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SOIL FERTILITY AND CROP NUTRITION

Crop–Livestock Interaction Effect on Soil Quality and Maize Yield in Northern Ghana

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ABSTRACT

Keeping livestock overnight on fallow arable lands (Corralling) is a traditional method of soil fertility amendment in West Africa. However, there is limited quantitative data on the interaction effects of stocking density of sheep and goats corralling (SDSG), maize plant density (MPD) and nitrogen fertilizer rate (NFR) on soil quality and yield of maize. A 2-yr study was conducted to determine the interaction effects of three SDSG (0, 70, and 140 head ha^{-1}), three MPD (66,667, 100,000, and 133,333 plants ha^{-1}) and three NFR (0, 60, and 90 kg ha^{-1} N) on soil quality index (SQI) and maize yield in northern Ghana. The study was conducted using a split-split plot experiment replicated on eight farms. An adult sheep or goat was corralled in an area of 4 m^2 and 1 m^2 for the 70 and 140 head ha^{-1} SDSG respectively for five nights during the dry seasons of 2014 and 2015 cropping seasons. Principal component and correlation matrix analysis were used to select minimum data set for SQI. The SQI for sheep and goats corralling increased by 51% compared with the control. The SDSG×MPD, SDSG×NFR and MPD×NFR interactions were significant on maize grain and biomass yields. The results suggest that, small-scale maize-livestock farmers could use either SDSG of 70 head ha^{-1} with 90 kg ha^{-1} NFR or SDSG of 140 head ha^{-1} with 60 kg ha^{-1} NFR and MPD at 133,333 plants ha^{-1} to increase grain yield on Ferric lixisols in northern Ghana and similar ecologies in West Africa.

Core Ideas

- Soil chemical and biological sub-indices increased with sheep and goats corralling.
- Soil physical sub-quality index declined with sheep and goats corralling.
- Sheep and goats corralling increased soil quality index of fallow arable lands.
- Interactions of sheep and goats corralling, plant density and nitrogen fertilizer increased maize yield in northern Ghana.

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Maize is among the most important food security crops in the world, cultivated for both human and animal consumption (Lana et al., 2017). Manyong et al. (2000) reported that, maize production accounts for slightly over 20% of gross domestic production in West African sub-region. However, maize yield on farmers' field is low due to several socio–economic and biophysical constraints, including low and declining soil fertility and poor agronomic practices such as low plant densities on farmers' fields. There are conflicting results on the effect of plant density on the yield of maize as some authors have reported higher yields with increasing density (Bavec and Bavec, 2002; Adeniyan, 2014) while Shapiro and Wortmann (2006) found no significant effect with increasing density and these conflicting results have renewed the interest for further studies.

Most farmers apply manure to croplands either by gathering manure from stalls or by holding their animals overnight on fallow fields between cropping seasons (corralling) as means of soil fertility amendments in small-scale crop–livestock systems (Powell, 2014). Corralling returns both manure and urine to soil which improves the soil chemical properties, requires less labor for manure handling, storage, and spreading, and reduces N loss by 40 to 60% (Defoer et al., 2000; Ikpe and Powell, 2002; Sangaré et al., 2002; Powell et al., 2004). Consequently, corralling results in greater crop yields than when only manure is collected from the stall and applied on arable land (Powell, 2014). According to Liniger et al. (2011), corralling an adult sheep or goat in an area of 4 m^2 for five nights deposit 1 kg of manure dry matter and to produce 2.5 t ha^{-1} of manure would require 70 head of sheep or goats for 178 nights of corralling. In Sudan, a savanna zone of Ghana, the average farm size is 0.6 ha with majority (87%) of farmers holding less than 1 ha of farm size while the average sheep and goats' production in the zone are 179,819 and 168,523 heads respectively (Karbo and Agyare, 2002; Amanor-Boadu et al., 2015).

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Abbreviations: 2RD, double the recommended density; AP, available phosphorus; EK, exchangeable potassium; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; MPD, maize plant density; NFR, nitrogen fertilizer rate; OC, organic carbon; PC, principal components; SDSG, stocking density of sheep and goats corralling; SMQ, soil microbial quotient; TN, total nitrogen.

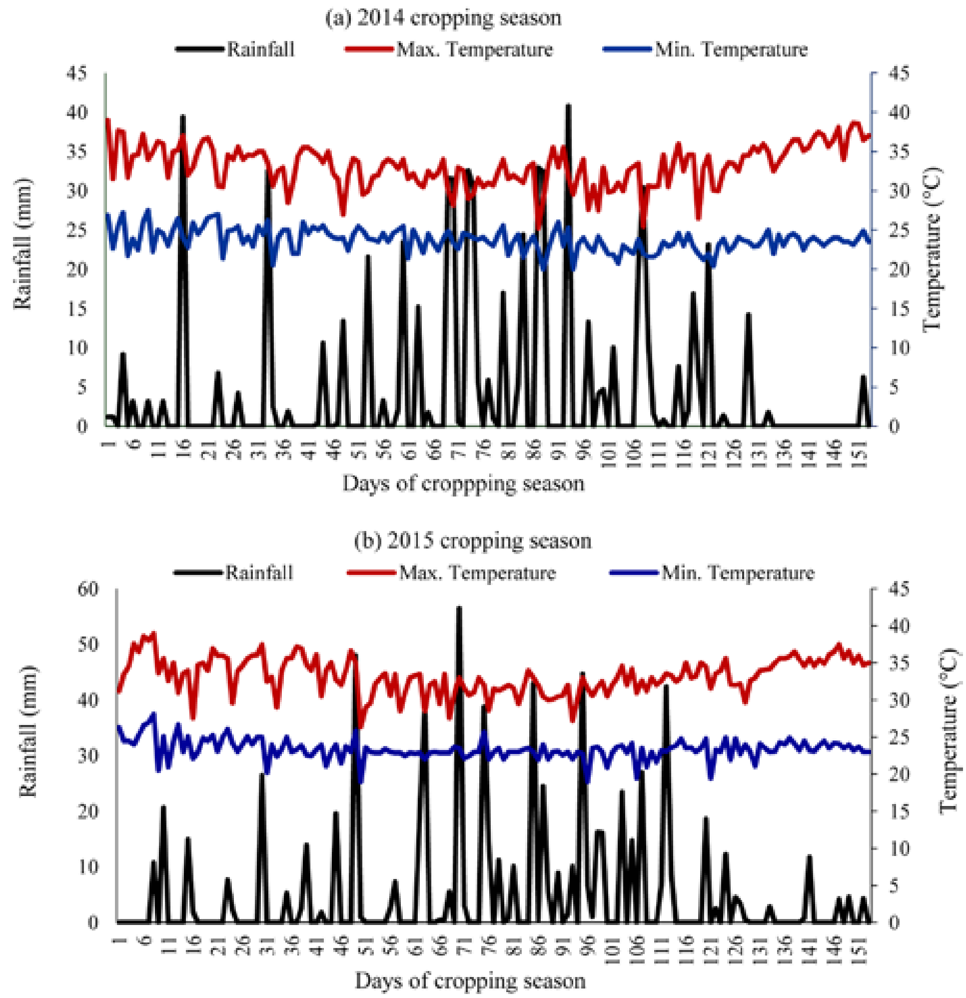

Fig. 1. Daily rainfall and temperature at Navrongo, Ghana, during June to October of 2014 and 2015 cropping seasons in Sudan savanna zone of northern Ghana (Navrongo Meteorological Agency Agro-Station, 2015).

