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Agro-ecosystem, Tillage, and Cropping Effects on Extractable Soil Nitrogen and Organic Carbon in Ghana

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Abstract: Extractable soil nitrogen species and organic carbon from four agro-ecosystems in Ghana (coastal savannah, forest, transition and Guinea savannah) under three tillage (no-till, traditional till and zonal till) and four cropping treatments (maize, maize-cowpea rotation, maize-mucuna rotation and maize-cowpea-mucuna relay) or (maize, maize-cowpea rotation, maize-cowpea intercrop and cowpea-maize rotation) were examined. Soils were collected at 0-10 cm, 10-30 cm and 30-60 cm for analysis of baseline conditions prior to initiation of tillage and cropping treatments. Two years after treatments commenced, soils were collected from a depth of 15 cm, air dried and sieved to 2 mm prior to acid extraction and analyses of nitrate-N, ammonium-N, dissolved organic N (DON) and dissolved organic carbon (DOC). Within agro-ecosystems, cropping had a significant effect on DOC under zonal tilling in the forest, and on NO_3-N and NH_4-N under traditional tillage and NO_3-N under zonal tillage in the transition. In the Guinea savannah, cropping had a significant effect on DON under DON under traditional and zonal tillage. Tillage had a significant effect on DON and DOC in the forest, DOC in the transition and on NH_4-N and DON in the Guinea savannah agro-ecosystems. The data represent the second year after experimental treatments on the effects of tillage and cropping on soil nutrients in Ghana.

Key Words: Cropping, Extractable Soil Nutrients, Tillage, W. Africa

1. Introduction

In Sub-Saharan Africa agricultural production relies on the productivity of smallholder farms (Xinshen *et al*., 2007). Major constraints to farm productivity include soil degradation, land competition, and climate change (Xinshen *et al*., 2007). As in many rainfall scarce environments, soils in the semi-arid Sahelian zone are inherently low in soil organic carbon (SOC), nitrogen and phosphorus (Srinivasarao *et al*., 2012). In rural appraisals, an increasing number of African farmers indeed mention soil fertility decline as a major constraint to farming (Smaling *et al*., 2012). Therefore, a multi-pronged approach to improving Africa's food security must include practices that effectively improve local soil fertility.

Conservation agriculture (CA) in semi-arid West Africa is currently being promoted to mitigate the effect of droughts, increase crop productivity and reduce production costs (Lahmar *et al*., 2012). The CA approach relies on the simultaneous use of minimum (zonal) or no-tillage, maintenance of a permanent soil cover and a diversified, profitable crop rotation (Lahmar *et al*., 2012) Research has shown that soil organic matter (SOM), nutrients, pH, and texture signify good soil quality (Reeves, 1997). Soil organic carbon (SOC) is used as a measure of SOM because its chemical structure and surface properties influence soil structural stability and cation exchange capacity while also serving as an energy source for soil biota (Logah *et al*., 2011).

This research aimed to evaluate the effects of tillage and cropping on soil extractable carbon and nitrogen in four agro-ecological zones. Although the effects of tillage and cropping on soil fertility have been well researched, relatively few studies have been reported on African based research.

2. Materials and Methods

2.1. Descriptions of agro-ecosystems

The coastal savannah agro-ecosystem is situated in the Ga West district and Pokuase community. The soil is classified (World Reference Base for soil resources (WRB, 2006) as a Haplic Lixisol formed on granite and has a loamy-sand texture to 60 cm. The forest agro-ecosystem is in the Amansie West district within the Ahwerewa community. The soil is classified as a Leptic Lixisol formed on phyllite and has a silty-loam texture to 60 cm. The transition ecosystem is a forest-savannah transition situated in the Ejura-Sekodumase district within the Ejura-Adiembra community. The soil is classified as Leptic Lixisol formed on sandstone and has a loamy sand texture to 30 cm. The Guinea savannah agro-ecosystem is in the Tolon-Kumbungu district within the Kumbungu-Kuko community. The soil is classified as a Pisolithic Plinthosol formed on shalestone and has a silty loam

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texture to 60 cm.

