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On-Farm Adaptation to Climate Change: Assessment of Effects of Groundwater-Based Deficit and Supplementary Irrigation on Soil Quality Under Semi-Arid Ecosystems

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ABSTRACT

Agriculture is one of the sectors most affected by climate change, especially through the reduction in the number of rainy days in semi-arid areas, which require deficit supplementary irrigation (DSI) to minimise crop failures. Few studies have utilised soil quality indices (SQIs) to evaluate the quality changes of soils under DSI practices in semi-arid agricultural ecosystems. This paper examines the effects of DSI activities on soil quality in the Ingawa area of Nigeria's semi-arid region. Plots subjected to different years of DSI (3, 5, 6, 8, 10, 11, 14 and 15 years) practices were chosen to serve as the controls. Soil samples were collected from each of the nine sites at depths ranging from 0 cm to 20 cm and 25 cm to 40 cm. The collected samples were analysed for physico-chemical properties. Soil quality change was estimated by computing percentage equivalence values that define the extent to which mean values of soils under DSI vary from those of the control. The results obtained show that the practices have caused significant negative changes in the levels of most of the properties considered, with significant deleterious effects on the selected physical and chemical indicators of soil quality to extents that might preclude sustainable agriculture on the soils. Potassium, organic carbon, organic matter, and some other essential nutrients needed for plant growth and soil stability have dropped a lot in irrigated farms compared to control farms, but salinization hasn't happened much. It was suggested that the right steps be taken to prevent the loss of important nutrients that crops need to grow well.

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Introduction

Climate changes like shorter growing seasons and fewer rainy days, more heat stress and floods, and rain that starts later are all things that farmers in many places must learn to deal with in order to keep growing crops in a sustainable way. In dry areas of the world, relying on rainfall for profitable crop cultivation is considered a very risky enterprise. Accordingly, inhabitants of such areas have for a very long time appreciated the need to adopt irrigation farming using both surface and ground water to complement rainfed crop production. With climate change impacts, the duration of effective rainfall upon which rainy season crop production is based is increasingly becoming shorter, and hence crop failures are common. With the rainy season being short, rainfall being highly variable, and soils largely sandy with low moisture retention and frequent rainfall failure, agricultural production is severely constrained. To cope with this challenge, farmers often employ supplementary irrigation activities, mostly from groundwater sources, to meet up with soil moisture needs whenever rainfall ceases before crops mature, so as to avoid failures and poor yields. Deficit and supplementary irrigation (DSI) is a term used to describe activities that help crops complete their production cycles when rain stops (Oweis, 1997; Oweis and Hachum, 2006; Geerts and Raes, 2009; Oweis and Hachum, 2012; Patane et al., 2015; Wang et al., 2015; Furgassa, 2017; Wale et al., 2019). However, several studies have shown that the ground water being used in DSI can contain levels of some dissolvable substances which over time could accumulate to levels that could affect physico-chemical and biological conditions of the soil (Abu-Awwad and Kharabsheh, 2000; Fox and Rockstro¨m, 2000; Costa, 2000; Fox and Rockstro m, 2003; Herrero and Perez Covetta, 2005; Truman and Rouland, 2005; Ali, et al., 2007; Bekele and Tilahun, 2007; Fereres and Soriano, 2007; Mon, et al., 2007; Asmamaw et al., 2021).

In general, it has been well documented in the literature that ground-water based irrigation practices, whether under DSI or dry-season based irrigation systems, have different effects on soil condition. Several studies have shown that irrigation practices that use ground water in especially dry areas can lead to serious soil degradation problems, such as alkalinity, salinity, toxicity, and sodicity, which could seriously limit productivity (Shady). When exchangeable sodium percentage (ESP) values become high and electrolyte concentration low, clay and organic matter begin to swell and disperse, which promotes negative physical conditions such as restricted aeration and permeability and reduced soil hydraulic conductivity (Shainberg et al., 1984). In Georgia, on relatively sandy soil with low organic matter content (like in most semi-arid soils), Truman and Rowland (2005) found high erosion risk due to reduced permeability when a supplementary irrigation system was used. Suarez et al. (2006) found that an increase in levels of sodium adsorption ratio (SAR) caused by irrigation water had an adverse impact on water infiltration, leading particularly to a greater likelihood of flood events. In Costa's study from 2000, he found that changes in sodicity were long-lasting but tended to settle down after a year without irrigation and 1129 mm of rainwater leached the soil. This was found in a similar study that looked at the effects of 10 years of extra irrigation on soil properties in Argentina's rolling pampa region.