Soil quality is the capacity of a soil to function within the natural or managed ecosystem boundaries to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation (Karlen et al., 1997). Measuring soil quality requires an accurate and systematic method for measuring and interpretation of soil properties that adequately serve as soil quality indicators. Soil quality indexing involves three main steps: (i) choosing an appropriate indicator for a minimum data set; (ii) transforming indicators into scores; and (iii) integration of indicators into the index (Andrews et al., 2002). Several methods for selecting indicators for minimum data set have been reported which involve expert opinion, principal component analysis, and multiple correlation analysis (Andrews et al., 2002). The scoring of indicators can also be done by either linear scoring or nonlinear scoring (Andrews et al., 2002). Integration of scores also involves additive, weighted additive, decision support system (Andrews et al., 2002), and the area of the triangle (Kang et al., 2005).

Previous studies on livestock corralling covered only soil chemical and physical properties with little or no data on the effect of corralling density on soil biological properties and quality index in the literature (Ikpe and Powell, 2002; Sangaré et al., 2002; Powell et al., 2004). Several studies have reported an increase in maize grain yield with application of nitrogen fertilizer (Sigunga et al., 2002; Abdul Rahman et al., 2015; Blanchet et al., 2016). However, there is limited information on the interaction effects of livestock corralling, maize plant density, and mineral fertilizer application on crop yields. Thus, there is the need for a more comprehensive quantitative data on the effect of stocking density of sheep and goat corralling (SDSG) on soil quality index of fallow arable lands and the interaction of SDSG, maize plant density (MPD), and nitrogen fertilizer rate (NFR) on grain yield under on-farm conditions. Such information will bridge the knowledge gap on corralling and unearth its full potentials as a soil fertility amendment practice by small-scale crop-livestock farmers. We hypothesized that the number of animals kept per unit area of fallow land overnight (corralling density) would not affect the soil quality index and the interactions of SDSG, MPD, and NFR would not affect maize grain yield.

MATERIALS AND METHODS

Study Site

The study was conducted on-farm in the Kasena-Nankana District of Sudan savanna zone of Ghana (10°30′11″ N; 0°1′30″ W; 300 m above sea level). The total amount of rainfall received during the 2014 and 2015 were 669.6 and 760.5 mm respectively (Fig. 1). The mean minimum and maximum temperatures were 23.7–33.2°C for the 2014 cropping season and 23.4–33.2°C for the 2015 cropping season (Fig. 1). The soil at the study site was a Ferric lixisols (IUSS Working Group WRB, 2015) with sandy loam to loamy sand texture, total nitrogen levels of 0.2 to 0.9 g kg^{-1}, available phosphorus levels of 0 to 8 mg kg^{-1} and organic matter of less than 20 g kg^{-1} (Tetteh et al., 2016).

Experimental Design

The study was conducted on the same field of land during 2014 and 2015 cropping seasons using a split-split plot experiment with all the treatments replicated on eight farms. The main plots were three SDSG (0, 70, and 140 head ha^{-1}) with a plot size of 263.5 m^2. The SDSG were selected to produce 2.5 t ha^{-1} and 5 t ha^{-1} of manure over the 178 nights of corralling based on the recommendations of Liniger et al. (2011). The sub plots were three MPD (66,667, 100,000, and 133,333 ha^{-1}) with a plot size of 67.5 m^2 and the sub-sub plots were three NFR (0–40–40, 60–40–40, and 90–40–40 NPK kg ha^{-1}) with a plot size of 22.5 m^2. The MPD were selected based on the recommended planting density for maize in Ghana and increasing it by 50 and 100% (Ragasa et al., 2013). The NFR were also selected based on the recommended NPK fertilizer application for maize in Ghana (Ragasa et al., 2013).

Corralling Management

Djallonke sheep and West African dwarf goat breeds belonging to the participating farmers were used for the study during both seasons. The farmers were selected based on their resource endowment (number of animals) and commitment of farmers toward communal activities. The flocks per household consisted of 55% sheep and 45% goats in both seasons. Average body weight of 27 ± 2.0 kg for adult Djallonke sheep and 24 ± 1.5 kg for West Africa Dwarf goat, i.e., an average body weight of 25.5 kg $head^{-1}$ were selected for the study. A head of animal was tethered in an area of 4 m^2 and 1 m^2 for the 70 and 140 head ha^{-1} SDSG respectively from 1900 to 0600 h GMT for five nights before moving to a new spot within the treatment plot to ensure uniform application of manure (Liniger et al., 2011). The animals were corralled during the dry season of 2014 and 2015 cropping seasons with no feed and water. The experimental fields were fenced to ensure that the animals stayed within the treatment plots.

Manure and Soil Analysis

Four sheep and goats were randomly sampled from each of the eight farms for manure collection with fecal matter collection bags after corralling the animals for 178 nights in both seasons. The manure samples were air dried, ground, and analyzed for total organic carbon (Nelson and Sommers, 1982), nitrogen (Bremner and Mulvaney, 1982), phosphorus (Bray and Kurtz, 1945), potassium (Thomas, 1982), lignin, and polyphenol (Anderson and Ingram, 1993).

After corralling the animals for 178 nights in each cropping season, composite surface soil (0–15 cm depth) samples were taken at five different spots along the diagonals of each plot. The composite soil samples were air dried, ground, sieved, and analyzed for pH (1:1 H_2O/soil), total nitrogen (TN) (Bremner and Mulvaney, 1982), available phosphorus (AP) (Bray and Kurtz, 1945), exchangeable potassium (EK) (Thomas, 1982), organic carbon (OC) (Nelson and Sommers, 1982), microbial biomass carbon (MBC), and nitrogen (MBN) (Anderson and Ingram, 1993). The soil microbial quotient (SMQ) was calculated as the ratio of MBC and OC (Li et al., 2011; Paz-Ferreiro and Fu, 2016). A galvanized iron cores of 4.5 cm inner diameter and 25 cm high were used to take six core samples along the diagonals of each treatment plot to measure soil bulk density, porosity and moisture content using standard procedures of Anderson and Ingram (1993). A quadrat of 0.25 m^2 was placed eight times at random in each treatment plot to count the number of earthworm cast in each quadrat.