Mean annual rainfall differs among the four agro-ecosystems. Coastal savannah has a mean annual rainfall of 800 mm, forest-1500 mm, forest-savannah transition-1300 mm and the Guinea savannah 1100 mm.

2.2. Experimental design

In each agro-ecosystem, a split plot design was implemented to test cropping × tillage and fertilizer amendments. This paper discusses the preliminary results for the cropping × tillage experiment. The main plots were 1) no till, 2) zonal or conservation tillage, and 3) traditional tillage. The sub-plots were either 1) maize (*Zea mays*) only, 2) maize - cowpea (*Vigna unguiculata*) rotation, 3) maize - mucuna (*Mucuna pruriens*) rotation, 4) maize - cowpea - mucuna relay or 5) cowpea - maize rotation and 6) maize - cowpea intercrop.

Soils were collected at 0-10 cm, 10-30 cm and 30-60 cm in 2011 prior to planting and the tillage and cropping treatments. Soils were analyzed for percent carbon and nitrogen and the C:N ratio was estimated.

2.3. Soil collection and processing

2.3.1. Experimental soil collection (2012 - Year 2)

Two years after the tillage and cropping treatments were initiated soils were collected for nutrient analyses. Soils were collected using a 2 cm diameter soil probe to a depth of 15 cm. Three soil cores were taken at each plot and bulked. Each sample was collected across the central row of the plot.

Soils were air-dried and larger peds gently broken down using a mortar and pestle prior to sieving to 2 mm. Soil samples (3.5 g) were dissolved in 35 g of 0.1 M HCl (1:10 soil:HCl ratio) and shaken for two hours at 500 rpm on a rotary shaker. Samples were then centrifuged for 15 minutes at 19,974 g-force and filtered using a Whatman GF/F filter (nominal pore size of 0.7 µm). Soil extracts were analyzed immediately after extraction.

2.3.2. Chemical analyses

DOC and total dissolved nitrogen (TDN) were measured using high temperature Pt-catalyzed combustion with a Shimadzu TOC-VCSH and Shimadzu total measuring unit TNM-1 (Shimadzu Corp. Houston, TX, USA). Ammonium-N was analyzed using the phenate hypochlorite method with sodium nitroprusside enhancement (USEPA method 350.1; USEPA 1993) and nitrate-N was analyzed using Cd-Cu reduction (USEPA method 353.2; USEPA 1997). Colorimetric methods were performed with a Smartchem Discrete Analyzer (Model 200 Westco Scientific Instruments Inc., Brookfield, CT, USA). Dissolved organic nitrogen was estimated by deducting NO_3-N plus NH_4-N from TDN. NIST

Table 1. Soil pH, carbon and nitrogen prior to tillage and cropping experiment.

Agroecosystem	Depth (cm)	pH	C (%)	N (%)	C:N
Coastal	0-10	6.2	0.40	0.04	10.00
	10-30	6	0.30	0.04	7.50
	30-60	5.9	0.10	0.02	5.00
Forest	0-10	6.3	2.50	0.2	12.50
	10-30	6.3	0.70	0.07	10.00
	30-60	5.6	0.70	0.07	10.00
Transition	0-10	4.8	0.35	0.03	11.70
	10-30	4.9	0.35	0.03	11.70
	30-60	4.7	0.29	0.02	14.50
Guinea Savannah	0-10	5.3	1.00	0.06	16.70
	10-30	5.3	0.60	0.04	15.00
	30-60	5.6	0.80	0.04	20.00

traceable standards, check standards, and water blanks were analyzed every 12th sample for instrument precision and accuracy.

2.3.3. Statistical analyses

Univariate analysis of variance was used to statistically analyze the data with $\alpha < 0.05$ to examine effects of agro-ecosystem, tillage and cropping across the whole dataset. Univariate analysis of variance was used to statistically analyze the effects of tillage, cropping and tillage × cropping interactions within each agroecosystem zone. Two-sample, 2-tailed *t*-tests ($\alpha < 0.05$) were used to examine significant differences resulting from tillage and cropping within each agro-ecosystem.

