spacing (Ayuke et al., 2011). Lack of significant interactive effects on soil properties would indicate that the independent variables had sole but similar effects across the experiment's response variable (Takoutsing et al., 2015). It was observed that some influences were significant at the MTs but not among the BTs. These variations in response to the CAWT intervention could be explained by the experimental host sites diverse spatial characteristics and changes in temporal

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).

variables and management skills during the experimental period (Jiang and Thelen, 2004). For instance, available plant P, ExBas, CEC, SOC, and TSN have been reported to be influenced by the soil parent material (Willy et al., 2019), soil management and farming practices (Takoutsing et al., 2017), climatic and agro-ecological conditions (FAO, 2015) among others. Our findings of significant effects of tillage systems are corroborated by studies such as Momtaz et al. (2009); Waswa et al. (2013); which reported changes in organic matter build-up (evident with SOC and TSN accumulation during our study) and increased base saturation due to intensive retention of crop and green residue as well as minimum soil disturbance. The efficiency of plot management could equally explain possible variations among the observed effects of different interventions at the MTs and BTs (Naab et al., 2017). With reference to bolstering the adoption of CAWT technologies among farmers, the duration of change and nutrient buildup plays an integral part (Mugwe et al., 2009). The changes in nutrient build-up depend on the rate and nature of the residue applied, soil type, and climatic variables, among others (Albiach et al., 2001; Tejada and Gonzalez, 2003). The duration for significant changes in the above soil quality indicators to be noted is often varied (Luo et al., 2010). For instance, studies suggest that an increase in SOC content happens immediately but proportionally after adopting CA, including NT strategies (Larney et al., 2012). In the CT systems, faster residue decomposition may lead to declining SOC content after residue application (Haynes et al., 1998). The CT systems may lead to approximately 18% decline in SOC content at an average rate of 0.3 Mg $ha^{-1}y^{-1}$ in the dry-land regions (Xu et al., 2015). Luo et al. (2010) showed that conventional soil cultivation for more than five years resulted in soil Carbon loss of more than 20 Mg C ha^{-1}. However, adopting a no-till system led to an increase of 3.15 ± 2.42 Mg ha^{-1} of SOC in the top 10 cm of the soil layer within five years (Luo et al., (2010). Another study by Spiegel et al. (2015) reported a 37% increase in SOC content within ten years of CA with NT implementation. Xu et al. (2015) reported significant but gradual changes in soil pH, BD, and plant-available N, P, and K and SOC after 7 years of CA adoption. Generally, persistent annual no-till enhances soil quality in the long term (Luo et al., 2010; Busari et al., 2015). These durations indubitably have an impact on farmers' decision to adopt CA. Generally, setting up strategically located and managed experimental sites, comparing NT versus CT systems under varied soil-climate types, and on-farm management would enhance predictive, but hands-on understanding of their (tillage systems) effects on soil quality and assess their feasibility in different socio-economic and biophysical settings to enhance adoption (Palm et al., 2014).

3.3.1. *Effects of CAWT on soil nitrogen, soil organic carbon and phosphorus*

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

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

The NT system combined with the leguminous trees increased TSN and SOC with positive trends of accumulating plant-available P

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							
	PC1	PC2	PC3	PC4	PC5	h2	u2	com	PC1	PC2	PC3	PC4	PC5	h2	u2	com
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																
	RC1	RC2	RC4	RC3	RC5					RC1	RC5	RC4	RC2	RC3		
SS loadings	3.76	2.93	2.12	1.93	1.37					6.01	2.19	2.14	1.84	1.8		
Proportion Var	0.25	0.2	0.14	0.13	0.09					0.4	0.15	0.14	0.12	0.12		
Cumulative Var	0.25	0.45	0.59	0.72	0.81					0.4	0.55	0.69	0.81	0.93		
Proportion Explained	0.31	0.24	0.18	0.16	0.11					0.43	0.16	0.15	0.13	0.13		
Cumulative Proportion	0.31	0.55	0.73	0.89	1					0.43	0.59	0.74	0.87	1		

Key: h2 =communalities, 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.

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

Palm et al. (2014) reported that crop residues are vital components of CA in terms of increasing soil carbon and fertility, water relations, and biological properties. However, these benefits depend on the amount the residue retained in the fields, residue quality and type alongside the N placement method (Naab et al., 2017). During our study, an estimated 3–6 Mg ha^{-1} of crop residue was retained into the cropping plots under the NT block. This amount of residue has been reported to significantly increase TSN and SOC quantities under NT (Gicheru et al., 2004, 2016). On the other hand, studies by Lal (1976), Agboola (1981), Govaerts et al. (2006), Verhulst et al. (2011), Muchabi et al. (2014) and Naab et al. (2017) attributed low SOC and N build-up in the CT systems to increased residue decomposition and mineralization of the organic matter occasioning losses in carbon and nitrogen brought about by reduced mineral stabilization. Other studies attributed NT with residue retention benefits to rhizospheric priming. Rhizosphere priming changes the rate and quantity of SOM decomposition brought about by root activity and is crucial for soil C and N biogeochemical cycling (Dijkstra et al., 2013). Even though rhizosphere priming is affected by nutrient availability, it significantly affects plants' nutrient supply. A study by Fontaine et al. (2011) showed that increased rhizosphere priming enhances the release of nitrogen through the decomposition of larger fractions of SOM. In soils with limited plant available P, such as those under our study; Rhizo-deposition is used for P mobilization, while rhizosphere priming enhances C sequestration in N poor than in P poor soils under increased atmospheric CO_2 concentrations (Dijkstra et al., 2013). Despite the observed evidence that NT systems enhance SOC, TSN, and P build-up, during our study, cropping fields in tropical African soils are highly deficient in soil N and P, partly, due to the removal of crop residues from the fields for multiple purposes (Valbuena et al., 2012; Takoutsing et al., 2015). For instance, crop residues are dependable sources of animal feeds and household fuel thus practicing CAWT would be undermined due to the unavailability of sufficient crop residues for mulch (Bationo et al., 2007). In more marginal environments, where CA confers even more ecological benefits, crop productivity is lower, and therefore

