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SOIL AGGREGATION, ORGANIC CARBON AND MICROBIAL BIOMASS AS AFFECTED BY TILLAGE, RESIDUE MANAGEMENT AND CROPPING SYSTEMS IN TROPICAL FERRALSOLS OF WESTERN KENYA

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ABSTRACT

Soil aggregates are important indicators of soil health, nutrient status and ability to resist erosion. This parameter is sensitive to soil disturbances that occasion disintegration of aggregate sizes, loss of organic carbon and physical killing of the soil dwelling macro- and micro-fauna. Numerous agronomic practices are promoted to enhance sustainable food production, but little concern has been taken on the effects of such practices on soil aggregate stability and microbial biomass and soil organic carbon, yet these are vital indicators of soil health, nutrient availability and structure maintenance. A study was conducted in western Kenya to assess the effects of tillage, cropping systems and residue management on soil aggregate stability, microbial biomass carbon and soil organic carbon in 2017 and 2020. At both depths assessed (0-5 and 5-15 cm), tillage, cropping systems and residue retention significantly ($P \leq 0.05$) affected soil aggregate stability indices. Mean weight diameter (MWD) was significantly higher ($P \leq 0.05$) in; Reduced tillage (RT) than conventional tillage (CT) ($P \leq 0.05$), maize-soybean intercrop compared to rotation system ($P \leq 0.05$), and in residue retention compared to residue removal treatment ($P \leq 0.05$). In 2017, microbial biomass carbon (MBC) was not significantly affected by either tillage, reside retention or cropping systems, but was 23 and 29%, respectively, higher in reduced tillage and maize-soybean intercropping systems respectively. In 2020, MBC positively correlated with total nitrogen, SOC and S as opposed to 2017. Soil organic carbon (SOC) was not significantly affected by treatments, but was slightly higher in residue retention (3.57%) and maize-soybean intercropping systems (6.0%). In 2017, large macro-aggregates (LM) at 5 cm depth significantly negatively correlated with Mn while LM (at 15 cm) positively correlated with soil pH, K and Mg. Small macro-aggregates (SM) at 15 cm positively correlated with S but negatively with Al (at both depths), P and Fe. Micro-aggregates (M) at 15 cm positively correlated with P and Al but negatively with Mg. Silt and clay (SC) positively correlated with Al while negatively with Mg and pH at 5 cm. The MWD positively correlated with Ca and Mg. Soil pH and Mg also positively correlated with GMD at 15 cm while Al showed negative correlation. These findings suggest that practicing reduced tillage, combined with residue retention while observing proper cropping systems can markedly reduce the susceptibility of soil to erosion, improve soil organic carbon and increase soil microbial biomass.

Keywords: Soil aggregates, microbial biomass carbon, organic carbon, tillage, residue

INTRODUCTION

Soil aggregate stability defines the susceptibility level of a soil to erosion, and is often an important indicator of the organic matter in the soil, biological activities as well as nutrient cycling in the soil (Barthes and Roose, 2002). A system with increased aggregate stability is not only less susceptible to soil erosion, but is also characterized by increased microbial biomass, reduced nutrient losses, high organic carbon contents as well as increased biodiversity (Kihara *et al.,* 2012; Chen *et al.,* 2015). In addition, increased soil aggregate stability increases organic matter protection and accumulation (Devine *et al.,* 2014), improves soil water holding capacity, drainage and soil porosity, and reduces soil compaction. Cumulatively,

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these determine the health and quality status of a system by supporting biological activities involving promotion of nutrient cycling.

Disruption of soil aggregate stability, either by poor tillage or farming practices often compromise the systems' abilities to maintain their structure (Šimanský, 2013), resist erosion and associated nutrient losses, and provide adequate moisture for maintaining soil flora and fauna biodiversity and activities. Tillage associated practices, involving cultivation and use of heavy implements can occasion breakage of soil aggregates (Kasper *et al.,* 2009), escalate physical killing of soil fauna and enhance loss of soil organic carbon and nutrients, thus worsening the level of fertility and productive potentials of a system.