Soil Quality Index Estimation

Soil quality index was measured using three main steps which involved (i) selection of minimum data set, (ii) transformation of minimum data set indicators into scores (Andrews et al., 2002), and (iii) integration of these scored indicators into index (Kang et al., 2005). Principal component and correlation matrix analysis was used to select minimum data set from the total data set (Andrews et al., 2002). Principal components (PC) with eigenvalues greater than or equal to 1 were considered to explain the total variability. Under a PC, soil indicators with absolute figures of 10% of the highest factor loading were selected as minimum data set. When more soil indicators are selected under a PC, multivariate correlation analysis was used to decide whether an indicator may be considered redundant and removed or significant and retained in the minimum data set. Correlation coefficient of 0.60 and above among selected variables was considered best fitted and less than 0.60 considered non-best fit. The variable with the highest loading factor was selected for minimum data set among the correlated variables. A linear scoring function of more is better or less is better approach was used to transform selected indicators into scores (Andrews et al., 2002). Scored values ranged from 0 to 1 with 0 as the least and 1 as the highest indicator strength. Transformed values of indicators were integrated into soil quality index using the area of triangle with chemical, biological, and physical sub-indices of soil at the three vertices (Kang et al., 2005).

Crop and Fertilizer Management

After corralling the animals for 178 nights, the farmlands were plowed with bullocks to form ridges at 75 cm apart in line with the farmer practice in the area. Early maturing maize variety (Omankwa: 95 d maturity) was planted as a test crop, because it is drought tolerant, Striga (*Striga hermontica*) resistant, and a high-quality protein maize (Ragasa et al., 2013). The maize was planted at three population densities: 66,667 plants ha^{-1} (75 × 40 cm^2 with two plants $hill^{-1}$), 100,000 plants ha^{-1} (75 × 40 cm^2 with three plants $hill^{-1}$), and 133,333 plants ha^{-1} (75 × 20 cm^2 with two plants $hill^{-1}$). The maize plants were planted from 28 June to 5 July in 2014 cropping season while in 2015 cropping season, the maize plants were planted from 6 to 11 July.

The NFR was applied at 10 d after planting with N P_2O_5 K_2O (15:15:15) fertilizer at 40 kg ha^{-1}. The control plots were also applied with triple superphosphate and muriate of potash at 40 kg ha^{-1} P_2O_5 and K_2O, respectively. The remaining N rates were top dressed with sulfate of ammonia fertilizer twenty-one days after the first application at 20 and 50 kg ha^{-1} N. Weeds were controlled manually with hoe at 2 and 5 wk after planting.

Measurement of Yield

The maize cobs from plants in the two middle rows of each sub-sub plots (7.5 m^2) were harvested at physiological maturity,

Table 1. Soil properties as affected by stocking density of sheep and goats corralling (SDSG) in Sudan savanna zone of northern Ghana, 2014 and 2015 cropping seasons.

	SDSG (head ha^{-1})					Contrast probability of F value	
Soil properties	0	70	140	SEM†	*p*-value	0 vs. (70 + 140)	70 vs. 140
2014 Cropping season							
Chemical							
pH (1:1, H_2O)	5.1	5.4	5.5	0.05	***	***	ns‡
OC (g kg^{-1})	7.3	12.3	14.9	0.69	***	***	*
Total N (g kg^{-1})	0.4	0.5	0.6	0.02	**	***	ns
Available P (mg kg^{-1})	2.0	2.8	2.8	0.21	*	**	ns
Exchangeable K (cmol kg^{-1}) × 10^{-2}	4.3	9.3	11.8	0.91	**	***	ns
Biological							
Microbial biomass carbon (g kg^{-1})	241.9	328.9	352.5	14.27	**	***	ns
Microbial biomass nitrogen (g kg^{-1})	18.7	21.8	21.2	0.80	*	**	ns
Soil microbial quotient (%)	2.7	3.1	3.1	0.08	**	**	ns
Earthworm cast (0.25 m^{-2})	9.3	16.5	20.7	1.13	***	***	*
Physical							
Bulk density (g cm^{-3})	1.4	1.6	1.7	0.02	***	***	***
Porosity	0.5	0.4	0.4	0.01	***	***	***
Moisture ($cm^3 cm^{-3}$) × 10^{-2}	2.4	2.8	2.4	0.38	ns	ns	ns
2015 Cropping season							
Chemical							
pH (1:1, H_2O)	5.4	5.8	5.8	0.12	*	*	ns
OC (g kg^{-1})	9.3	15.4	18.2	0.44	***	***	**
Total N (g kg^{-1})	0.6	0.8	0.9	0.05	**	**	ns
Available P (mg kg^{-1})	2.5	3.8	3.4	0.26	**	**	ns
Exchangeable K (cmol kg^{-1}) × 10^{-2}	5.1	20.8	24.9	3.17	**	**	ns
Biological							
Microbial biomass carbon (g kg^{-1})	260	358.7	384.8	10.8	***	***	ns
Microbial biomass nitrogen (g kg^{-1})	22.9	26.3	26.9	0.52	**	***	ns
Soil microbial quotient (%)	2.5	2.9	2.8	0.07	**	**	ns
Earthworm cast (0.25 m^{-2})	8.8	14.9	20.2	0.57	***	***	***
Physical							
Bulk density (g cm^{-3})	1.5	1.6	1.7	0.01	***	***	***
Porosity	0.4	0.4	0.3	0	***	***	***
Moisture ($cm^3 cm^{-3}$) × 10^{-2}	2.8	2.4	2.3	0.27	ns	ns	ns

† SEM, standard error of mean.
‡ ns, $p > 0.05$.
* $p \leq 0.05$.
** $p \leq 0.01$.
*** $p \leq 0.001$.

dehusked, shelled, and oven dried at 65°C to a moisture content of 13% to measure grain yield. The two middle row plants from which the cobs were harvested were also cut at ground level and oven dried at 65°C to constant weight to measure stover weight. The grain and stover yield were summed to measure aboveground biomass yield.

Statistical Analysis

General Linear Model procedures of the Statistical Analysis System for windows software was used to analyze the data on seasonal basis (SAS Institute, 2011). The soil data were taken across the main plots after corralling of sheep and goats, therefore the soil data were analyzed using randomized complete block design. The yield data was analyzed in a split-split plot design. Orthogonal contrast was used to separate means of significant difference at a probability level of 0.05.

RESULTS

Manure Quality and Soil Properties

The chemical composition of the manure varied among the farms. The average values were: total organic carbon (178.1 ± 3.5 g kg^{-1}), total nitrogen (18.6 ± 0.6 g kg^{-1}), total phosphorus (3.5 ± 1.0 g kg^{-1}), total potassium (5.9 ± 3.0 g kg^{-1}), polyphenol (57.8 ± 14.2 g kg^{-1}), lignin (105.5 ± 24.5 g kg^{-1}) and C/N ratio (9.5 ± 1.7).

Table 1 shows the effect of SDSG on soil chemical, biological, and physical properties. Soil chemical properties generally increased with sheep and goats corralling relative to the control in both cropping seasons. Increasing SDSG from 70 to 140 head ha^{-1} significantly increased soil organic carbon in both cropping seasons.