3. Results

3.1. Baseline soil nutrients

Results for composite soil samples collected prior to planting and initiation of tillage treatments indicated that soils in the coastal savannah and forest agro-ecosystems aremoderately to slightly acidic across the three depths, with pH ranges of 5.9 - 6.3 in the coastal savannah and 5.6 - 6.5 in the forest. Soils in the transition site were very acidic (pH 4.3 - 5.0), and those in the Guinea savanna site were acidic (pH 5.1 - 5.6). Soil percent C and N tended to decline with depth (**Table 1**).

Soil C:N ratios are important indicators of whether extractable nutrients might be transported to surface or ground waters. Soil C:N ratios ranged from 10.0 to 5.0 in the coastal savannah indicating a larger soil pool ofeN at 30-60 cm depth compared to 0-10 cm depth. In the forest soil C:N ratio ranged from 12.0 to 10.0 illustrating a steady C:N ratio with depth. The transition zone had a soil C:N ratio of 11.7 to 14.0 and the Guinea savannah a C:N ratio of 16.7 to 20.0.

Table 2. Soil nitrogen species and DOC in the Coastal Savannah agro-ecosystem. ± = standard deviation.

Till	Crop	NO_3-N	NH_4-N	DON	DOC
			mg kg^{-1}		
None	M	19.8±16.1	7.2±2.5	6.2±5.4	56.0±7.9
None	MC	10.9±0.6	5.8±0.9	6.3±5.6	58.8±8.8
None	MM	10.8±3.6	7.0±2.4	6.4±5.7	53.9±6.4
None	MCM	9.9±2.8	6.1±1.5	7.8±5.5	53.0±6.4
Trad	M	10.6±1.8	7.2±0.7	10.2±1.8	74.9±14.6
Trad	MC	12.8±3.0	5.7±1.1	5.9±5.2	49.6±9.4
Trad	MM	9.9±1.1	6.6±0.1	5.7±5.0	51.1±3.0
Trad	MCM	9.9±1.1	6.7±0.1	8.0±3.9	63.6±30.2
Zonal	M	11.3±3.0	6.5±1.4	8.2±2.6	52.7±3.6
Zonal	MC	12.7±2.0	6.7±1.4	5.0±2.8	48.9±6.4
Zonal	MM	10.2±1.8	5.6±0.7	5.7±4.9	51.3±7.5
Zonal	MCM	10.1±1.2	5.8±0.9	12.0±3.7	62.0±6.2

M = sole Maize; MC = Maize-Cowpea rotation; MM = Maize Mucuna rotation and MCM = Maize-Cowpea-Mucuna relay.

Table 3. Soil nitrogen species in the Forest agro-ecosystem. ± = standard deviation. Differences in superscript lowercase letters (ab) within each tillage groups shows significant effect of cropping at α<0.05. Differences in superscript letters (xz) within cropping groups shows a significant effect of tillage at α<0.05.

Till	Crop	NO_3-N	NH_4-N	DON	DOC
			mg kg^{-1}		
None	M	8.6±2.8	10.4±3.9	22.2±2.3	^{x}113.9±9.6
None	MC	9.2±2.2	8.9±2.7	17.0±2.9	90.0±20.2
None	MM	12.7±5.1	8.2±4.0	21.5±15.5	99.1±9.0
None	MCM	9.3±3.6	9.8±5.7	18.0±4.2	126.9±72.4
Trad	M	14.7±4.5	8.7±4.9	14.9±12.7	^{y}89.1±8.6
Trad	MC	13.0±2.4	12.5±7.0	17.9±1.7	87.2±28.3
Trad	MM	9.8±2.6	8.4±3.8	^{x}15.8±2.9	82.5±15.5
Trad	MCM	11.0±2.4	10.4±5.4	20.2±8.8	80.3±17.2
Zonal	M	12.2±6.5	10.4±5.2	15.9±10.5	^{ay}89.2±3.4
Zonal	MC	11.8±2.5	11.8±4.8	17.9±13.1	106.6±21.7
Zonal	MM	14.2±4.0	14.6±2.3	^{y}26.6±3.1	^{b}113.5±6.8
Zonal	MCM	8.6±2.6	9.0±4.0	20.2±2.5	101.9±17.3

M = sole Maize; MC = Maize-Cowpea rotation; MM = Maize Mucuna rotation and MCM = Maize-Cowpea-Mucuna relay.