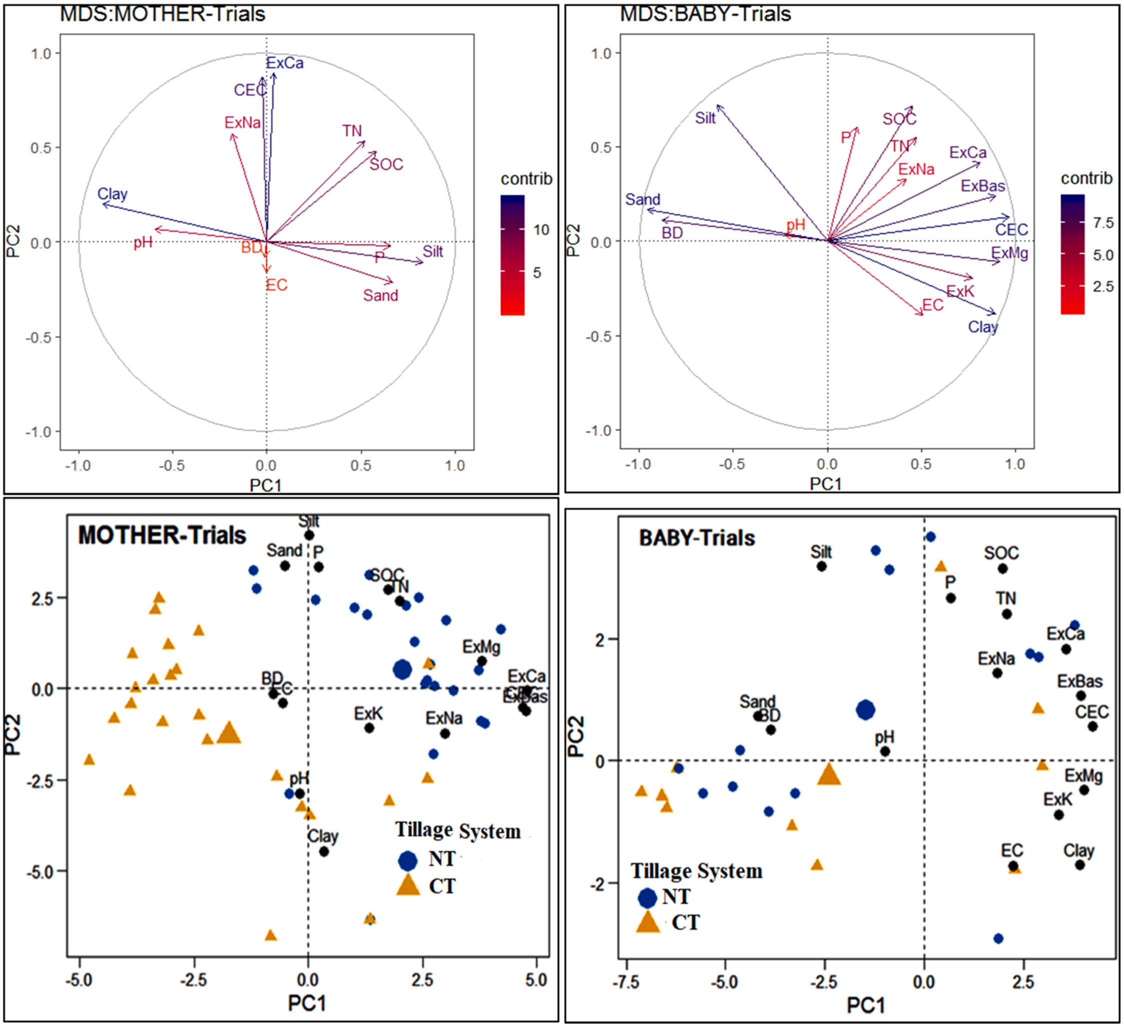

Fig. 3. The Variable factor loading map (**above**) between Dimension 1 and 2 (PC1 and PC2) showing soil properties responsible for maximum variance and in the CAWT system (Below): Arrows (in above) represent the directions of maximum variation.

volumes of crop residues are lower, making competition for them even higher. As a result, achieving optimum CA benefits is difficult, as evidenced by the lower TSN and SOC quantities in the farmer-managed BTs during the current study (Table 4 A). Generally, a focus on strategies that maximize rain-water retention within the soils' root zone conserves soil nutrients status and provides sustainable alternatives for the farm's fodder, feed, food, and fuel requirements are required to enhance promotion, adoption and implementation of CAWT (Naab et al., 2017). It has been suggested that soil quality (soil organic carbon, nitrogen, and P build-up) and productivity can be achieved by combining trees and crops in agroforestry systems, assuming that the trees can exploit resources currently under-utilized by crops and confer more household benefits (Cannell et al., 1996).