Reduced tillage systems are often characterized by increased carbon storage (Moussadek *et al.,* 2014), abundant faunal and floral diversity, reduced nutrient losses and increased nutrient and water use efficiency. Minimal soil disruptions characterizing reduced tillage systems often results to increased accumulation of organic matter (Quintero and Comerford, 2013) that provide food for the active microbial populations in the soil, thus influencing nutrient formation and cycling, aggregate formation and stabilization as well as increased soil moisture retention. Appropriate agronomic practices involving crop rotations and intercropping, residue retention and observation of integrated soil fertility management not only improve soil health, but also augment soil and crop productivity (Kihara *et al.,* 2012).

Previous studies have pointed out that long-term tillage have several demerits on soil aggregate formation as well as stabilization, together with variable adverse effects on soil organic carbon stocks (Xie *et al.,* 2015; Zhang *et al*., 2016) and microbial biomass (Wright *et al.,* 2005; Kabiri *et al.,* 2016). Tillage associated disturbances have been attributed to reduced microbial biomass, aggregate formation and stabilization through breakdown of large macro aggregates and reduction in soil organic carbon stocks. However, little information is available on the impact of different cropping systems, involving crop rotation, intercropping cereals and legumes, as well as integration of crop residues on soil aggregate stability and microbial biomass carbon.

Sustainable agronomic production not only pegs on crop productivity, but the holistic biophysical and chemical interactions within a system. Agronomic practices should often champion meeting all these interactions holistically for sustainable production in the systems. Several agronomic practices have been widely promoted to enhance sustainable food production, but little concern has interrogated the effects of such practices on soil aggregate stability and microbial biomass, yet these are vital indicators of soil health, nutrient availability and structure maintenance. The aim of this study was to assess the effects of different agronomic practices on soil aggregate stability, organic carbon and microbial biomass carbon under different long-term agronomic management practices.

MATERIALS AND METHODS

Study area

The long-term experimental trial (CT1) site was established in 2003 in Gem (0º 07' N and longitude 34º 24' E), Siaya County, western Kenya. The region is characterized by sub-humid climate with biannual rainfall ranging between 1200-1600 mm and temperature averaging 23.2±1.52 ^{0}C (Kihara, 2009). Soils are mainly Ferralsols, characterized by low pH (5.08 ± 0.27). Maize is the dominant staple food crop, with production mainly done for subsistence, highly reliant on rainfall, and practiced under conventional tillage in smallholder farms.

Experimental design

The experiment was set up in a split-split plot design with 48 treatments replicated four times and two tillage systems namely conventional tillage (CT) and reduced tillage (RT) were used. In the sub-plots were three cropping systems [maize and soybean rotation, maize and soybean intercropping and continuous maize], sub-sub plot were two residue application rates (with or without 2 t/ha residue application), and sub-sub-sub plots were four rates of N fertilization (0, 30, 60 and 90 kg N/ha) as urea, two rates of P (0 and 45 kg P/ha as TSP), and blanket application of K (at 60 kg/ha) as muriate of potash during planting). The whole experiment had 192 plots each measuring 4.5 by 7 m. Within the trial, maize were planted at a spacing of 25 by 75 cm and in a rotation system, with two seeds placed per hill and later thinned to one. Soybean was planted either as sole crop or intercropped with maize at a spacing of 5 by 75 cm. Urea was applied in two splits; whereby ⅓ was applied during planting and ⅔ applied during topdressing. Hand weeding was done in the conventional tillage plots while in the reduced tillage plots, weeding was restricted to surface scratching to approximately 3-5 cm depth.

Treatment selection

Five treatments (except one in 2020) representing the common best-bet agronomic management practices recommended for maize-legume based systems, were selected for study in the experiment (Table I). These treatments allowed for inference of few contrasts embedded in different agronomic management practices involving different tillage practices, cropping systems, residue retention (i.e., maize stover) and fertilizer application.