3.2. Effect of agro-ecosystem on soil N and C

Location, or agro-ecosystem, had a significant effect on soil nitrogen species and DOC. The Guinea savannah had significantly higher extractable nitrate-N (16.8 ± 3.0 mg kg^{-1}) and the forest-savannah transition significantly lower nitrate-N (3.3 ± 0.5 mg kg^{-1}) compared to the coastal savannah (11.6 ± 2.8 mg kg^{-1}) and forest (11.3 ± 2.1 mg kg^{-1}) agro-ecosystems.

Extractable ammonium-N was significantly higher (10.3 ± 1.9 mg kg^{-1}) in the forest compared to the other three agro-ecosystems (range 6.3 ± 1.2 to 6.8 ± 0.9 mg kg^{-1}). The forest also had significantly higher DON (19 ± 3 mg kg^{-1}) and the Guinea savannah significantly lower DON (5.2 ± 3 mg kg^{-1}) compared to the forest-savannah transition. Extractable DOC in the forest soil was significantly higher (98 ± 14 mg kg^{-1}) than in the other three agro-ecosystem soils (range 50 ± 7 to 56 ± 7 mg kg^{-1}).

Table 4. Soil nitrogen species and DOC in the Transition agro-ecosystem. ± = standard deviation. Differences in superscript lowercase letters (ab) within each tillage groups shows significant effect of cropping at α<0.05. Differences in superscript letters (xy) within cropping groups shows a significant effect of tillage at α<0.05.

Till	Crop	NO_3-N	NH_4-N	DON	DOC
			mg kg^{-1}		
None	M	3.6±0.9	6.2±2.0	10.2±8.1	56.1±6.3
None	MC	2.9±0.4	4.9±0.3	6.0±9.5	55.7±8.4
None	MM	3.7±0.5	8.3±3.8	23.8±9.4	^{x}67.4±5.0
None	MCM	3.7±0.9	6.7±3.8	4.0±6.9	54.5±13.2
Trad	M	^{a}3.8±0.4	5.6±1.6	10.8±9.3	46.9±6.9
Trad	MC	^{b}2.6±0.1	^{a}4.9±0.2	11.2±9.7	53.7±11.1
Trad	MM	3.9±2.1	^{b}5.7±0.2	10.9±9.5	^{y}49.8±5.0
Trad	MCM	3.0±0.3	^{a}4.3±0.5	5.3±9.3	42.0±11.3
Zonal	M	^{a}3.9±0.4	7.7±4.8	5.6±8.1	47.9±6.1
Zonal	MC	^{b}2.8±0.4	6.6±2.6	17.3±18.2	51.3±13.4
Zonal	MM	^{b}2.9±0.3	7.4±3.5	5.4±8.2	^{y}44.5±3.7
Zonal	MCM	^{b}2.8±0.3	6.8±3.2	13.0±10.7	49.5±7.7

M = sole Maize; MC = Maize-Cowpea rotation; MM = Maize Mucuna rotation and MCM = Maize-Cowpea-Mucuna relay.

Table 5. Soil nitrogen species in the Guinea Savannah agro-ecosystem. ± = standard deviation. Differences in superscript lowercase letters (ab) within each tillage groups shows significant effect of cropping at α<0.05. Differences in superscript letters (xz) within cropping groups shows a significant effect of tillage at α<0.05.