Though the literature on the effect of irrigation on soil condition is very large, there are very few studies that used soil indices to assess quality changes. Traditionally, soil quality assessment has been done by comparing the individual soil properties of different land uses or cropping systems with each other or with those of a control site, such as a natural forest reserve, to find out how and how much the soil quality has changed (Abubakar, 1997). However, because soil quality is best defined by the cumulative effects of multiple soil properties, the use of an inferential approach is thought to be limited in providing comprehensive details on a soil's overall quality change. For example, organic matter is one of the single best indicators of soil quality. However, significant biological, chemical, and physical differences can exist between two soils in the same organic matter condition. It is therefore considered that the best way to carry out soil quality assessment is to adopt an integrative evaluation approach involving the use of indices (called soil quality indices, or SQIs) that integrate multiple soil properties to identify the nature and extent of soil quality changes. Consequently, different indices have been developed and used in soil quality assessment in many areas. Among these indices, those based on SMAF (Soil Management Assessment Framework) were found to have wider applicability across multiple environmental settings (Ippolito et al., 2018). Despite this, quality change assessment of soils under groundwater irrigation is largely being done using an inferential approach, and little is known about the efficacy of SQIs for use in evaluating the quality of soils under irrigation practices in general and DSI in particular.

This paper advances an understanding in this regard by utilising SQIs to assess the quality of soils under supplementary irrigation in the Ingawa area of Nigeria’s semi-arid region. The objective of the study is to utilise SMAF-based SQIs to evaluate the quality of soils under different years of DSI practices in the area.

Study Area and Methods

Location of The Study Area

The study was conducted in the Ingawa area (longitudes 12^{0}38’55.91’’ to 12^{0}41’18.93’’N and latitudes 7^{0}42’58.06’’ to 7^{0}45’44.66’’E) of Katsina state in Nigeria’s semi-arid region (Figure 1). The area is situated on the Hausa plains, approximately 620m above sea level, and the soils are generally sandy, very low in organic matter content, and characterized by low-activity kaolinitic clay minerals. The long-term annual rainfall average is 525mm and is received from May to early September each year. Despite this, the soils are put to intensive cropping, though annual crop failures are common.

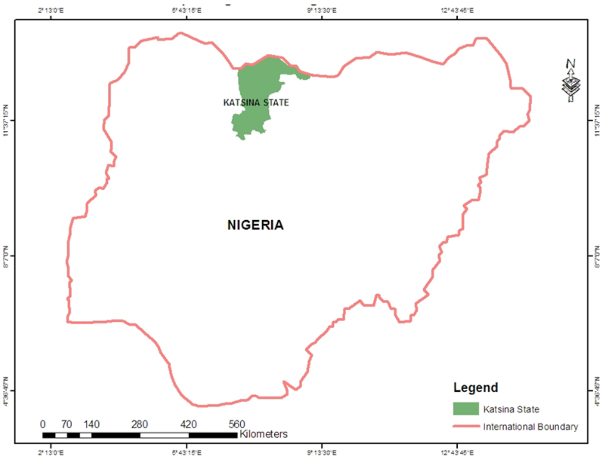

Figure 1. Loction of Ingawa area witihn Katsina state of Nigeria

Soil Quality Assessment Approach Adopted

The term "soil quality" is widely used to refer to the soil’s capacity to continue functioning as a living ecosystem capable of sustaining the food production needs of plants, animals, and human beings. Many approaches (i.e., SQIs) have been developed for quantifying SQ, but all the major approaches recognise that certain sets of properties (called quality indicators) need to be measured, quantified, and scored first. The major indicators recognized by such approaches include soil organic C, macroporosity, bulk density, exchangeable bases, pH, total N, pH, electrical conductivity (EC), salt content, nitrate N, sulphur, available P and K (Rousseau et al., 2012 ; Cherubin et al., 2016; Zhang et al., 2016). Most of the time, quantitative data on the levels of these properties in a soil is put through inferential statistical treatments (like principal components, cluster, multivariate, and discriminant analyses) to make indices that can be used to measure SQ. Of the many indices developed, those based on SMAF (Soil Management Assessment Framework) have been shown to have a wider range of applicability across different environmental settings (Stott et al., 2011). The SMAF has been shown to be capable of providing easy-to-use criteria for indicator selection, interpretation, and integration into a series of SQIs (Andrews et al., 2004; Wienhold et al., 2009; Stott et al., 2011; Ippolito et al., 2018). (Karlen et al., 2008; Stott et al., 2013) The SMAF guidelines suggest using at least five indicators, with at least one for chemical, physical, and biological soil properties and processes. A soil quality index (SQI) is made by giving each of these indicators a score and figuring out how they affect the soil as a whole.

SMAF provides a user-friendly algorithm that runs on an Excel spreadsheet environment to calculate unitless scores of (0) to (1) for each soil indicator selected to carry out SQ assessment in a given area. The unitless scores are added together for each index and then divided by the number of indicators used to calculate a particular index.