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

Other studies attribute the accumulation of N in closely spaced legume trees to their specific physiological and chemical composition. For instance, the observed high N quantities in closely spaced *C.calothyrsus* during our study could be linked to the reduced N-mineralization due to polyphenols quantities in the *C.calothyrsus* residue materials. Constantinides and Fownes (1994) noted that soluble polyphenols, whose high levels have been found in the leaves, twigs, and roots of *C. calothyrsus*, prevent N-mineralization during decomposition. A study by N Schroth and Lehmann (1995) showed that N release in the early weeks of legume tree intercrops was inversely related to polyphenols-N ratios; a potential pointer towards its (TSN) high accumulation. As a result, *C. calothyrsus* has been extensively used to restore degraded lands for agricultural production due to its physiological nature, nitrogen-fixing

Table 4A
Least Square Means for available 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		Conventional	CA		Conventional	CA	
	Mean	Mean	P-value	Mean	Mean	P-value	Mean	Mean	P-value
Calliandra.c	24.7a	24.4a	0.830	28.7bcd	40.1e	<.0001	22.8bc	34.4e	<.0001
Grilicidia.s	25a	26.6a	0.265	26.7abc	39.9e	<.0001	20.4ab	33.9e	<.0001
No tree	23.3a	24.8a	0.206	20.9ab	35.1de	0.0001	15.8a	29.7de	<.0001
P-peas	23.7a	24.5a	0.604	22.5a	30.6 cd	<.0001	17.1a	25.1 cd	<.0001
Cal1.5 m	27.2a	26a	0.637	34.3def	41.9 g	0.000	27.4def	35.7 g	<.0001
Cal3.0 m	20.3a	23.5a	0.194	26.2bc	38.2fg	<.0001	20.9bc	33fg	<.0001
Cal4.5 m	26.7a	23.7a	0.233	25.5abc	40fg	<.0001	20.1abc	34.6 g	<.0001
control	23.3a	27.8a	0.193	20.9ab	35.1defg	<.0001	15.8ab	29.7efg	<.0001
Gril1.5 m	26.4a	25.3a	0.658	30cde	41.8 g	<.0001	23.4cde	35.5 g	<.0001
Gril3.0 m	22.9a	28.8a	0.018	25.8bc	38.8fg	<.0001	19.7abc	32.7fg	<.0001
Gril4.5 m	25.5a	25.6a	0.968	24.4abc	39fg	<.0001	18.2abc	33.4 g	<.0001
Ppeas1.5 m	22.8a	25.1a	0.344	18.8a	36.4efg	<.0001	15a	30.1fg	<.0001
Ppeas3.0 m	23.4a	26.0a	0.291	24abc	28.9bcd	0.010	18.1abc	23.1cde	0.002
Ppeas4.5 m	24.9a	22.2a	0.282	24.7abc	26.5bc	0.337	18.4abc	22bcd	0.023
					Baby Trials				
Calliandra.c	17.4ab	20.7ab	0.287	27ab	34bA	0.074	21.5ab	27.2b	0.052
Grilicidia.s	17ab	14.0a	0.208	25.1ab	28.7ab	0.240	19.8ab	24.3ab	0.051
No tree	16ab	16.0ab	0.991	20.1ab	23.4ab	0.497	15a	17.3ab	0.521
P-peas	23.6ab	24.5b	0.787	20.2a	27.8ab	0.070	15.6a	23.2b	0.016
Cal1.5 m	21.8a	25.9a	0.504	40.9 cd	41.6d	0.898	32.7c	28.1abc	0.291
Cal3.0 m	22.1a	25.2a	0.617	24.6abcd	38.3bcd	0.027	19.5ab	32.8c	0.003
Cal4.5 m	13.4a	16.3a	0.497	21.2abc	28abcdA	0.116	16.9ab	24c	0.025
control	16.1a	16.0a	0.991	20ab	23.4abcd	0.384	15a	17.3ab	0.395
Gril1.5 m	16.6a	13.5a	0.313	29.7abcd	32.3bcd	0.401	23.2abc	27.2c	0.071
Gril3.0 m	14.8a	17.9a	0.045	17.7a	23abcd	0.171	14.2a	19.6abc	0.059
Ppeas1.5 m	22.1a	22.7a	0.922	16.8ab	34.6 cd	0.005	13.2a	29.6bc	0.000
Ppeas3.0 m	25.2a	26.6a	0.777	21.2abcd	27abcd	0.239	16.3ab	22abc	0.110
Ppeas4.5 m	23.7a	24.1a	0.952	22.4abcd	22.4abcd	1.000	17abc	18.7abc	0.696