Till	Crop	NO_3-N	NH_4-N	DON	DOC
			mg kg^{-1}		
None	M	14.4±5.0	6.2±1.1	^{x}5.5±2.7	43.5±9.0
None	MC	17.9±7.8	7.1±1.0	^{x}5.5±4.9	51.7±8.2
None	MCI	22.0±6.0	6.6±1.4	2.3±4.0	46.2±9.5
None	CM	20.9±12.8	^{x}6.7±0.5	^{x}2.3±4.0	52.3±16.2
Trad	M	20.5±7.9	6.4±1.4	^{ay}0±0	44.2±8.5
Trad	MC	13.4±5.3	7.5±1.6	^{b}6.1±5.0	44.3±15.2
Trad	MCI	14.4±7.6	5.8±1.6	^{b}8.9±0.5	48.5±9.3
Trad	CM	14.3±4.9	7.0±1.2	^{b}8.5±2.3	63.0±8.9
Zonal	M	16.9±11.4	5.8±0.6	^{x}4.3±4.1	46.0±10.8
Zonal	MC	13.2±1.6	7.5±2.4	^{ay}2.6±2.3	45.7±10.9
Zonal	MCI	17.5±3.1	8.7±3.2	6.7±2.8	65.7±40.2
Zonal	CM	16.7±6.4	^{y}5.8±0.2	^{by}9.3±1.2	55.0±12.4

M = sole Maize; MC = Maize-Cowpea rotation; MCI = Maize-Cowpea intercrop and CM = Cowpea-Maize rotation.

3.3. Effect of tillage on soil N and C

There was no effect of tillage on extractable soil N and C in the coastal savannah (**Table 2**). Tillage had a significant effect on extractable soil nutrients in the forest, forest-savannah transition and Guinea savannah agro-ecosystems two years after tillage treatments were initiated but only for specific cropping treatments (**Tables 3, 4** and **5**). In the forest, zonal tillage significantly increased DON in the maize-mucuna rotation relative to the traditional tillage and no-till significantly increased DOC in the maize only relative to the traditional tillage (Table 3). In the forest-savannah transition, no-till significantly increased extractable DOC compared to traditional tillage in the maize-mucuna rotations (Table 4).

In the Guinea savannah agro-ecosystem, no-till significantly increased extractable ammonium-N in the cowpea-maize rotation compared to soil ammonium-N under zonal tillage (Table 5). Extractable DON was also significantly affected by tillage in the Guinea savannah under maize only cropping (Table 5). No-till significantly increased the concentration of DON under maize-cowpea rotation compared to zonal tillage. Zonal tillage had significantly higher DON under cowpea-maize rotation compared to no-till under cowpea-maize rotation (Table 5). Tillage had no significant effect on extractable soil nitrate-N or DOC in the Guinea savannah (Table 5).

3.4. Effect of cropping on soil N and C

The type of crop grown appeared to have a greater effect on soil N and C dynamics than tillage, but that often depended upon the type of tillage being practiced. There were no significant effects of cropping in the coastal savannah (Table 2). Under zonal tillage in the forest agro-ecosystem, extractable DOC was significantly higher under the maize-mucuna rotation (113.5 ± 6.8 mg kg^{-1}) compared to maize only (89.2 ± 3.4 mg kg^{-1}; Table 3).

The forest-savannah transition also experienced significanteffects of cropping. Under traditional tillage, the soil beneath maize only exhibited significantly higher soil nitrate-N concentrations (3.8 ± 0.4 mg kg^{-1}) compared to the maize-cowpea rotation (2.6 ± 0.1 mg kg^{-1}). Similarly under zonal tillage, maize only had significantly higher nitrate-N compared with the other cropping treatments. Ammonium-N was significantly higher in the maize-mucuna rotation compared to maize only and maize-cowpea-mucuna relay under traditional tillage (Table 4). Only DON was significantly affected by cropping in the Guinea savannah. Under traditional tillage DON was significantly under all cropping treatments compared to maize only crops (Table 5).