Soil sampling and characterization

Study sites

Nine sites were selected in an area with similar pedo-geomorphic characteristics and land use history, of which eight were under different durations of DSI (3,5,6,8,10,11,14 and 15 years) activities, and another one not under DSI practice was chosen to serve as the control. The 8 DSI plots have been under similar cropping systems for over 60 years prior to the conduct of this study (October 2020), with sorghum (*Sorghum bicolor*) as the main crop. Due to the high number of crop failures, especially after the terrible droughts of the 1970s and 1980s, which hurt crop production in Nigeria's semi-arid region, aggressive extension services were started in the 1990s to get farmers to start using DSI when the rain stops before the crops are done growing.

Collection and analysis of soil samples

For the purpose of soil sampling, a quadrat of 20m x 20m was selected within every plot. Every quadrat was divided into 25 equal-sized grid squares and at the mid-point of every square, soil samples were collected using a soil auger at depths of 0 to 20cm (top/surface soil) and 25 to 40cm (subsurface soil) from each of 9 sites. The collected samples were marked and labelled with the points and depths of collection and transported to the Soil Science Laboratory of the Institute of Agricultural Research, Ahmadu Bello University, Zaria, Nigeria for analysis. While in the laboratory, the samples were air-dried and passed through 2mm sieve to remove gravel fractions. The sieved fractions were then subjected to detailed analyses, as follows: Organic carbon by using the Walkley and Black wet acid dichromate digestion method as described by Allison (1965) The collected samples were marked and labelled with the points and depths of collection and transported to the Soil Science Laboratory of the Institute of Agricultural Research, Ahmadu Bello University, Zaria, Nigeria for analysis.

While in the laboratory, the samples were air-dried and passed through a 2 mm sieve to remove gravel fractions. The sieved fractions were then subjected to detailed analyses, as follows: Organic carbon was derived by using the Walkley and Black wet acid dichromate digestion method as described by Allison (1965), and the organic carbon values obtained were multiplied by 1.72 to derive percent organic matter values. Using a method described by Peech (1965), soil pH was measured using a pH meter with a soil to water ratio of 1:2.5, and total nitrogen was measured using a semi-micro Kjeldahl digestion (Bremner, 1965). Total nitrogen (TN) was measured in the samples by using the Kjeldhal digestion method, followed by distillation and titration, while available P was determined using the Olsen method (Olsen and Sommers, 1982). Exchangeable K and Na were extracted using the ammonium acetate method, while exchangeable Ca and Mg were extracted using the titration method (Rhoades, 1982). Flame emission photometry was used to estimate the concentrations of K and Na in the extracts, and atomic absorption spectroscopy was used to evaluate the concentrations of Ca and Mg (Hesse, 1971). Using a flame emission photometer to extract ammonium acetate and buffer it at pH 7, the cation exchange capacity (CEC) was calculated (Rhoades, 1982). Using the Murphy and Riley technique of reaction with ammonium molybdate and ascorbic acid as a reductant in the presence of antimony, available P was recovered spectrophotometrically (Rodriguez et al., 1994). Using a formula, the values of exchangeable cations and CEC were used to figure out the values of percentage base saturation (%BS).

$$\%BS = ([Ca2+ + Mg2+ +K+/CEC])\times 100 \qquad (1)$$

Calculating Soil Indices

Measured values of the seven soil indicators selected in this study (pH, organic carbon, total N, available P, exchangeable cations, CEC, and %BS) were converted into scores between 0 (lowest SQ values) and 1 (highest SQ values) using established algorithms as described by Andrews et al. (2004), Wienhold et al. (2009), and Stott et al. (2011). The various quality indicators were assigned weighted scores following a PCA (Principal Components Analysis), with each principal component used to explain a certain amount of variation in the dataset. Ray et al. (2014) describe a way to get the weighted factor value by dividing the total percentage of variance from each principal component by the percentage of cumulative variance.

Statistical Evaluation

Analysis of variance (ANOVA) was used to test for significance differences in mean values of laboratory characterization, the parameter scoring of each of the seven measured soil indicators, and the overall SQI scoring of each plot between the various DSI cropping plots. A t-test analysis was also used to test for significant differences between the control and each of the DSI cropping plots in mean values of the computed SQI score values of each plot. The goal was to find the DSI plot that changed the quality of the soil the most compared to the control.

Results and Discussion

Variation in Levels of SQ Indicator Variables

Soil acidity (pH)

Table 1 presents a descriptive statistical summary of soil chemical properties for both surface and subsurface layers for all the supplementary irrigation and control sites. It could be observed from this table that mean soil pH values for all the DSI and control sites ranged between 4.1 and 6.5, indicating that the soils ranged from moderately to slightly acidic in nature, which unfortunately limits crop growth due to insufficient mineral elements (Schmidt, 1982). When evaluating the environment and soil fertility, soil pH is a crucial indicator. For example, the typical pH range for the availability of minerals is 6.0 to 7.5 for the majority of crops (Sanchez et al., 2003).