Generally, the soil biological properties for SDSG at 70 and 140 head ha^{-1} increased ($p < 0.01$) compared with the control. Similarly, the earthworm cast for SDSG at 140 head ha^{-1} was

Table 2. Eigenvectors of principal components analysis for selecting soil quality indicators under stocking density of sheep and goats corralling in Sudan savanna zone of northern Ghana, 2014 and 2015 cropping seasons.

	2014 season				2015 season			
Principal component	PC1	PC2	PC3	PC4	PC1	PC2	PC3	PC4
Eigenvalue	5.6	1.9	1.3	1.0	5.7	1.6	1.2	1.0
Percent of variance	46.5	15.4	10.5	8.4	47.64	13.09	9.63	8.08
Cumulative percent	46.5	61.9	72.4	80.8	47.64	60.73	70.36	78.44
Eigenvectors†								
pH	0.309	–0.332	0.212	–0.135	0.210	–0.166	0.310	**0.370**
Organic carbon	0.332	–0.223	0.075	**–0.367**	**0.372**	–0.096	–0.012	–0.270
Total nitrogen	**0.355**	–0.290	0.102	0.121	0.252	0.314	**0.360**	**–0.487**
Available phosphorus	0.262	–0.096	–0.163	**0.528**	0.210	–0.339	0.318	**0.372**
Exchangeable potassium	0.345	–0.111	–0.281	0.113	0.312	–0.172	**0.401**	0.181
Microbial biomass carbon	0.323	0.188	0.211	–0.320	0.344	0.095	0.081	–0.111
Microbial biomass nitrogen	0.168	–0.135	**0.680**	0.226	0.274	–0.312	**–0.456**	0.126
Soil microbial quotient	0.135	**0.609**	0.114	0.129	0.192	**0.430**	–0.242	**0.382**
Earthworm cast	0.264	0.349	–0.043	**–0.491**	0.314	0.296	0.152	–0.095
Bulk density	**0.361**	0.187	–0.239	0.176	**0.366**	0.085	–0.329	0.034
Porosity	**–0.360**	–0.180	0.236	–0.162	**–0.369**	–0.084	0.301	–0.031
Moisture	–0.004	0.348	**0.445**	0.268	–0.119	**0.571**	0.135	**0.444**

† Bold eigenvectors correspond to the indicators included in the minimum data set.

higher ($p < 0.05$) than that of 70 head ha^{-1} in both cropping seasons.

The soil bulk density increased linearly, while porosity declined significantly with increasing SDSG from 0 to 140 head ha^{-1} in both cropping seasons. The soil moisture was not affected ($p > 0.05$) by SDSG in both cropping seasons.

Soil Quality Index

The first four principal components with eigenvalues ^{3}1 accounted for 75% of the total variation in the total data set for both cropping seasons (Table 2). In 2014 cropping season, PC1 accounted for 47% of the total variation while the other three accounted for 34%. In PC1, TN, bulk density, and porosity were selected for minimum data set (Table 2), but all of them correlated with (Table 3). Bulk density had higher eigenvector than TN and porosity, hence bulk density was retained in the minimum data set. The PC2 had SMQ as the only indicator selected for minimum data set (Table 2). The PC3 had MBN and soil moisture selected for minimum data set (Table 2). They were uncorrelated and all of them were retained in the minimum data set (Table 3). The PC4 had OC, AP, and earthworm cast selected for minimum data set, they were uncorrelated and therefore retained in the minimum data set (Tables 2 and 3).

In 2015 cropping season, PC1 accounted for 48% of the total variation and the other three PCs accounted for 31%. The PC1 had OC, bulk density and porosity selected as minimum data set (Table 2) but they were all correlated (Table 3). However, OC was retained in the minimum data set due to its higher eigenvector. With regard to PC2, SMQ, and soil moisture were selected, they were uncorrelated and hence, they were retained in the minimum data set. The PC3 had TN, EK, and MBN selected and they were uncorrelated (Tables 2 and 3). Therefore, they were all retained in the minimum data set. Soil pH, TN, AP, SMQ, and moisture were selected under PC4 and they were all uncorrelated (Tables 2 and 3). However, soil pH and AP were added to the minimum data set since SMQ, soil moisture, and TN have already been included in the minimum data set.

The SDSG at 70 and 140 head ha^{-1} increased the chemical and biological soil quality sub-indices compared with the control in both cropping seasons (Fig. 2). In contrast, the physical soil quality sub-index for SDSG at 70 head ha^{-1} declined compared with the control in 2015 cropping season while that of 140 head ha^{-1} declined relative to the control in both cropping seasons (Fig. 2). Generally, the soil quality index for SDSG at 70 and 140 head ha^{-1} were consistently above one in both cropping seasons, indicating better soil quality index than the control (Fig. 2).

Yield

The SDSG×MPD×NFR interaction was not significant on grain and biomass yields, however, the SDSG×MPD, SDSG×NFR, and MPD×NFR were significant on grain and biomass yields (Table 4). Maize grain and biomass yields of SDSG at 70 and 140 head ha^{-1} combined with MPD at double the recommended density (2RD) increased significantly compared with the control in both cropping seasons (Table 5). The SDSG at 140 head ha^{-1} combined with MPD at 2RD had higher ($p < 0.01$) grain and biomass yields relative to that of 70 head ha^{-1} combined with 2RD in both cropping seasons (Table 5).

The SDSG at 70 and 140 head ha^{-1} combined with 90 kg ha^{-1} N significantly increased maize grain and biomass yields compared with the control in both cropping seasons (Table 6). Similarly, the biomass yield of SDSG at 140 head ha^{-1} combined with 90 kg ha^{-1} N was higher ($p < 0.01$) than that of 70 head ha^{-1} by 90 kg ha^{-1} in both cropping seasons (Table 6). However, SDSG at either 70 or 140 head ha^{-1} combined with 90 kg ha^{-1} N had no significant effect on grain yield in both cropping seasons (Table 6).

Increasing MPD from the recommended density to 2RD combined with NFR at either 60 or 90 kg ha^{-1} resulted in higher ($p < 0.01$) grain and biomass yields than increasing MPD combined with 0 kg ha^{-1} N in both cropping seasons (Table 7). Also, the MPD at 2RD combined with 90 kg ha^{-1} N had higher ($p < 0.01$) grain and biomass yields than that of 50% above the recommended density (1.5RD) with 90 kg ha^{-1} N in 2015 cropping season (Table 7).