KEY: CA=Conservation tillage block, conventional=Conventional tillage block. *Cal1.5=Calliandra calothyrsus spaced at1.5m, 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

capacity, and ability to survive in acidic soils (Sebuliba et al., 2012). It was observed that Pigeon peas spaced at 1.5 m recorded higher TSN and SOC quantities at the BTs compared to MTs (Table 4 A). This can be attributed to the capacity of *C.cajan* N-fixing legume properties and the exceptional management they receive from the host farmers. *C.cajan* 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 cropping season (Valenzuela, 2011). On the other hand, farmers tend to provide optimal management to crops and trees that earn them immediate benefits than long-term speculation (Mugwe et al., 2009; Willy et al., 2019). *Cajanus cajan* being a legume crop, farmers are assured of the direct grain harvest and thus tend to provide the most favorable management practices to realize their immediate benefits in terms of grain yield. The consistently higher amounts of P in plots with *C.cajan* can further be linked to its deep taproots that can extract P from the lower horizons into the upper soil layers for crop growth and production (Valenzuela, 2011). Notably, in the CT system, smaller quantities of plant-available P were recorded in closely spaced *C.cajan* compared to sparsely spaced ones. Plant available P adsorption onto the soil constituents such as high soil organic matter (high SOC and TSN reported in closely spaced species), clay and sesquioxides could explain its lower quantities in closely spaced *C.cajan* (Hinsinger et al., 2011; Hopkins et al., 2014; Hill et al., 2015). This could generally further influence adoption of *C.cajan*, whose contribution towards plant available P can be realized within shorter periods. For instance, Xu et al. (2015) reported significant but gradual changes in plant-available P after 7 years of NT with *C.cajan* adoption.

3.3.2. *Response of exchangeable bases and CEC to CAWT intervention*

The exchangeable bases and CEC showed a significant ($P < 0.05$) response to the tillage systems (Table 4). The mean differences in CEC were consistently high in the NT blocks with high CEC quantities recorded in sub-plots under *C.calothyrsus*, *G.sepium*, and *C.cajan* as compared to the control sub-plots without any trees both at the MTs and BTs (Table 4 B). Similarly, high values of ExBas were observed in the NT block compared to those under the 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 (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 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 (2.81 cmol$_c$ kg^{-1}) and 4.5 m (2.81 cmol$_c$ kg^{-1}) at the MTs and BTs, respectively (Table 4 B).

Generally, these results show that integrating tree species within cropping fields under NT system significantly improves the soil CEC and build-up of ExBas in the study area. The significant rise in ExBas and CEC in response to the CAWT interventions could be attributed to the accumulation of crop residues, agroforestry litter and twigs, as well as their high sensitivity to soil organic matter amendments (Yemefack et al., 2006). This implies that fertile conditions are evident in NT systems. Having observed no significant differences in texture and clay content between CT and NT tillage systems (Table 4), yet SOC and TSN, which are critical indicators of soil organic matter differed significantly (Table 4 A); then the observed significant differences in CEC must be attributed to soil organic matter accumulated (Schwab et al., 2015). Soils with high clay and organic matter content have high probabilities of retaining positively charged ions and consequently show high concentration of CEC (Selassie et al., 2015). A host of studies (such as Schwab et al., 2015, Challa et al., 2016 and Belayneh, 2019) reported significant differences in CEC and ExBas between CT and NT cropping fields. According to Sinore et al. (2018) and Belayneh et al. (2019), significantly high CEC and ExBas concentration in farming fields under CA would be as a result of improved soil aggregate stability, the high biomass generated, increased organic matter, and controlled erosion. During our study, the *relative abundance* in ExBas was as follows: K$^+$ < Mg^{2+} < Ca^{2+} both at the MTs and BTs (Table 1). High values of ExBas

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

Mother	CEC			ExBas			ExK			ExCa			ExMg		
Species	Conventional mean	CA mean	P-value	Conventional mean	CA Mean	P-Value	Conventional mean	CA mean	P-value	Conventional mean	CA mean	P-value	Conventional mean	CA Mean	P-Value
Calliandra.c	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
Grilicidia.s	13.6abc	14.2bc	0.098	12.1abc	12.4abc	0.478	2.05a	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
Cal1.5 m	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
Cal3.0 m	14.1bcd	15.0 cd	0.125	12.9abc	14.3c	0.091	2.02ab	1.79a	0.051	7.90abcde	9.13e	0.005	2.59abc	2.88c	0.039
Cal4.5 m	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
Gril1.5 m	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
Gril3.0 m	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
Gril4.5 m	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
Ppeas1.5 m	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
Ppeas3.0 m	12.1a	14.9 cd	<.0001	10.2a	13.4bc	0.000	1.84ab	1.89ab	0.676	6.53a	8.62deB	<.0001	2.26a	2.81bc	0.000
Ppeas4.5 m	12.9ab	15.2d	<.0001	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															
Calliandra.c	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
Grilicidia.s	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
Cal1.5 m	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
Cal3.0 m	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
Cal4.5 m	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
Gril1.5 m	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
Gril3.0 m	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
Ppeas1.5 m	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
Ppeas3.0 m	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
Ppeas4.5 m	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 = $\text{cmol}_c\ \text{kg}^{-1}$, ExBas= $\text{cmol}_c\ \text{kg}^{-1}$, ExK= $\text{cmol}_c\ \text{kg}^{-1}$, ExCa= $\text{cmol}_c\ \text{kg}^{-1}$, ExMg= $\text{cmol}_c\ \text{kg}^{-1}$. *Cal1.5=Calliandra calothyrsus spaced at1.5m, 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.