TABLE I-TREATMENTS SELECTED FOR SOIL PHYSICO-CHEMICAL AND BIOLOGICAL STUDY UNDER DIFFERENT TILLAGE SYSTEMS

Treatment	Trial	Tillage	Cropping system	Residues	Fertilizers	Target phase
CT + Residue	CT1	CT	M-S	+R	60N 60P	Maize
RT + Residue	CT1	RT	M-S	+R	60N 60P	Maize
RT + Intercrop	CT1	RT	M/S	+R	0N 60P	N/A
RT + Rotation	CT1	RT	M-S	+R	60N 60P	Soybean
RT - Residue	CT1	RT	M-S	-R	60N 60P	Maize

CT= Conventional till, RT=reduced tillage, R= crop residue, M-S=Maize soybean rotation, M/S=maize soybean intercropping

Soil sampling and laboratory analysis

Soil samples were collected from surface depths (0-5 cm and 5-15 cm) for soil aggregate analysis in September 2016. Soil aggregate assessment was done following the procedure developed by Six *et al.* (2002). Samples for the determination of microbial biomass carbon were taken in January 2017 from 5 points within each plot at 0-20 cm depth to adequately represent the plough layer. The samples were mixed before taking a composite sample. The samples were kept cool in a cooler box and transported to the laboratory the same day where they were sieved over a 2 mm sieve and refrigerated at -20 °C until extraction and determination of microbial biomass carbon. Microbial biomass carbon was determined using Chloroform fumigation direct extraction method (Vance *et al.,* 1987). Briefly, the sieved samples were weighed into three sets of 25 g each. One set of 25 g of sieved (2 mm) field moist soil sample, previously kept under refrigeration (-20 ^{o}C), was fumigated using ethanol-free chloroform for 24 hours in sealed desiccators. Afterwards, the fumigated samples and the non-fumigated samples were extracted with 0.5 M K_2SO_4 for C. These extracted solutions were centrifuged (Rotina Hettich Benchtop Centrifuge, DDETDR brand) at 5000 revolutions per minute (rpm) for 10 minutes followed by filtration and reading of the concentrations using spectrophotometer. Microbial biomass carbon was obtained by calculating the difference between the fumigated and non-fumigated samples.

In 2020, a repeat study was done only on microbial biomass C and soil chemical parameters in all the selected treatments except the initial rotation system that targeted soybean phase. Here, the microbial biomass C was determined by using MicroBiometer Soil Test kit (https://microbiometer.com), which is a method different from the Chloroform Fumigation previously used in 2017. Briefly, fresh soil samples were sifted. Using a calibrated syringe, 1ml of samples were taken, compacted to 0.5 ml and the excess soil removed from the tip of the syringe. One sachet of the provided powder from the Kit was transferred into clean tube; water added and briefly mixed using a whisker. Soil samples were added, briefly mixed with the contents, whisked for 30 seconds to fully mix with the fluid and allowed to settle for 20 minutes. After every five minutes, the contents were briefly tapped to allow the floating debris to settle down the tube. After 20 minutes settling time, the samples were extracted using pipette and three drops carefully applied to the reading card without wetting the surrounding of the card. The readings for microbial biomass carbon were thereafter taken by imaging the card using MicroBiometer App from

Google Play Store.

Soil organic carbon (SOC) was assessed using Carbon Nitrogen Elemental Analyser while permanganate oxidisable carbon (POxC) was determined using the procedure of Weil *et al.* (2003). Briefly, 2.5 g of air-dried soil were weighed, followed by addition of 18 mL of distilled water and 2 mL of potassium permanganate (0.2 M). The mixture was shaken for 2 minutes (at 240 rpm using a vortex mixer (AGE model and Velp Brand) and allowed to rest for 10 minutes. This was followed by removal of supernatant (0.5 mL) and mixing with distilled water (45.5 mL). Afterwards, 200 µl of aliquots were extracted and their concentrations read using spectrophotometer (at 550 nm).

Data analysis

Variations in means were determined using analysis of variance (ANOVA) and significantly different results further separated using Fisher's least significant difference (LSD). Data was analyzed using R. Pearson's correlations on the variables were conducted using Statistical Packages for Social Sciences (SPSS).