Table 3. Co-efficient of correlation (*r*) among soil chemical, biological and physical properties in Sudan savanna zone of northern Ghana, 2014 and 2015 cropping seasons.

	pH	OC†	TN	AP	EK	MBC	MBN	SMQ	ECST	BD	PSTY	MST
						2014						
pH	1											
OC	0.76***	1										
TN	0.78***	0.72***	1									
AP	0.37ns‡	0.32ns	0.60**	1								
EK	0.51**	0.64**	0.69**	0.59**	1							
MBC	0.46*	0.61**	0.52**	0.31ns	0.45*	1						
MBN	0.43*	0.27ns	0.51**	0.23ns	0.15ns	0.38ns	1					
SMQ	–0.14ns	–0.06ns	0.04ns	0.19ns	0.05ns	0.44*	0.15ns	1				
ECST	0.29ns	0.48*	0.28ns	0.18ns	0.42*	0.69**	0.04ns	0.54**	1			
BD	0.46*	0.50**	0.58**	0.50**	0.72***	0.57**	0.12ns	0.41*	0.51**	1		
PSTY	–0.46*	–0.51**	–0.58**	–0.48*	–0.73***	–0.57**	–0.14ns	–0.40*	–0.51**	–1.00***	1	
MST	–0.05ns	–0.06ns	–0.16ns	–0.11ns	–0.10ns	0.05ns	0.14ns	0.28ns	0.03ns	0.08ns	–0.06ns	1
						2015						
pH	1											
OC	0.43ns	1										
TN	0.20ns	0.57**	1									
AP	0.28ns	0.37ns	0.13ns	1								
EK	0.52**	0.56**	0.40*	0.64**	1							
MBC	0.38ns	0.80***	0.61**	0.33ns	0.57**	1						
MBN	0.32ns	0.65**	0.02ns	0.36ns	0.33ns	0.46*	1					
SMQ	0.10ns	0.18ns	0.25ns	0.07ns	0.25ns	0.47*	0.21ns	1				
ECAST	0.23ns	0.66**	0.63**	0.27ns	0.57**	0.52**	0.31ns	0.36ns	1			
BD	0.32ns	0.73**	0.42*	0.30ns	0.49**	0.60**	0.64**	0.48*	0.64**	1		
PSTY	–0.34ns	–0.73**	–0.44*	–0.31ns	–0.52**	–0.60**	–0.62**	–0.48*	–0.65**	–0.10***	1	
MST	–0.06ns	–0.37ns	–0.06ns	–0.22ns	–0.32ns	–0.18ns	–0.39*	0.18ns	0.08ns	–0.19ns	0.20ns	1

† OC, organic carbon.; TN, total nitrogen; AP, available phosphorus; EK, exchangeable potassium; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen; SMQ, soil microbial quotient; ECST, earthworm cast; BD, bulk density; PSTY, porosity; MST, moisture.

‡ ns, $p > 0.05$.

* $p \leq 0.05$.

** $p \leq 0.01$.

*** $p \leq 0.001$.

DISCUSSION

Manure Quality and Soil Properties

Palm et al. (2001) classified quality of manures as medium (contain $N > 25$ g kg^{-1}, lignin > 150 g kg^{-1}, and polyphenol > 40 g kg^{-1}) or low (contain $N < 25$ g kg^{-1}, lignin < 150 g kg^{-1}, and polyphenol < 40 g kg^{-1}). Therefore, the manure used for this study could be classified as low quality based on the total N and lignin content. The low quality of the manure and the variation in the chemical composition of the manure among the farms could be attributed to the poor quality of feed resources mostly dry grass and crop residues grazed by the animals during the study period.

The increase in the soil chemical and biological properties could possibly be due to the addition of feces and urine from the sheep and goats. The feces and urine from the animals add organic matter to soil which serve as substrate for soil organisms and increase microbial activity in the soil. The activities of these soil organisms decompose the organic matter to release nutrients such as OC, N, and P. The urine releases hydroxide ions during hydrolysis of urea which improves soil pH and contains nutrients such as N and K. The results support earlier report that corralling of livestock improves soil pH, N, OC, and K (Ikpe and Powell, 2002). Derbit and Utter (1994) reported that soil organisms such as earthworms ingest a large amount of soil and organic matter and excrete casts that influence the chemical and physical properties of soil. The effect of SDSG on soil MBC, MBN, and SMQ was in line with earlier reports that application of manure to arable land increases the above soil biological parameters (Li et al., 2011; Blanchet et al., 2016). In contrast with our results, Sangaré et al. (2002) reported no changes in soil organic carbon and nitrogen from the corralling of cattle on arable land while Salton et al. (2014) reported no difference in the SMQ under integrated crop–livestock system and conventional system.

The effect of the SDSG on soil bulk density and porosity might possibly be due to the trampling effect of the animals on the soil which led to compaction of the soil. In agreement with our results, other authors reported an increase in soil bulk density and a decreased porosity with grazing of livestock on grazing or arable lands (Drewry et al., 2008; Bell et al., 2011).

Soil Quality Index

The higher variation observed under PC1 in both cropping seasons could be due to the significant correlation among more indicators selected for the minimum data set. The selection of soil pH, OC, TN, AP, and EK among the minimum data set supports the finding of Andrews et al. (2002). The selection of MBN and SMQ in the minimum data set confirms earlier report on the key

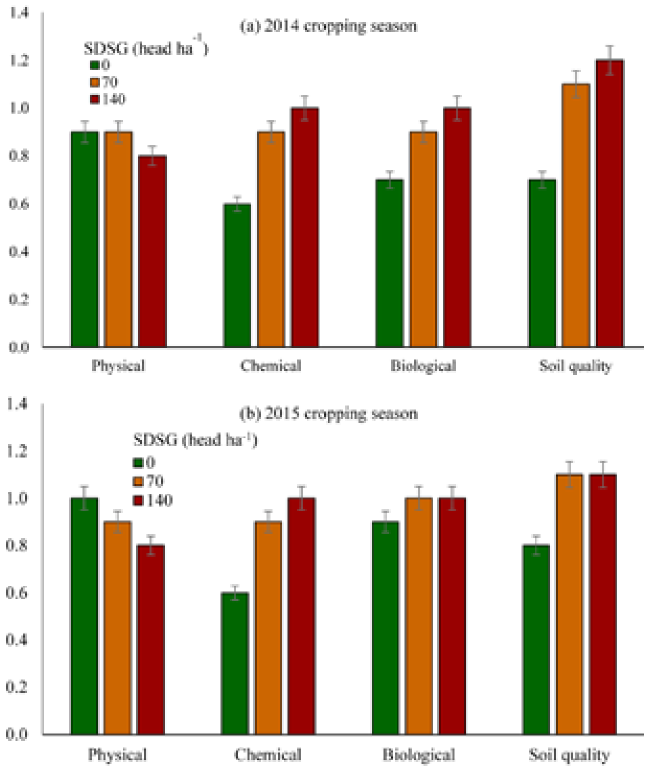

Fig. 2. Stocking density of sheep and goats corralling (SDSG) effects on soil quality index in Sudan savanna zone of northern Ghana, 2014 and 2015 cropping seasons. Error bars represent standard error of mean.

Table 4. Summary of ANOVA for stocking density of sheep and goats (SDSG), maize plant density (MDP), and N fertilizer rates (NFR) effect on maize grain and biomass yield in Sudan savanna zone of northern Ghana, 2014 and 2015 cropping seasons.