Table 1. Desriptive statistics of physico-chemical soil properties under different years of deficit supplementary irrigation (DSI) practices and the control

PUV	SD	pH	SOC	SOM	TN	CN	AP	Exchangeable Cations (me/100g)				CEC (me/ 100g)	ESP (%)
								Ca	Mg	K	Na		
Site 1 (3 yrs)	Top	6.1	0.187	0.323*	0.021*	8.91*	10.12*	3.89	1.99*	0.15	0.35*	5.88	6.2*
	Sub	5.1	0.158	0.273*	0.016*	9.88*	9.77*	3.06	1.46	0.11	0.27*	3.33*	5.2*
Site 2 (5 yrs)	Top	5.6	0.152*	0.262*	0.026*	5.85*	11.62*	3.24	1.43*	0.14	0.51*	5.62*	7.3*
	Sub	4.8	0.141	0.243*	0.015*	9.41*	9.83*	2.88	1.31	0.10	0.31*	5.11	5.1*
Site 3 (6 yrs)	Top	5.8	0.163*	0.281*	0.027*	6.79*	12.36	2.97*	1.68*	0.11*	0.42*	5.34*	8.2*
	Sub	4.9	0.151*	0.261*	0.018*	8.39*	10.63	2.47	1.28*	0.08	0.39*	5.01	8.6*
Site 4 (8yrs)	Top	5.4	0.155*	0.267*	0.028*	5.54*	12.57	3.47	1.57	0.10*	0.58*	5.39*	9.31*
	Sub	4.6	0.143	0.247*	0.020*	7.15*	10.75	3.06	1.21	0.09	0.37*	4.68	7.51*
Site 5 (10 yrs)	Top	5.5	0.160*	0.276*	0.031*	6.96*	13.11	2.79*	1.29*	0.12*	0.49*	4.89	9.35*
	Sub	4.5	0.144	0.257*	0.018*	8.01*	9.92	2.41	1.12	0.10*	0.39*	4.26*	8.81*
Site 6 (11 yrs)	Top	5.1	0.151*	0.261*	0.034*	5.88*	12.66	2.45*	1.32*	0.10*	0.61*	5.31*	11.9*
	Sub	4.7	0.140*	0.242*	0.019*	7.37*	10.56	2.36	1.03	0.04*	0.44*	5.11	9.80*
Site 7 (14 yrs)	Top	4.9	0.143*	0.247*	0.035*	4.93*	13.07	2.33*	1.26*	0.10*	0.52*	5.20*	12.9*
	Sub	4.3	0.132	0.228*	0.021*	6.29*	11.13	2.20	1.12	0.03*	0.48*	4.79	11.5*
Site 8 (15 yrs)	Top	4.6	0.139*	0.240	0.038*	4.63	13.81	2.25*	1.20*	0.07*	0.88*	5.13*	14.8*
	Sub	4.1	0.123	0.212*	0.020*	3.15	11.23	2.09	1.09	0.02*	0.51*	4.95	13.9*
DBM	Top	NS	S	S	S	S	S	NS	NS	S	NS	S	S
	Sub	NS	NS	NS	NS	NS	S	NS	NS	S	NS	NS	S
MC	Top	6.5	0.223	0.421	0.05	4.46	14.54	4.14	1.92	0.20	0.96	6.36	15.6
	Sub	4.3	0.115	0.205	0.03	3.83	11.23	2.56	0.87	0.12	0.72	5.16	8.56
M8	Top	5.4	0.156	0.27	0.026	6	12.41	2.92	1.47	0.111	0.55	5.35	9.99
	Sub	4.6	0.142	0.25	0.018	7.89	10.48	2.57	1.2	0.145	0.39	4.65	8.81
SDC	Top	0.24	0.011	0.013	0.002	0.25	1.123	0.58	0.27	0.025	0.16	0.3	2.99
	Sub	0.13	0.00411	0.009	0.001	0.13	0.58	0.38	0.14	0.022	0.08	0.6	2.18
SD8	Top	0.49	0.015	0.026	0.003	0.56	1.123	0.72	0.47	0.052	0.28	0.74	3.92
	Sub	0.32	0.011	0.019	0.002	0.27	0.58	0.26	0.23	0.031	0.13	0.38	2.45