RESULTS

Tillage affected ($P \leq 0.05$) soil aggregate stability. Large macro-aggregates (LM) were affected ($P \leq 0.01$) at 0-5cm depth only (Table II). Reduced tillage systems recorded higher macro-aggregate size fractions compared to conventional tillage systems irrespective of the depths. In addition, mean weight diameter (MWD) was 16.31% higher in the reduced tillage compared to conventional tillage systems. Residue (maize stover) application increased ($P \leq 0.05$) MWD at 0-5 cm and 5-15 cm depths, respectively (Table II). Aggregate stability was affected ($P \leq 0.01$) by cropping systems, and was significantly higher at 5% confidence level in the maize-soybean intercropping compared to maize-soybean rotation systems (Table I). The MWD and large macro-aggregates were higher ($P \leq 0.05$) in the maize-soybean intercrop system compared to the rotation system.

Microbial biomass carbon was not affected ($P \geq 0.05$) by either tillage, residue retention or cropping systems, but was 23% higher in reduced tillage than conventional tillage systems, and 29% higher in maize-soybean intercropping compared to rotation systems (Table II). Agronomic management practices did not significantly affect soil organic carbon, but SOC was slightly higher in residue retention (3.57%) and maize-soybean intercropping system (6.0%).

TABLE II- EFFECT OF TILLAGE, RESIDUE RETENTION AND CROPPING SYSTEMS ON MICROBIAL BIOMASS CARBON AND SOIL AGGREGATE STABILITY

Treatment	MBC (mg g^{-1})	SOC (%)	LM (< 8mm >2 mm)		MWD	
	0-20 cm	0-20 cm	A	B	A	B
CT + Residue	44.15a	1.99a	4.11d	14.50cd	1.03e	1.51c
RT + Residue	57.48a	1.96a	10.61bc	16.14bcd	1.38bcd	1.66abc
RT + intercrop	83.00a	2.00a	15.40a	21.17a	1.62a	1.88a
RT + Rotation	58.90a	1.88a	13.33ab	20.00ab	1.52ab	1.84a
RT - Residue	87.95a	1.89a	9.93bc	12.47de	1.32cd	1.52c

MBC=Microbial biomass carbon; SOC = Soil organic carbon; LM=Large macro-aggregates; MWD= Mean weight diameter; RT=Reduced Tillage, CT= Conventional Tillage, intercrop= maize-soybean intercrop; rotation=maize-soybean rotation; A = 0-5 cm depth, B = 5-15 cm depth. Means followed by the same letters in each columns are not significantly different from each other as determined by Fisher's LSD.

Amongst the aggregate size fractions assessed in 2017, large macro-aggregates (LM) at 5 cm depth significantly negatively correlated with Mn while LM (at 15 cm) positively correlated with soil pH, K and Mg (Table III). Small macro-aggregates (SM) at 15 cm positively correlated with S but negatively with Al (at both depths), P and Fe. Micro-aggregates (M) at 15 cm positively correlated with P and Al but negatively with Mg. At 5 cm depth, silt and clay (SC) was positive for Al while negatively correlated with Mg and pH. Silt and clay at 15 cm positively correlated with P and Al positively but negatively with S. Amongst the aggregate stability indices, at 5 cm depth, mean weight diameter negatively correlated with Mn. On the other hand, at 15 cm depth, MWD and geometric mean diameter (GMD) positively correlated with Ca and Mg while Mn showed negative correlation with GMD. Soil pH and Mg also positively correlated with GMD at 15 cm while Al showed negative correlation.

TABLE III. RELATIONSHIP BETWEEN SOIL CHEMICAL PARAMETERS VERSUS AGGREGATE SIZES AND MICROBIAL BIOMASS CARBON IN 2017.