Source of variation	Degree of freedom	Grain yield ($kg\ ha^{-1}$) 2014	Grain yield ($kg\ ha^{-1}$) 2015	Biomass ($kg\ ha^{-1}$) 2014	Biomass ($kg\ ha^{-1}$) 2015
FARM† (REP)	7				
SDSG	2	**	**	**	***
Error for SDSG	14				
MPD	2	**	***	***	***
SDSG×MPD	4	ns‡	*	ns	**
Error for MPD	42				
NFR	2	***	***	***	***
SDSG×NFR	4	*	***	ns	**
MPD×NFR	4	ns	**	ns	**
SDSG×MPD×NFR	8	ns	ns	ns	ns
Residual	126				

† FARM represents replication.
‡ ns, $p > 0.05$.
* $p \leq 0.05$.
** $p \leq 0.01$.
*** $p \leq 0.001$.

role of soil microbial biomass for soil quality assessment and the importance of SMQ in determining substrate availability for soil microbes (Paz-Ferreiro and Fu, 2016). The inclusion of earthworm cast as part of the minimum data set was in line with the finding that application of organic manure as soil fertility amendment improves the number of earthworm activities in the soil (Blanchet et al., 2016). Soil bulk density and moisture were also selected in the minimum data set and these indicators have been reported among key indicators for assessing livestock corralling effect on soil properties (Drewry et al., 2008; Bell et al., 2011).

Table 5. Maize grain and biomass yield as affected by stocking density of sheep and goat corralling (SDSG) and maize plant density (MPD) in the Sudan savanna zone of northern Ghana, 2014 and 2015 cropping seasons.

SDSG (head ha^{-1})	MPD (plants ha^{-1})	Grain yield ($kg\ ha^{-1}$) 2014	Grain yield ($kg\ ha^{-1}$) 2015	Biomass ($kg\ ha^{-1}$) 2014	Biomass ($kg\ ha^{-1}$) 2015
0	Recommended density (RD)	1151.1	597.9	3067.8	3599.4
	RD×1.5 (1.5RD)	1251.6	925.0	3940.4	5362.8
	RD×2 (2RD)	1328.4	1528.9	3972.9	6779.3
70	RD	2016.0	1347.0	5260.4	5835.9
	1.5RD	2199.1	2365.0	5971.3	8572.4
	2RD	2282.9	2128.6	6766.2	7588.6
140	RD	2121.8	1511.7	5727.3	6459.9
	1.5RD	2441.3	2147.0	6863.6	8139.6
	2RD	2628.9	2806.5	7340.0	9341.0
SEM†		88.18	159.78	256.05	308.10
Contrast probability of F value					
0×RD vs. (70×RD + 140×RD)		***	***	***	***
70×RD vs. 140×RD		ns‡	ns	*	*
0×1.5RD vs. (70×1.5RD + 140×1.5RD)		***	***	***	***
70×1.5RD vs. 140×1.5RD		*	ns	**	ns
0×2RD vs. (70×2RD + 140×2RD)		***	***	***	***
70×2RD vs. 140×2RD		**	***	**	***

† SEM, standard error of mean.
‡ ns, $p > 0.05$.
* $p \leq 0.05$.
** $p \leq 0.01$.
*** $p \leq 0.001$.

Table 6. Maize grain and biomass yield as affected by stocking density of sheep and goat corralling (SDSG) and nitrogen fertilizer rate (NFR) in the Sudan savanna zone of northern Ghana, 2014 and 2015 cropping seasons.

SDSG	NFR	Grain yield ($kg\ ha^{-1}$)		Biomass yield ($kg\ ha^{-1}$)	
(head ha^{-1})	($kg\ ha^{-1}$)	2014	2015	2014	2015
0	0	791.1	565.3	2452.2	3306.1
	60	1418.7	1151.4	4146.4	5896.6
	90	1521.3	1335.1	4382.4	6538.8
70	0	1571.1	912.6	4815.6	4724.4
	60	2247.8	2257.2	6253.3	8182.4
	90	2679.1	2670.8	6929.1	9090.1
140	0	1694.7	1124.1	5011.3	5183.4
	60	2666.2	2459.9	7299.6	8827.3
	90	2831.1	2881.2	7620	9929.7
SEM†		80.13	106.39	162.28	220.19
Contrast probability of F value					
0×0 vs. (70×0 + 140×0)		***	**	***	***
70×0 vs. 140×0		ns‡	ns	ns	ns
0×60 vs. (70×60 + 140×60)		***	***	***	***
70×60 vs. 140×60		**	ns	***	*
0×90 vs. (70×90 + 140×90)		***	***	***	***
70×90 vs. 140×90		ns	ns	**	**

† SEM, standard error of mean.
‡ ns $p > 0.05$.
* $p \leq 0.05$.
** $p \leq 0.01$.
*** $p \leq 0.001$.

The increase in soil chemical and biological quality sub-indices with sheep and goats corralling could be due to addition of urine and feces from the animals which resulted in an increase in the values of indicators selected as minimum data set under chemical and biological properties. This result was in line with findings from other studies (Ikpe and Powell, 2002; Li et al., 2011). The observed decline in the soil physical quality sub-index with the corralling of sheep and goats could possibly be due to the trampling effect of the animals on the soil. In both cropping seasons, corralling resulted in a soil quality index of one and above indicating a better soil quality index compared with the control. Thus, corralling of sheep and goats on the average increased soil quality index by 32% relative to the control. This indicates the potential of the technology for improving the soil fertility of arable land used for the cultivation of maize, rice, sorghum, millet, and soybean which requires more N, P, and K nutrients for growth. Giving the average population of sheep and goats in the study area to be 348,342 heads, then corralling of sheep and goats has the potential to improve the soil quality of 4976.3 ha of land annually which could cover 71% of maize, 96% of rice, and 93% of soybean farmers who hold less than 1 ha of farm size (Karbo and Agyare, 2002; Amanor-Boadu et al., 2015). In agreement with our results, Kang et al. (2005) reported an increase in soil quality and sustainability index of rice-wheat cropping system with addition of organic manure to mineral fertilizer. Salton et al. (2014) also reported an improved soil quality under integrated crop-livestock system compared to other systems in Brazil.

From the knowledge of the authors, there is little or limited quantitative data on the effect of corralling density on soil quality index. Thus, the methods used in the current study could provide a framework for assessing soil quality under corralling. Although information used was collected over a short period, it could be easily used to evaluate soil quality over longer periods.

Table 7. Maize grain and biomass yield as affected by stocking density of maize plant density (MPD) and nitrogen fertilizer rate (NFR) in the Sudan savanna zone of northern Ghana, 2014 and 2015 cropping seasons.