under *G.sepium* can be attributed to the total quantities of green biomass produced and retained within the cropping fields. *G.sepium* has been reported to yield as high as 20 Mg ha^{-1} of residue, which, when incorporated into the soils, contributes towards ExBas concentration (Palmer et al., 1994). A study by Kang et al. (1989) observed 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 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 m) yielding 20 Mg ha^{-1} would significantly contribute to the build-up of these nutrients in the soil as compared to sparsely spaced *G.sepium, as observed at* the MTs during our study.

On the other hand, Palmer et al. (1994), reported that incorporation of *C.calothyrsus* (11.3 Mg ha^{-1}) 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 in the soil, further corroborating our findings. An assessment of each base quantities in relation to the documented 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}; Takoutsing et al., 2017) showed that the measured quantities during our study were way above these limits. This sufficiency of exchangeable bases in the soils could generally justify the dominant use of NPK (23:23:10) fertilizers in our study area (Kisaka et al., 2016).

3.3.3. *CAWT effects on soil pH and electrical conductivity (EC)*

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

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

Results further showed that EC (whose toxicity threshold level is >4 dS m^{-1}) could not limit maize cropping in the current study since all the observed values were less than 1 dS m^{-1} (Table 4 C). Electric conductivity has been reported to affect maize yield production, soil nutrient availability, and microbial activities (Vargas Gil et al., 2009). Maize is susceptible to soil salinity, but its productivity can endure levels of up to 4 dS m^{-1} without significant effects on final yields (Takoutsing et al., 2017). These levels can be reversed and stabilized by the use of *G.sepium* spaced at 3.0 m in maize and legumes' cropping fields.

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

The majority of the selected soil quality indicators recorded minimum values that are way above the documented threshold for optimal maize production (Takoutsing et al., 2017). In part, this could be attributed to the CAWT interventions that had been implemented in the study area. However, some of the soil quality indicators identified during this study recorded minimum values below the documented thresholds for maize production (Takoutsing et al., 2017). These are TSN (mean = 23.92 *Mg N ha^{-1}*, and minimum = 10.12 *Mg N ha^{-1}*), plant-available P (mean = 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 CEC (mean = 12.87 cmol$_c$ kg^{-1}, and minimum = 5.04 cmol$_c$ kg^{-1}) (Table 5). These results showed that, to some extent, maize production on average was constrained during the experimental period. Besides, a succinct comparison of the average threshold values against

Table 4C
The soil pH and Electrical conductivity 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 mean	CA mean	P-value	Conventional mean	CA mean	P-value	Conventional mean	CA mean	P-value	Conventional mean	CA mean	P-value
Calliandra.c	7.06^{a}	7.03a	0.539	0.05a	0.06a	0.901	7.19a	7.17a	0.856	0.052a	0.048a	0.646
Grilicidia.s	7.03^{a}	6.97a	0.445	0.06a	0.06a	0.129	7.11a	7.09a	0.733	0.048a	0.053a	0.390
No tree	7.15^{a}	6.92a	0.272	0.06a	0.06a	0.755	7.05a	7.14a	0.508	0.059a	0.060a	0.949
Pigeon-peas	7.04^{a}	6.97a	0.445	0.06a	0.06a	0.799	6.95a	6.85a	0.391	0.057a	0.052a	0.481
Cal1.5 m	6.93^{a}	6.98a	0.532	0.06ab	0.07ab	0.248	6.9a	7.07a	0.468	0.040a	0.039a	0.966
Cal3.0 m	7.12^{a}	7.13a	0.894	0.06ab	0.04a	0.108	7.18a	7.25a	0.769	0.036a	0.046a	0.512
Cal4.5 m	7.13^{a}	6.97a	0.064	0.05ab	0.06ab	0.487	7.34a	7.19a	0.331	0.062a	0.050a	0.283
Control	7.15^{a}	6.92a	0.058	0.06ab	0.06ab	0.743	7.06a	7.15a	0.511	0.059a	0.059a	0.949
Gril1.5 m	7.03^{a}	6.94a	0.251	0.06ab	0.06ab	0.817	7.12a	7.01a	0.353	0.052a	0.056a	0.576
Gril3.0 m	7.03^{a}	6.96a	0.405	0.08b	0.06ab	0.004	7.14a	7.22a	0.528	0.041a	0.048a	0.501
Gril4.5 m	7.04^{a}	7.01a	0.713	0.06ab	0.06ab	0.817	-	-	-	-	-	-
Ppeas1.5 m	7.12^{a}	7.05a	0.372	0.05ab	0.06ab	0.248	7.10a	6.94a	0.472	0.056a	0.041a	0.327
Ppeas3.0 m	7.04^{a}	6.89a	0.081	0.06ab	0.05ab	0.355	6.93a	6.81a	0.508	0.054a	0.051a	0.789
Ppeas4.5 m	6.96^{a}	6.96a	0.968	0.06ab	0.06ab	0.817	6.82a	6.81a	0.946	0.056a	0.056a	0.998