4. Discussion

Soil C:N ratios from different biomes have a very large range (Aitkenhead and McDowell, 2000). Across Ghana, the upper soil horizon C:N ratio was relatively low compared to other biomes found around the world. It can be expected that tillage and cropping will have an effect on soil nitrogen and carbon. As an example, tillage aerates the soil, which is needed for nitrification. The aeration induced by tillage will also benefit soil heterotrophs to utilize and mineralize carbon whereas no-till benefits carbon sequestration (Gonzalez -Chavez *et al.*, 2010). Therefore, it is expected that under traditional tillage nitrate should be high and DOC low. No-till on the other hand has been shown to increase soil carbon content (Gonzalez-Chavez *et al.*, 2010). This expectation for nitrate-N was not met in a 27 year study in Texas where higher extractable nitrate-N was found under no-till and rotational wheat compared to conventional tillage and rotational wheat (Carrillo-Gonzalez *et al.*, 2013). This is further supported by a five-year study in Western Nigeria comparing no-till plots to ones prepared under conventional tractor plowing. The study found that the no-till plots had a higher organic matter content in the surface soil horizons and higher concentrations of nitrate-nitrogen, Bray-1 available phosphorus, and ammonium acetate extractable cations such as Ca^{2+}, Mg^{2+} and K^{+} than the plowed plots (Lal, 1976).

Soil extract concentrations can be different depending upon the type of extracting agent used (Carrillo-Gonzalez *et al.*, 2013). This can be a challenge when trying to compare one's results with those of other studies. For soils under a long-term tillage and cropping experiments in Texas examining DOC, DON, nitrate-N and ammonium-N, cold water extraction of soil best simulated DOC observed in soil leachate (Carrillo-Gonzalez *et al.*, 2013). Concentrations of DOC under coastal savannah, transition and Guinea savannah were much lower under no till (range: 44-127 mg kg^{-1}) than observed in soil water extracts of a silty clay loam after 27 years of no-till and continuous wheat (116-272 mg kg^{-1}) and no-till with a sorghum, wheat, soybean rotation wheat (133-290 mg kg^{-1}) in Texas, USA (Carrillo-Gonzalez *et al.*, 2013). The difference in extractable DOC may be due to a difference in %C in the two locations; in Texas %C ranged from 0.9% (conventional tillage) to 1.6% (no-till) and in Ghana savannah %C ranged from 0.4-1.0% prior to tillage and cropping treatments.

Dissolved organic nitrogen concentrations were similar in our study (no-till: 2-24 mg kg^{-1}; traditional tillage: 0-20 mg kg^{-1}) compared to the long-term Texas study where DON ranged from 4.0 to 32.6 mg kg^{-1} under no-till and 2.4 to 18.0 mg kg^{-1} under conventional tillage (Carrillo-Gonzalez *et al.*, 2013). Nitrate-N concentrations in our study (8.6-20.9 mg kg^{-1}) were similar to those reported in the Carrillo-Gonzalez (2013) study (10-30 mg kg^{-1}) for all of our agro-ecosystems except the transition zone where the nitrate-N concentrations were lower. This suggests that after 27 years of no-till and rotational cropping that nitrate-N concentrations and potential for leaching will likely remain high in our plots. Ammonium-N concentrations tended to be higher in our study (5-15 mg kg^{-1}) compared to the concentrations in the Texas study which had water extractable ammonium-N concentrations ranging from 3.0-4.0 mg kg^{-1} (Carrillo -Gonzalez *et al*., 2013).

Glomalin related proteins are important for soil aggregate formation and tend to be much higher under no-till relative to conventional tillage (Gonzalez-Chavez *et al*., 2010). These should perhaps be an additional measure of soil quality in future research to monitor potential for soil erosion.

Based on our results it was evident that the different agro-ecosystems had significantly different nitrogen species and organic carbon across all tilling and cropping treatments. This suggests that a blanket directive of tillage and cropping practices across all the agro-ecosystems in Ghana should not be in place. Instead, tailored recommendations for tillage and cropping practices for each agro-ecosystem would likely be a better option to maintain soil fertility and improve food security based on our results.

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