MPD	NFR	Grain yield ($kg\ ha^{-1}$)		Biomass yield ($kg\ ha^{-1}$)	
(plants ha^{-1})	($kg\ ha^{-1}$)	2014	2015	2014	2015
Recommended density (RD)	0	1242.2	560.0	3486.7	3323.0
	60	1865.3	1243.9	5037.6	5631.3
	90	2181.3	1652.7	5531.3	6940.9
RD×1.5 (1.5RD)	0	1356.0	973.6	4194.9	4884.7
	60	2162.2	2199.1	6095.6	8368.7
	90	2373.8	2264.3	6484.9	8821.3
RD×2 (2RD)	0	1458.7	1068.4	4597.6	5006.2
	60	2305.1	2425.5	6566.2	8906.2
	90	2476.4	2970.1	6915.3	9796.4
SEM		80.13	106.39	162.28	220.19
Contrast probability of F value					
RD×0 vs. (1.5RD×0 + 2RD×0)		ns‡	**	***	***
1.5RD×0 vs. 2RD×0		ns	ns	ns	ns
RD×60 vs. (1.5RD×60 + 2RD×60)		**	***	***	***
1.5RD×60 vs. 2RD×60		ns	ns	*	ns
RD×90 vs. (1.5RD×90 + 2RD×90)		**	***	***	***
1.5RD×90 vs. 2RD×90		ns	***	ns	**

† SEM, standard error of mean.
‡ ns, $p > 0.05$.
* $p \leq 0.05$.
** $p \leq 0.01$.
*** $p \leq 0.001$.

Yield

The differences in the grain and biomass yields between the two cropping seasons could be attributed to the amount of rainfall received during the cropping seasons (Fig. 1). The 2015 cropping season received higher amount of rainfall than the 2014 cropping season at both vegetative and grain filling growth stages. The higher amount of rainfall received during the vegetative growth stage of maize in 2015 cropping season saturated the soil with water, removed oxygen on which the roots of the maize plants would depend for respiration which affected the growth and yield of maize. The higher amount of rainfall could also lead to loss of nutrients through leaching and run-off. The significant interaction effects of SDSG×MPD and MPD×NFR on grain and biomass yields could possibly be due to the supply of plant nutrients from the urine and manure of the sheep and goats and mineral fertilizer to the high plant stands per unit area. The above interaction results indicated that, increasing MPD to double of the recommended density requires higher plant nutrients supply to achieve significant yields. These results agree with earlier reports that increased plant density could lead to increased yields of maize under optimum climatic and agronomic management conditions due to higher number of plants and small cobs per unit area (Bavec and Bavec, 2002; Adeniyan, 2014). However, Shapiro and Wortmann (2006) reported no interaction effect of MPD and NFR on grain and biomass yields of maize.

The significant effect of SDSG×NFR interaction on grain and biomass yields in both cropping seasons could possibly be due to the adequate plant nutrient supply from the urine and feces of the sheep and goats and the mineral fertilizer. The manure from the sheep and goats released nutrients gradually over a long period while the mineral fertilizer supplied readily available plant nutrients over a short period. The SDSG×NFR interaction on the average, increased grain yield by 106% compared with the sheep and goats corralling and 92% compared with the application of mineral N fertilizer. However, increasing SDSG from 70 to 140 head ha^{-1} combined with 90 kg ha^{-1} N had no significant effect on grain yield in both growing seasons. This observation could be due to the antagonistic and synergistic effect of the manure and mineral N fertilizer. In the 2014 cropping season, the manure and mineral fertilizer had antagonistic effect on grain yield thus grain yields of SDSG at either 70 or 140 head ha^{-1} combined with 90 kg ha^{-1} N were lower than those of the sum of grain yields from each of their treatment combination. Whereas in 2015, the manure and mineral fertilizer had synergistic effect on grain yield thus grain yield of SDSG at either 70 or 140 head ha^{-1} combined with 90 kg ha^{-1} N were higher than that of the sum of grain yield from each of their treatment combination. The increase in grain and biomass yields with SDSG and NFR supports earlier report that integrated application of mineral fertilizer and organic manure results in improved soil fertility and crop yield in many parts of the world (Vanlauwe et al., 2011).

CONCLUSION

The corralling of sheep and goats increased soil chemical and biological properties relative to the control treatment in both cropping seasons. The soil chemical and biological sub-indices increased while soil physical sub-index decreased with sheep and goats corralling compared with the control in both cropping seasons. The soil quality index for the sheep and goats corralling were consistently above one in both cropping seasons indicating better soil quality compared with the control. The interactions of SDSG×MPD, SDSG×NFR, and MPD×NFR were significant on maize grain and biomass yields. The results suggest that small-scale maize-livestock famers with low resource endowment could use either SDSG at 70 head ha^{-1} or apply 60 kg ha^{-1} NFR with maize plant density at 100,000 plants ha^{-1} for improved maize grain yield. Those with more resource endowment could use either SDSG of 70 head ha^{-1} with 90 kg ha^{-1} NFR or SDSG of 140 head ha^{-1} with 60 kg ha^{-1} NFR and a maize density of 133,333 plants ha^{-1} to increase grain yield on Ferric lixisols of Sudan savanna zone of Ghana and similar ecologies in West Africa.

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REFERENCES

Abdul Rahman, N., F.M. Tetteh, M. Fosu, G.W. Quansah, and A.S. Osuman. 2015. Improving maize yield on ferric lixisol by NPK fertilizer use. J. Agric. Sci. 7:233–237.

Adeniyan, O.N. 2014. Effect of different population densities and fertilizer rates on the performance of different maize varieties in two rain forest agro ecosystems of South West Nigeria. Afri. J. Plant Sci. 8:410–415.

Amanor-Boadu, V., Y. Zereyesus, K. Ross, A. Ofori-Bah, S. Adams, J. Asiedu-Dartey, E. Gutierrez, A. Hancock, A. Mzyece, and M. Salin. 2015. Agricultural production survey for the Northern regions of Ghana: 2013–2014 results. Final Rep. METSS/USAID, Ghana.

Anderson, J.M., and J.S.I. lngram. 1993. Tropical soil biology and fertility: A handbook of methods, 2nd ed. CAB International, Wallingford, UK.

Andrews, S.S., D.L. Karlen, and J.P. Mitchell. 2002. A comparison of soil quality indexing method for vegetable production system in Northern California. Agric. Ecosyst. Environ. 90:25–45. doi:10.1016/S0167-8809(01)00174-8

Bavec, F., and M. Bavec. 2002. Effects of plant population on leaf area index, cob characteristics and grain yield of early maturing maize cultivars (FAO 100–400). Eur. J. Agron. 16:151–159. doi:10.1016/S1161-0301(01)00126-5

Bell, L.W., J.A. Kirkegaard, A. Swan, J.R. Hunt, N.I. Huth, and N.A. Fettell. 2011. Impacts of soil damage by grazing livestock on crop productivity. Soil Tillage Res. 113:19–29. doi:10.1016/j.still.2011.02.003

Blanchet, G., K. Gavazov, L. Bragazza, and S. Sinaj. 2016. Responses of soil properties and crop yields to different inorganic and organic amendments in a Swiss conventional farming system. Agric. Ecosyst. Environ. 230:116–126. doi:10.1016/j.agee.2016.05.032

Bray, I.L., and L.T. Kurtz. 1945. Determination of total organic and available form of phosphorus in soils. Soil Sci. 59:39–46. doi:10.1097/00010694-194501000-00006

Bremner, J.M., and V.A. Mulvaney. 1982. Steam distillation methods for ammonium nitrate and nitrite. Anal. Chim. Acta 32:485–495. doi:10.1016/S0003-2670(00)88973-4

Defoer, T., A. Budelman, C. Toulmin, and S.E. Carter. 2000. Managing soil fertility in the tropics. Building common knowledge: Participatory learning and action research. Royal Tropical Institute, KIT Press, Amsterdam, the Netherlands.