	LM_5	LM_15	SM_5	SM_15	M_5	M_15	SC_5	SC_15	MWD_5	MWD_15	GMD_5	GMD_15	MBC
pH	.351	.530*	.297	.131	-.310	-.328	-.557*	.062	.365	.499	.505	.584*	.253
POxC	.023	.164	-.123	.141	.157	-.224	-.228	-.023	-.016	.200	.107	.225	-.143
N	-.091	.251	-.067	.022	.175	-.117	-.224	.052	-.104	.219	-.010	.272	-.326
SOC	-.171	-.016	-.222	.195	.283	-.149	.041	.078	-.204	.029	-.147	.143	-.263
P	.000	-.185	-.483	-.633*	.178	.673**	.304	.617*	-.066	-.413	-.171	-.403	.049
K	.247	.561*	.043	-.109	-.134	-.217	-.380	-.095	.230	.507	.314	.328	-.273
Ca	.416	.425	.271	.317	-.340	-.508	-.348	-.328	.409	.515*	.562*	.462	.253
Mg	.400	.598*	.428	.359	-.386	-.632*	-.569*	-.403	.422	.693**	.597*	.614*	.137
Mn	-.572*	-.210	-.082	-.048	.442	.114	.304	.114	-.550*	-.198	-.516*	-.230	-.076
S	-.083	-.351	.058	.636*	.048	-.419	.208	-.545*	-.081	-.084	-.068	-.011	.064
Cu	-.077	.008	-.473	-.396	.238	.328	.358	.133	-.143	-.113	-.221	-.236	-.020
B	.321	.071	-.086	.324	-.115	-.316	-.157	-.244	.271	.173	.338	.243	-.014
Zn	.323	.322	-.105	-.436	-.246	.180	.205	-.039	.287	.191	.240	-.098	-.144
Al	-.282	-.292	-.583*	-.699**	.392	.761**	.518*	.537*	-.338	-.513	-.489	-.572*	-.124
Fe	.098	.180	-.172	-.626*	-.070	.451	.197	.308	.076	-.034	.000	-.229	-.049

Values are Pearson's correlation coefficients for the soil chemical variables versus aggregate stability indices and microbial biomass carbon. MBC = Microbial biomass carbon, LM= Large macro-aggregates; SM = Small macro-aggregates; M = micro-aggregates; SC= silt and clay; MWD = Mean weight diameter; GMD= Geometric mean diameter; _5 and _15 = at 5 cm and 15 cm, respectively; POxC=Active carbon.

No significant correlation between soil chemical variables and microbial biomass carbon was evident in 2017 although some trends showed slight positive correlation coefficients with soil pH and Ca. However, in 2020, microbial biomass carbon positively correlated with total nitrogen, SOC and S (Table IV).

TABLE IV- RELATIONSHIP BETWEEN SOIL CHEMICAL PARAMETERS AND MICROBIAL BIOMASS CARBON IN 2020.

	BD	pH	N	SOC	P	K	Ca	Mg	Mn	S	Cu	B	Zn	Fe	MBC
BD	1	-.244	-.283	-.220	-.390	-.149	-.114	.038	.129	.518	.382	.009	-.378	.169	-.097
pH	-.244	1	.024	.087	.306	.300	.683**	.652**	.306	.123	.128	.018	.063	.354	.433
N	-.283	.024	1	.956**	.077	.016	-.271	-.274	-.024	-.666**	-.239	.072	.128	-.206	.567*
SOC	-.220	.087	.956**	1	.144	.150	-.134	-.122	.008	-.570*	-.226	.155	.169	-.219	.543*
P	-.390	.306	.077	.144	1	.407	.487	.058	-.548*	-.007	.165	-.082	.017	.112	.125
K	-.149	.300	.016	.150	.407	1	.634*	.493	-.160	.085	-.160	.376	-.027	-.177	-.084
Ca	-.114	.683**	-.271	-.134	.487	.634*	1	.770**	-.095	.304	.065	.444	-.162	-.045	.176
Mg	.038	.652**	-.274	-.122	.058	.493	.770**	1	.232	.182	-.286	.468	-.053	-.201	.072
Mn	.129	.306	-.024	.008	-.548*	-.160	-.095	.232	1	.103	-.095	-.013	.222	.291	.085
S	.518	.123	-.666**	-.570*	-.007	.085	.304	.182	.103	1	.712**	-.224	-.367	.484	-.539*
Cu	.382	.128	-.239	-.226	.165	-.160	.065	-.286	-.095	.712**	1	-.546*	-.157	.735**	-.083
B	.009	.018	.072	.155	-.082	.376	.444	.468	-.013	-.224	-.546*	1	-.248	-.701**	.356
Zn	-.378	.063	.128	.169	.017	-.027	-.162	-.053	.222	-.367	-.157	-.248	1	.025	.021
Fe	.169	.354	-.206	-.219	.112	-.177	-.045	-.201	.291	.484	.735**	-.701**	.025	1	-.083
MBC	-.097	.433	.567*	.543*	.125	-.084	.176	.072	.085	-.539*	-.083	.356	.021	-.083	1

Values are Pearson's correlation coefficients for the different soil chemical variables and microbial biomass carbon. BD = Bulk density; MBC = Microbial biomass carbon.