PUV: Plots under various yrs of DSI practices; SD: Soil Depth; SOC: Soil Organic Carbon (mg/kg); SOM: Soil Organic Matter (%); TN: Total Nitrogen (mg/kg); CN: C:N ratio; AP: Avail. P. (mg/kg); MC: Mean for the Control; M8: Mean for the 8 DSI Sites; SDC: S.D. for the control site; SD8: S.D. for the 8 DSI Sites

Note: DBM = Difference between mean values of each property among the 8 DSI plots, as tested using ANOVA; NS/S mean differences are Not Significant/Significant between topsoil and subsoil values of each property, as tested using t-test; The asteriks denote the mean value for the SDI plots that are statisitcally different (at 0.05 probability level) from those of the control

The status of soil pH in the surface layer for all the DSI sites ranged between 4.6 to 6.1, with 5.4 and 0.489 as the mean and standard deviation, respectively. Similarly, in the subsurface soil layer, pH ranged between 4.1 and 5.1, with 4.6 and 0.324 as the mean and standard deviation, respectively. It could, however, be observed from these figures that soils in the surface layer were moderately acidic while soils in the subsurface layers were slightly acidic. It could further be seen from the table that differences between the means of control and all the DSI sites were only statistically significant in the 8th site, which has the longest duration of DSI activity. The results further indicated that soil pH was decreasing with the duration of SI among the sampled plots. This could be observed from table 1, where the 3-year DSI site has the highest soil pH at both layers, and the 8-year SI site has the lowest values. The loss of exchangeable cations due to faster soil erosion and crop uptake, which would be expected to increase as cultivation time and intensity go up, could be one reason why the pH value of the soil goes down as DSI goes up.

Soil organic carbon (SOC)

Based on the soil fertility rating of Landon (1991), the soil organic carbon (SOC) content of the study area was generally rated as low to very low in all the SI and control sites. Mean values for surface and subsurface layers ranged from 0.187 gkg^1 to 0.123 gkg^1. At the surface soil layers, the SOC values ranged between 0.187 gkg^1 and 0.139 ^{gkg1,} with 0.156 and 0.015 as the mean and standard deviation. Similarly, at the sub-surface layers of the sampled sites, SOC values ranged between 0.158 gkg^1 and 0.123 gkg^1 with 0.142 and 0.011 as mean and standard deviation values, respectively. There was no significant difference in the SOC values among all the SI sites at both upper and lower soil layers (Table 1).

Overall, SOC status was declining at both layers when compared with values from control sites. Besides, it could further be observed that the SOC values were also decreasing with the duration of DSI. Site 1 (which has the least duration among the SI sites) has the highest mean value of SOC at both the upper and lower layers of sampled sites, while Site 8 (being the oldest SI site, with 15 years of duration), has the lowest mean SOC values at both layers. This suggests that SOC values decline with an increase in the length of supplementary irrigation and this agrees with the findings of Cho et al. (2004). This is partly expected since continuous cropping typically promotes loss of organic materials through litter oxidation, accelerated decomposition, and crop residue removal. The generally low organic matter of the soils of the study area could be attributed to the scarce vegetation cover that characterizes the area as well as the rapid degradation of woodlands and forest biomes due to indiscriminate removal of trees through wood fuel collection, land use/land cover conversions, and grazing, among others. These things change the way organic carbon and matter are spread out in the soil profile, which in turn changes the structure and functions of the soil (Brady and Weil, 2002).

Soil organic matter (SOM)

Organic matter's main jobs in soil are to add nutrients, improve soil structure, and keep water in the soil. The pattern of variation of organic matter over the various SI plots is isimilar to that of soil organic carbon, and this is expected since the value of the former was derived from that of the latter. Loveland and Webb (2003) found that if the amount of organic matter in a soil is less than 3.4 gkg1, the quality of the soil is likely to go down.

Soil organic matter content across all the sites was generally very low (Table 1). At the upper layer, SOM ranged between 0.240 gkg^{1} and 0.323 gkg^{1} for all the eight DSI sample sites, with 0.27 gkg^{1} and 0.026 as mean and standard deviation values, respectively. The values of SOM at lower layers for all the sites ranged between 0.212 gkg^{1} and 0.273 gkg^{1} with 0.25 gkg^{1} and 0.019 as mean and standard deviation values, respectively. It could, however, be observed from Table 1, that values of SOM seem to be decreasing with the duration of SI. Site 1 (which has the least duration among the DSI sites) has the highest mean SOM values at both the upper and lower layers of sampled sites. Conversely, site 7 (being the oldest SI site) has the lowest mean SOM values at both layers, with mean values of 0.247 gkg^{1} and 0.228 gkg^{1} at surface and subsurface layers. The decrease in mean values of organic matter with an increase in years under SI is partly expected since an increase in length of cultivation has been shown by many authors to be associated with a decline in soil organic matter level (Joachim and Patrick, 2008). When plants are cleared away to make room for farming, biomass production is usually low because there is less turnover of plant litter. This is especially true when crop residue is not left on the cultivated field (Nye and Greenland, 1960).