Key: CA=Conservation tillage block, conventional=Conventional tillage block. *Cal1.5=Calliandra calothyrsus spaced at1.5m, 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 threshold values vs. observed quantities of the soil quality indicators under the CAWT system for maize production.

	pH (H_2O)	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	6.84	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

those under the control treatment (Table 5) showed that only clay (threshold=10–30% against control=74.5%,) and TSN (threshold=40–60% against control=15.0%,) fell out of range for optimal maize production. The rest of the quality indicators (pH, P, ExCa, ExMg, ExK, ExBas, CEC, and EC) were within range of the threshold requirements for optimal maize production.

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

3.4.1. *Nitrogen*

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 coefficient of variation (CV) of 31% (Table 5). This range implies that some test plots recorded indicative TSN quantities that could not fully support maize production (Takoutsing et al., 2017). The recommended available N for maize production in the study area is 60 Mg N ha^{-1} (Horneck et al., 2011; Willy et al., 2019). However, this depends on the soil type and other environmental variables, including climatic conditions and soil management. In whatever case, there is an indication that the adoption of CAWT would significantly raise the base soil TSN supplement for maize production to just less than 30 Mg N ha^{-1}. Through mineralization and nitrification processes, the observed TSN during our study is made available for plant uptake. Due to the chemical composition of organic N, it is very resistant and unavailable for plant uptake (Beegle, 1996). Through mineralization, organic N is converted into mineral ammonium-N (NH_4^+), which is further converted (through nitrification) into nitrate-N (NO_3). The nitrate-N is available for plants. In the soils, mineral N is highly susceptible to complex processes that involve weather and soil microbes' interaction, leading to N availability losses through immobilization, denitrification, leaching and volatilization (Beegle, 1996). Generally, the concentration of mineral N in the soils and the changes in its availability to plants is unpredictable. Farmers need to regularly top up the deficient amounts through organic and inorganic fertilizer application. In the CAWT system, lower amounts of TSN were significantly affected by soil pH (Fig. 4A). These findings are consistent with Takoutsing et al. (2017), who reported reduced soil nitrogen in soils 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 showed evidence of negatively affecting TSN (Fig. 4B). According to USDA (2011) and Eve et al. (2014), EC quantities of such range (0.02 and 2.8 ds m^{-1}) could lead to increased production of nitrous oxide (N_2O) through denitrification under anaerobic conditions. This can potentially contribute towards losses in TSN and emissions of greenhouse gas emissions (USDA, 2011; Eve et al., 2014). However, it should be acknowledged that our study area is typically a rain-fed dryland region. Two main conditions necessitate the denitrification process. These conditions are saturated soils and a source of energy for the microbes in the form of organic matter (Beegle, 1996). In the dryland regions, rains have been reported to be poorly redistributed, with over 25% falling within a couple of rainstorms spanning between two to four weeks, during which soil saturation conditions are high (Recha et al., 2012; Kisaka et al., 2016). Estimating the extent of N losses through denitrification is difficult. However, significant losses can occur within a week of saturated conditions, hypothetically explaining our observations in the current study (Beegle, 1996). In addition, denitrification conditions are enhanced under reduced tillage systems due to high organic matter concentration and soil water content (Beegle, 1996). Conditions of high organic matter and soil water content are favored by the CAWT system (Rabach et al., 2017).

3.4.2. *Phosphorus (Available P)*

The critical suggested available P for maize production is 8.5 mg kg^{-1} (Olufemi and Omotoso, 2008). During our study, cases of available P less than this threshold were recorded in some experimental sub-plots (Table 5). Some of the potential explanatory factors of the deficiencies could be low P concentration in the parent material (Bünemann et al., 2004), low P fixation potential (Van der Eijk, 1997) and the dominance of highly weathered hornblende gneisses (Willy et al., 2019). According to Waswa et al. (2013), the maximum available soil P occurs within a pH range of 6.5 and 7.0. Consistent with this argument, it could be observed during our study that pH values above 7.1 occasioned significant declines in available P (Fig. 4C.). More iron and aluminium are available at lower pH to form insoluble phosphate compounds; therefore, less phosphate is available. Soil P is generally characterized by its immobility within the soil often lost through runoff or erosion (Beegle, 1996; Nyawade et al., 2019b). Even though little soluble Phosphate (PO_4) can be detected in soils, large quantities of P are always present, some of which are part of SOM (Busari et al., 2015). The availability of organic P is seasonal during warm, moist seasons with heightened microbial activities. However, due to P immobility and fixation, the placement of phosphorus fertilizer affects its availability to plants. Broadcasting P fertilizer under CT mixes P uniformly with large amounts of soil maximizing crops' root contact for uptake (Busari et al., 2015). However, it increases P contact with soils' surface, which is then fixed into less available forms (Beegle, 1996). Banded application of P fertilizers limits crops' root contact. Generally, loss of sediment-bound P is significantly reduced with CA implementation (Busari et al., 2015). However, immobile nutrients like P tend to become concentrated in the topsoil due to inadequate mixing under the no-tillage (NT) system.