DISCUSSIONS

Microbes often assume active roles in aggregate formation and stabilization, and conditions aimed at promoting their growth and abundance also increase their activities, thus explaining the observed increase in aggregate stability indices and microbial biomass. Practicing reduced tillage can reduce the susceptibility of soil to erosion, increase microbial biomass and nutrient capacity of the soil. Increase in soil aggregation with corresponding increase in microbial biomass following residue retention is well-documented (Helgason *et al.,* 2010) and can be attributed to soil organic matter (SOM) accumulation (Chen *et al.,* 2015). Kihara *et al.* (2012) reported higher mean weight diameter (MWD) in reduced tillage systems and attributed this to the increased carbon stock with the associated minimal soil disturbance in the reduced tillage systems. Compared to conventional tillage, reduced tillage systems greatly promote organic carbon build-up, which alongside acting as substrate and source of energy for the microbes and creation of microhabitats (Hargreaves *et al.,* 2008) for microbial colonization; also produce organic compounds with soil aggregate cementing capabilities.

Soil aggregate stability and microbial biomass improved in the maize-soybean intercropping systems. This could be probably due to the characteristic higher microbial populations (Kihara *et al.,* 2012), intense and dense rooting network and increased plant density, together with increased quantities of high quality organic matter in the intercropped systems that promote soil aggregation. Besides, increased and continuous deposition of root exudates and high quality organic matter from the higher plant density in the intercropped systems probably provided more organic carbon and polysaccharides that increased aggregate binding alongside providing food and energy for microbes, thus enhancing microbial biomass carbon and activities like aggregation. Increased plant density in the intercropped systems could also increase aggregate binding via root enmeshment (Haynes *et al.,* 1991), exudates (Baldock and Kay, 1987) and residues (Latif *et al.,* 1992).

The findings in this study corroborate those previously reported in Oxisols of Brazil (Seidel *et al.,* 2017) following assessment of aggregate distribution under legume-cereal intercropping systems. This finding was attributed to the increased availability of organic matter that provided binding properties to the aggregates. Previous studies supporting the positive influence of soil organic matter on aggregation are well established (An *et al.,* 2010; Six and Paustian, 2014), adding to the possibility of organic matter influencing the soil structure and stability.

The positive correlation between soil pH, K and Mg to large macro-aggregates (at 15 cm) indirectly imply the positive influence of these soil chemical parameters on microbes whose activities ultimately influence aggregate stability. Increases in soil pH and other associated chemical properties often favor microbial proliferation (Bolo *et al.,* 2021). The positive influence of Calcium and Magnesium on aggregate stability indices like MWD and GMD are also attributed to improvement of soil pH that enhance soil microbial parameters. Aggregate formation and stabilization are some of the roles played by soil microbes, whose activities depend on favorable soil microclimate contributed by enabling soil conditions like favorable soil pH, nutrients among others. This corroborates previous observations in United Kingdom that suggested that microbial biomass and activity tended to stabilize at soil pH values ranging between 5 and 7 owing to the fact that at those pH ranges, the differences in organic carbon, total nitrogen as well as concentrations of aluminum (which is a major determinant of acidity) were very negligible (Pietri and Brooke, 2008). In our study however, although soil pH did not significantly affect microbial biomass carbon, there was positive indication of such trends.

CONCLUSION

Practicing reduced tillage combined with appropriate agronomic management, involving residue retention and proper cropping systems can increase soil aggregate stability and microbial biomass. Large macro-aggregates were improved with practicing intercropping and residue retention, pointing to improved soil aggregate stability. In addition, the improved aggregate stability indices like MWD and GMD under different agronomic management systems point to the possibility of increasing soil carbon stock/storage in such systems thereby enhancing carbon sequestration and its associated climate related benefits. These practices are not only beneficial in reducing the susceptibility of soil to erosion, but also minimizing nutrient losses, increasing microbial diversity and functions, as well as improving the soil health and nutrient availability.

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