Total nitrogen (TN)

Total nitrogen status in the study area was rated as generally low, with values ranging between 0.015 gkg^{1} and 0.030 gkg^{1} for all DSI sites at both layers (Table 1). The main obstacle to plant growth and development in many regions of the world is a lack of N in the soil (Tilman, 1984). At the upper layer, TN values ranged between 0.021 gkg^{1} and 0.030 gkg^{1} with 0.026 gkg^{1} and 0.003 as the mean and standard deviation, respectively. At the lower layer, values of TN ranged between 0.015 gkg^{1} and 0.021 gkg^{1} with 0.018 gkg^{1} and 0.002 as the mean and standard deviation, respectively. Facelli and Pickett (1991) found that microbial activity in the soil has a big effect on the amount of organic matter in the soil, which could explain why all of the sites had low amounts of N.

It could further be observed from Table 1 that N values are generally increasing with an increase in the length of SI practices in the area, though the increases are generally very low. Because organic matter is a major source of fixing N in tropical soils of low rainfall areas, one would expect that as more organic amendment is made on the SI plots, N build up will gradually occur. However, the low buildup of the property as observed here might be a reflection of the very low level of native N in the soils of Nigeria's semi-arid region. Due to this low level, very high doses of organic manure and inorganic N applications are required before a significant buildup of the property should be expected. Similarly, it could be observed from (Tables 2 and 3 that differences in mean TN values between control and all the SI sites for both surface and sub-surface layers were statistically significant (P = 0.05).

C:N ratio

The most favorable C:N ratios, which are typically thought to be between 8 and 12, indicate a reasonably quick mineralization of nitrogen from the organic components. Stronger C:N ratios larger than 23 have been shown to favor sluggish residue decomposition by the related microorganisms, higher immobilization effects, and limited N in the soil, all of which may result in lower crop yields (NSS, 1990). Only one SI site had a C:N ratio of 13.1, indicating that the study area has a moderate to good level of property. The C:N ratio among the SI sites ranged from 1.0 to 9.4. (Table 1). Because immobilization happens less often than mineralization at all of the study sites, the C:N ratios show that the soil is a good place for plants to grow.

Available phosphorous (AP)

The plant available phosphorus content in the soils for all the SI sites studied ranged between 9.77 mg/kg^{-1} and 13.81 mg/kg^{-1} for both layers. The mean AP values for the control site ranged between 11.23 mg/kg^{-1} and 14.54 mg/kg^{-1} for the surface and subsurface layer. AP values at the upper layer ranged between 10.12 mg/kg^{-1} and 13.81 mg/kg^{1,} with a mean of 12.41 mg/kg^{-1} and a standard deviation of 1.123. The values of AP at the subsurface soil layer in the sampled sites ranged from 9.77 mg/kg-1 to 11.23 mg/kg-1, with the mean and standard deviation being 10.48 mg/kg-1 and 0.58, respectively (Table 1). These values are rated as low to medium (Landon, 1991) and fall short of the suggested critical level of 15.0 mg/kg^{-1} (Adepetu et al., 1979) for sustainable crop cultivation. Even at this, AP values manifested some increase with the age of SI, as could be seen from Table 1. Observed improvements in soil P among the sampled sites might be due to yearly application of both animal manure and NPK fertilizers. Similarly, crop residues usually left on the farmstead after harvest quickly decompose and add up to soil P values. When compared with the mean AP values of the control site, it could be observed that values for all sites declined with the age of SI. At the surface layer, differences in mean AP values between the control and SI sites were significant (P=0.05) only at the first SI site that had 3 years of duration. This implies that AP values for the control site were almost the same in the remaining SI sites with longer periods of practice (Table 2). This further suggests that though some research workers (such as Lopez-Fando and Almendros, 1995; Nweke and Nsoanya, 2013) have established that P build up occurs in cultivated soils receiving NPK fertiliser applications, in the study area the buildup becomes significant only after the first three years of cultivation. On the other hand, there wasn't much difference between the mean AP values of the control sites and all the SI sites below the surface layer (Table 2).