An increase in the BD was equally observed to be negatively influencing the presence of available P (Fig. 4D). Hypothetically, high BD negatively affects physical soil properties, thus limiting microbial and biochemical activities and processes crucial for nutrients such as P, availability (Beegle, 1996). Conversely, due to high P insolubility and immobility, its losses are expected through runoff or erosion (Beegle, 1996). High BD reduces water infiltration and increases runoff and erosion, further explaining the inverse relationship between BD and P observed during our study (Fig. 4D).

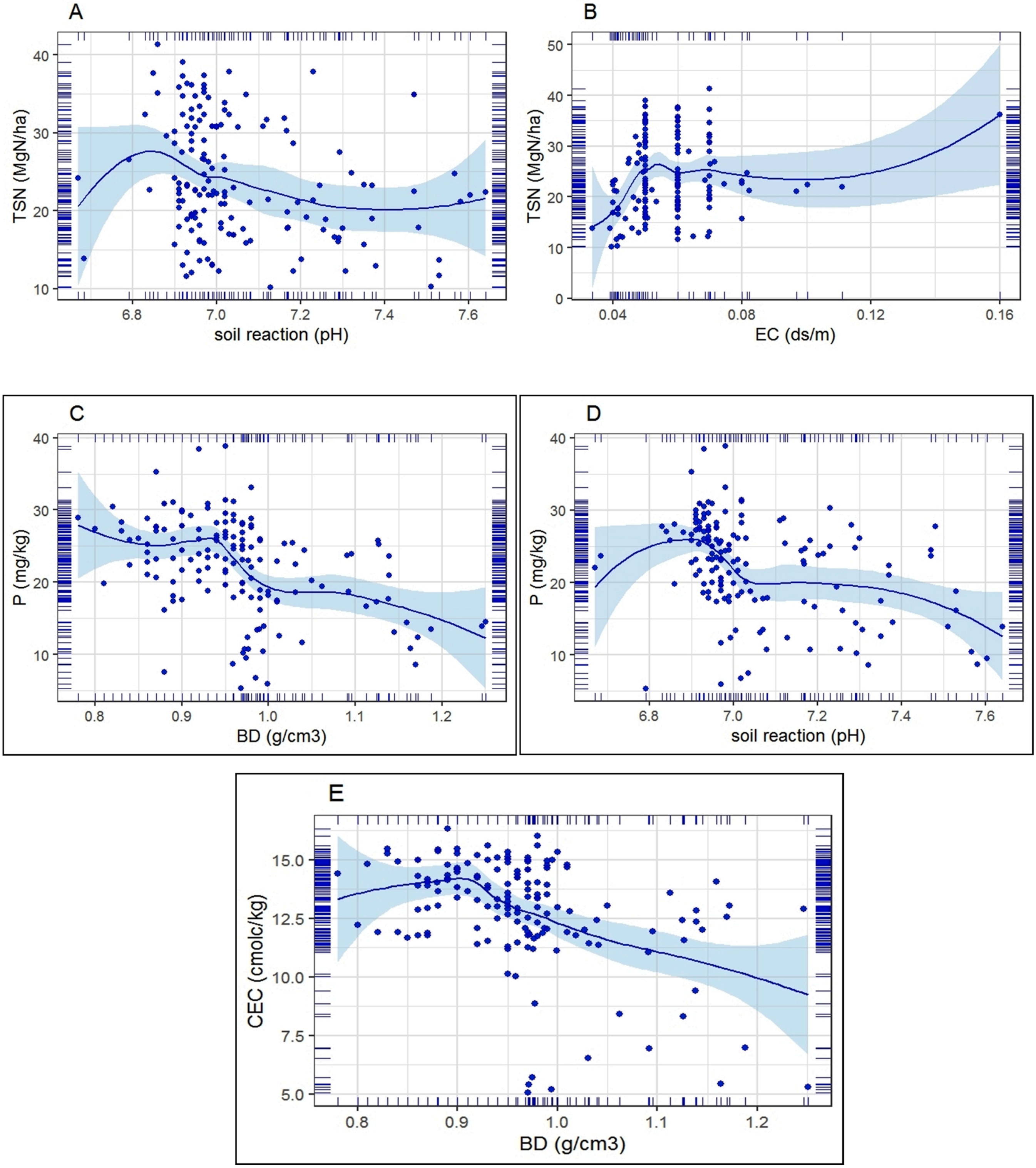

Fig. 4. A&4B: Influence of soil pH (4A) and Electrical Conductivity (4B) on total soil Nitrogen. C and 4D: Influence of Bulk Density (4C) and soil pH (4D) on plant-available soil Phosphorus. **E**: Influence of Bulk Density on Cation Exchange Capacity (CEC).