Derbit, E.J., and R.A. Utter. 1994. Earthworm populations related to soil and fertilizer management. Better Crops 78:9–11.

Drewry, J.J., K.C. Cameron, and G.D. Buchan. 2008. Pasture yield and soil physical property responses to soil compaction from treading and grazing: A review. Aust. J. Soil Res. 46:237–256. doi:10.1071/SR07125

Ikpe, F.N., and J.M. Powell. 2002. Nutrient cycling practices and changes in soil properties in the crop-livestock farming systems of western Niger Republic of West Africa. Nutr. Cycling Agroecosyst. 62:37–45. doi:10.1023/A:1015199114833

IUSS Working Group WRB. 2015. World reference base for soil resources 2014. Updated 2015. International soil classification system for naming soils and creating legends for soil maps. World Soil Resource Rep. 106. FAO, Rome, Italy.

Kang, G.S., V. Beri, B.S. Sidhu, and O.P. Rupela. 2005. A new index to assess soil quality and sustainability of wheat-based cropping systems. Biol. Fertil. Soils 41:389–398. doi:10.1007/s00374-005-0857-4

Karbo, N., and W. Agyare. 2002. Crop–livestock systems in northern Ghana. Improving crop–livestock systems in the dry savannas of West and Central Africa. International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria. p. 112–126.

Karlen, D.L., M.J. Mausbach, J.W. Doran, R.G. Cline, R.F. Harris, and G.E. Schuman. 1997. Soil quality: A concept, definition, and framework for evaluation. Soil Sci. Soc. Am. J. 61:4–10. doi:10.2136/sssaj1997.03615995006100010001x

Lana, M.A., F. Eulenstein, S.L. Schlindwein, F. Graef, S. Sieber, and H. von Hertwig Bittencourt. 2017. Yield stability and lower susceptibility to abiotic stresses of improved open-pollinated and hybrid maize cultivars. Agron. Sustain. Dev. 37:30. doi:10.1007/s13593-017-0442-x

Li, J.T., X.L. Zhong, F. Wang, and Q.G. Zhao. 2011. Effect of poultry litter and livestock manure on soil physical and biological indicators in a rice-wheat rotation system. Plant Soil Environ. 57:351–356. doi:10.17221/233/2010-PSE

Liniger, H.P., R. Mekdaschi Studer, C. Hauert, and M. Gurtner. 2011. Sustainable land management in Practice: Guidelines and best practices for Sub-Saharan Africa. TerrAfrica, World Overview of Conservation Approaches and Technologies (WOCAT) and Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Manyong, V.M., J.G. Kling, K.O. Makinde, S.O. Ajala, and A. Menkir. 2000. Impact of IITA-improved germplasm on maize production in West and Central Africa. International Institute of Tropical Agriculture, Ibadan, Nigeria.

Navrongo Meteorological Agency Agro-Station. 2015. Navrongo. http://www.meteo.gov.gh/website/ (accessed 22 Jan. 2019).

Nelson, D.W., and L.W. Sommers. 1982. Total carbon, organic carbon and organic matter. In: A.L. Page, R.H. Miller, and D.R. Keeney, editors, Methods of soil analysis Part 2. Chemical and microbiological properties, Agronomy No. 9. ASA and SSSA, Madison, WI. p. 539–579.

Palm, C.A., C.N. Gachengo, R.J. Delve, G. Cadisch, and K.E. Giller. 2001. Organic inputs for soil fertility management in tropical agroecosystems: Application of an organic resource database. Agric. Ecosyst. Environ. 83:27–42. doi:10.1016/S0167-8809(00)00267-X

Paz-Ferreiro, J., and S. Fu. 2016. Biological indices for soil quality evaluation: Perspectives and limitations. Land Degrad. Dev. 27:14–25. doi:10.1002/ldr.2262

Powell, J.M. 2014. Feed and manure use in low-N-input and high-N-input dairy cattle production systems. Environ. Res. Lett. 9:115004. doi:10.1088/1748-9326/9/11/115004

Powell, J.M., R.A. Pearson, and P.H. Hiernaux. 2004. Crop-livestock interaction in the West African drylands. Agron. J. 96:469–483. doi:10.2134/agronj2004.4690

Ragasa, C., A. Dankyi, P. Acheampong, A.N. Wiredu, A. Chapoto, M. Asamoah, and R. Tripp. 2013. Patterns of adoption of improved maize technologies in Ghana. IFPRI Ghana Strategy Support Program. Working Paper 36. IFPRI, Washington, DC.

Salton, J.C., F.M. Mercante, M. Tomazi, J.A. Zanatta, G. Concenço, W.M. Silva, and M. Retore. 2014. Integrated crop-livestock system in tropical Brazil: Toward a sustainable production system. Agric. Ecosyst. Environ. 190:70–79. doi:10.1016/j.agee.2013.09.023

Sangaré, M., S. Fernández-Rivera, P. Hiernaux, A. Bationo, and V. Pandey. 2002. Influence of dry season supplementation for cattle on soil fertility and millet (*Pennisetum glaucum* L.) yield in a mixed crop/livestock production system of the Sahel. Nutr. Cycling Agroecosyst. 62:209–217. doi:10.1023/A:1021237626450

Shapiro, C.A., and C.S. Wortmann. 2006. Corn response to nitrogen rate, row spacing, and plant density in Eastern Nebraska. Agron. J. 98:529–535. doi:10.2134/agronj2005.0137

Sigunga, D.O., B.H. Janssen, and O. Oenema. 2002. Effects of improved drainage and nitrogen source on yields, nutrient uptake, and utilization efficiencies by maize (*Zea mays* L.) on Vertisols in sub-humid environments. Nutr. Cycling Agroecosyst. 62:263–275. doi:10.1023/A:1021242918555

SAS Institute. 2011. SAS 9.3 procedures guide. SAS Institute Incorporation, Cary, NC.

Tetteh, F.M., A. Larbi, K.A. Nketia, J.N. Senaya, I. Hoeschle-Zeledon, and N. Abdul Rahman. 2016. Suitability of soils for cereal cropping in Northern Ghana. Evaluation and recommendations. International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria.

Thomas, G.W. 1982. Exchangeable cations. In: A.L. Page, R.H. Miller, and D.R. Keeney, editors, Methods of soil analysis Part 2. Chemical and microbiological properties, Agronomy No. 9. ASA and SSSA, Madison, WI. p. 159–165.

Vanlauwe, B., J. Kihara, P. Chivenge, P. Pypers, R. Coe, and J. Six. 2011. Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. Plant Soil 339:35–50. doi:10.1007/s11104-010-0462-7