Exchangeable sodium percentage (ESP)

The soil's exchangeable Na concentrations range from 0.6cmol^{+}kg^{-1} to 4.5cmol^{+}kg^{-1}, which corresponds to ESP values between 2.1 and 54.9% (Tables 1, 2). 15% is identified as the crucial value of ESP at which the majority of crops are adversely affected (Lebron et al., 2002). Na levels were below the suggested threshold levels in 50% of the sites (Tables 2, 3 and 4). These places' moderately high Na or somewhat sodic to severely sodic conditions may be caused by excessive evaporation, inadequate irrigation water management, a lack of drainage systems, and low Ca2+ because of the exchange complex's high Na+ concentrations. Lower net photosynthesis, energy losses for salt exclusion mechanisms, a bigger decrease in mineral element uptake, poor NO^3 assimilation necessary for plant growth, inhibition of essential enzymes, and competition with K+ are all possible effects of higher Na+ levels in soil and it is possible that too much Na+ in the soil may inhibit plant growth, which will result in lower crop yields (Seilsepour et al., 2009). The findings indicate that the research area needs to consider changes that could help prevent sodium-related problems. Makoi and Ndakidemi (2007) found that adding Ca2+ to the soil with things like organic manure and gypsum ($CaSO_4.2H_2O$) that are easy to get has worked well in northern Tanzania.

Table 2. SQI scores for the control and various DSI plots across the two sampling depths

Control and DSI plot under various yrs of cropping	Variable	SQI score and quality rating for the two sampling depths		Significance of the Difference between the two depths
		0-10	25-40	
Control	SQI Score	0.76	0.52	S
	Quality rating	High	Moderate	
15yrs	SQI Score	0.36*	0.31*	S
	Quality rating	Low	Low	
14yrs	SQI Score	0.48*	0.32*	S
	Quality rating	Low	Low	
10yrs	SQI Score	0.54*	0.34*	S
	Quality rating	Moderate	Low	
8yrs	SQI Score	0.57*	0.41*	S
	Quality rating	High	Moderate	
6yrs	SQI Score	0.63*	0.43*	NS
	Quality rating	High	Moderate	
5yrs	SQI Score	0.65	0.49	NS
	Quality rating	High	Moderate	
3yrs	SQI Score	0.76	0.54	NS
	Quality rating	Very High	High	
Significance of difference among the DSI practices		S	S	

Note: S (Difference significant; at 0.05 probability level), NS (Difference not significant; at 0.05 probability level); The quality rating criteria used was: Low (SQI values of 0.1 to 0.39), Moderate ((SQI values of 0.4 to 0.59), High (SQI values of 0.6 to 0.79) and Very High (SQI values of 8 and above); The asterisks denote the SQI values of the DSI plots that are statistically different (at 0.05 probability level) from those of the control; tested using t-test

Exchangeable cations

Calcium (Ca) concentrations in both soil layers ranged between 2.09 m/100 g and 3.89 m/100 g. Ca levels in the upper soil layers ranged between 2.25me/100g to 3.89me/100g, with 2.92me/100g and 0.58 as the mean and standard deviation for the sampled sites. In the subsurface soil layers, mean Ca values ranged between 2.0me/100g to 3.06me/100g with 2.57me/100g and 0.38 as the mean and standard deviation for all sites. It could be observed (Table 1) that the Ca content of the soils generally decreased with depth and duration of SI activities. Moreover, differences in mean Ca values at the surface layers (Table 2) between the control and all SI sites were statistically significant (P=0.05) in the much older SI sites (10 to 15 years old). But at the subsurface layer, most of the differences between the control and SI sites were not very big (Table 2).

Potassium (K) levels range between 0.019me/100g and 0.147me/100g for all SI sites in the study area (Table 1). The K values in the surface layer ranged between 0.068 me/100g to 0.147 me/100g with 0.111me/100g and 0.025 as the mean and standard deviation, respectively. In the sub-surface layers, exchangeable K values were found to range between 0.019me/100g and 0.110me/100g with 0.072me/100g and 0.038 as the mean and standard deviation, respectively. At the surface layer, differences between control and all the SI sites were generally significant (Table 2). At the subsurface layer, differences between control and the SI sites were only significant in the SI sites with 3- and 5-year durations, and not significant in the remaining sites (Table 2).

The exchangeable magnesium (Mg) ranged between 1.03me/100g and 1.99me/100g for all supplementary irrigation sites, which is rated as low (Awotunde, 1973). Mg values in the surface layers ranged between 1.20me/100g to 1.99me/100g, with 1.47me/100g and 0.27 as the mean and standard deviation, respectively. Similarly, the values in the subsurface layers ranged between 1.03 me/100g and 1.46 me/100g, with 1.20me/100g and 0.14 as the mean and standard deviation, respectively. Generally, the levels of Mg found in all the DSI sites at both layers were below the critical level of 2.0me/100g as established for Nigerian soils (Idris and El-ladan, 2013).

The exchangeable sodium (Na) ranged between 0.27me/100g and 0.88me/100g for all the SI sites. Na values in the surface layers ranged from 0.35me/100g to 0.88me/100g, with 0.55me/100g as the mean and 0.16 as the standard deviation. Na values in the sub-surface soil ranged between 0.27me/100g to 0.51 me/100g with 0.39 me/100g and 0.08 as the mean and standard deviation, respectively. It could be observed that values of all exchangeable cations manifested some decline from the upper layers to the subsurface layers among all the supplementary irrigation sites. In the same way, the values of all exchangeable cations seemed to go down as the length of supplementary irrigation went on (Faruk, 1997).