3.4.3. Exchangeable bases (ExBas) and cation exchange capacity (CEC)

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

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

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

4. Conclusion and recommendations

Integration of legume trees into maize-legume intercrops under CA influences soil quality. CAWT influence on soil organic carbon and TSN was found to be statistically significant. The tillage systems and the inter-row spacing of the legume trees significantly influenced available soil P, exchangeable bases (K, Ca, Mg, Na), CEC, and stabilized soil pH. The main properties accounting for soil quality in the region were established as ExBas, CEC, TSN, SOC, pH, P, EC, clay, and BD. Despite most soil quality indicators recording values above threshold for maize cropping, some components (P, TSN, ExBas, and CEC) recorded minimum values that may hamper optimum maize production. To enhance soil N accumulation, use of *C.calothyrsus* or *G.sepium* both spaced at 1.5 m by 1 m is recommended. However, a contextualized recommendation should consider competing trade-offs to account for competitions, complementarily, and the farmers' land use preferences. In addition to *C.calothyrsus* and *G.sepium*; intercropping with pigeon peas and retaining its residue on the farms can potentially complement and compensate for the available P in the soil. A shift towards CAWT shows evidence of improving soil nutrient availability and bridging their documented thresholds for maize farming. By establishing the minimum datasets for soil quality determination through this study, farmers, policymakers, researchers, extension personnel, and all agricultural stakeholders in agroforestry and CA have an efficient cost-effective and rapid tool for soil quality assessment, especially in dry-land agro-ecosystems of eastern Kenya. Generally, soils under the CAWT system in the study area can sustain maize production. However, this information can be used as a baseline to critically evaluate maize-legume production to account for possible trade-offs on land use. A critical understanding of how this system affects yield productivity, fodder, and general household needs are recommended to complement our findings.

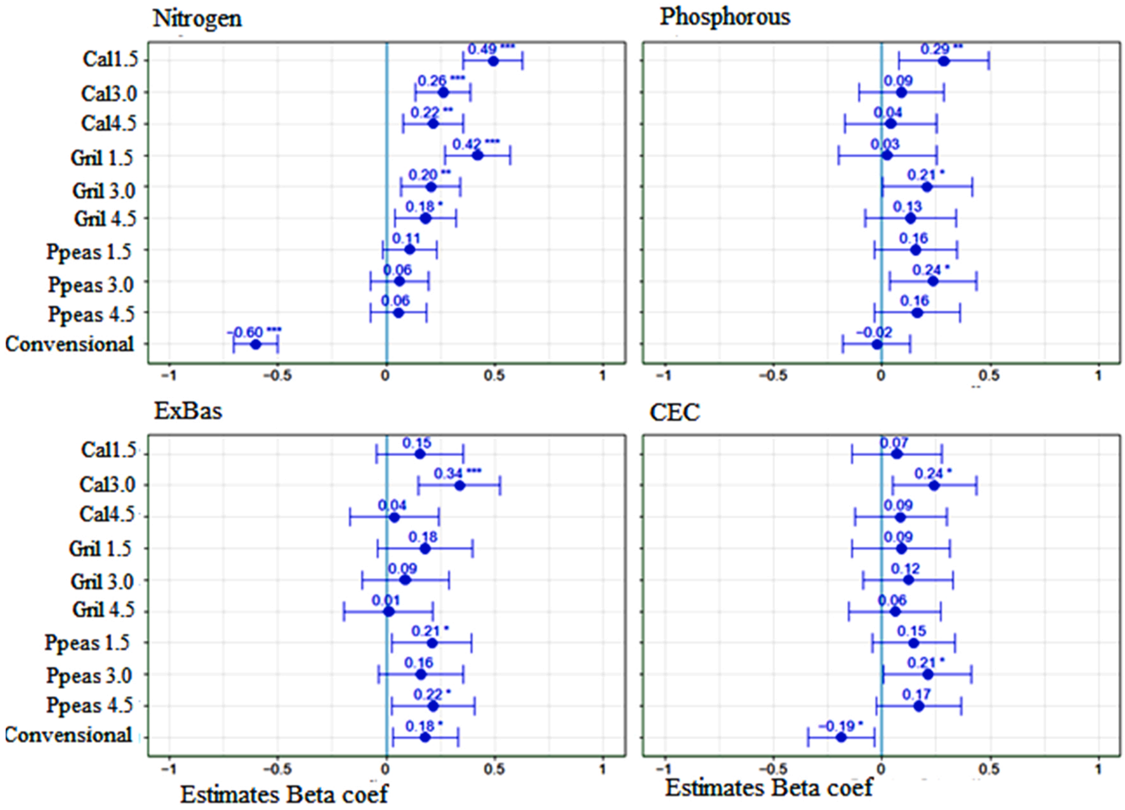

Fig. 5. Estimates of the linear regression model testing the relationship between explanatory variables of the soil quality indicators with below threshold values for maize production (soil properties) against tillage systems and spacing. Reference groups are indicated against the intercept rows.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2022.105586.

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