Cation exchange capacity (CEC)

The CEC determines how much cation soil can hold and adsorb. The capacity of soil clay and organic matter to absorb and exchange cations with those in soil solution is known as cation exchange. The amount of organic matter and clay in the soils determines this. The ability of the soil to retain mineral components increases with soil CEC (Joachim et al., 2008). Studies have revealed that exchangeable bases are low in soils, with CEC values of between 6 me/100g and 12 me/100g (NSS, 1990). Sanchez and Logan (1992) say that soils with low CEC are often worn down and can't grow plants well even when they have enough mineral elements like calcium.

The CEC values in the soil samples analysed ranged from 3.33me/100g to 5.88me/100g (Table 1). In the higher soil layers, the values ranged from 4.89 me/100g to 5.88 me/100g, with a mean and standard deviation of 5.35me/100g and 0.30, respectively. CEC values in the bottom layer varied from 3.33 mg/kg to 5.11 me/100g, with a mean of 4.65 me/100g and a standard deviation of 0.60. With the length of the SI, some drop in CEC values could be seen throughout the surveyed sites (Table 1). This could be explained by a decrease in SOM and a decrease in the amount of clay in the soil, two characteristics of the majority of Nigerian savannah soils. Kaolinite, the type of clay found in these soils, hardly makes a dent in CEC formation. It is widely acknowledged that SOM accounts for 25–90% of the total CEC of mineral soils' surface layers (Van Dijk, 1971; Oades, 1986). The property is regarded as the primary source of fixing CEC in soils with low-activity clays. The low CEC discovered in the study area may be attributed to the low organic matter of the soils (Table 1). Soils with lower CEC values are also linked to lower crop production (Sanchez and Logan, 1992).

SQI Assessment

Table 2 gives a summary of SQI computations for the control and DSI plots. It also presents a summary of the comparison of the SQI values of every plot with that of the control. It could be seen from the table that the values decrease with an increase in the number of years a plot has been under DSI, which indicates that the practice overtime promotes a decline in soil quality in the area. The decrease in soil quality with an increase in years of DSI practice could be a reflection of increases in trends of degradation (such as slope wash, accelerated destruction of litter and nutrient mining by crops' uptake) as soil is put under continuous cultivation. The values are, however, higher in the topsoil than in the subsoil in all the DSI and control plots, indicating that the upper layer has higher quality than the lower layer, which is expected given that biochemical activities and processes that promote soil quality are largely concentrated and more active in the upper soil layer (Karlen et al., 2008). It could also be seen from the table that the SQI values decreased with years under DSI practices, but it was not until the 8th year that the values were significantly lower than those of the control. This means that, even though the practice makes the soil less good, the quality doesn't change much until about the eighth year of DSI in the area.

Conclusion

The analysis of the characteristics of the soils under SI and control in the study area indicated that the practice had caused significant negative changes in the levels of most of the properties considered to extents that could preclude sustainable crop production in the area, which corroborates empirical evidence found in the literature on the effects of the use of ground water in irrigating soils of drylands The results obtained indicate in general that the SI activities as practiced in the area had significant deleterious effects on the selected physical and chemical indicators of soil quality to extents that might preclude sustainable agriculture on the soils. In particular, frequent draining and re-flooding of the soils every year as rain ceases in order to allow the crops to complete their growth cycle is causing sequential nitrification and de-nitrification, resulting in a loss of soil nitrogen in the irrigated farms. The percentage contents of potassium, organic carbon, organic matter, and some other essential nutrients required for plant growth and soil stability in irrigated farms have also decreased significantly when compared to the control. As the soils continue to be affected by increased salinisation and water logging, irreversible damage to them could result. Unfortunately, without SI activities, crop production cannot be made profitable in the area. Thus, it is recommended here that future developments of SI activities should factor the ecosystem change trade-offs associated with irrigation in dryland irrigation into the suitability criteria for its development. In particular, not only should drainage be made an important component of the SI activities (since sustainable irrigation cannot be undertaken without drainage), but additional steps should be taken to minimise the loss of critical nutrient elements required for effective crop growth. Studies have demonstrated, for instance, that sodic soils may require the addition of suitable amendments, such as FYM or gypsum, to lower the concentration of Na+ on the exchange complex. The soluble Na+ on the soil colloids will then be replaced by leaching, irrigation, or rainwater, and acidifying fertilizers like ammonium sulfate will be used to lower the pH of the soil (Clark et al., 2009).

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