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Changes in soil physical health indicators of an eroded land as influenced by integrated use of narrow grass strips and mulch

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ABSTRACT

Soil erosion remains a major threat to sustainable use of soil and water resources, and often leads to degradation of soil physical health. An erosion study was conducted on a sloping (7% slope) Rhodic kandiudult land at Ikenne (6° 51'N, 3° 42'E), Nigeria, to assess changes in soil physical health index (SH_{phy}) following integrated use of vetiver grass strips (VGS) and vetiver mulch (VM). The VGS spaced at 10 m (10VGS) and 20 m (20VGS) intervals were integrated with VM of 2 (VM_2) and 4 (VM_4) t/ha as: 10VGS + VM_2, 10VGS + VM_4, 20VGS + VM_2 and 20VGS + VM_4. The four integrated treatments and 10VGS, 20VGS, VM_2, VM_4, VM_6 and no vetiver (NV) were assessed for their effectiveness in reducing soil loss and improving SH_{phy} with NV served as a control. Soil physical health indicators (particle-size distribution, bulk density, water stable aggregates (WSA), mean-weight-diameter, moisture retention, pore-size distribution, saturated hydraulic conductivity, soil strength and soil organic carbon) were determined and integrated to form data set for SH_{phy}, using the soil management assessment framework. The aggregate-associated carbon (Agg-C) in < 2000 μm and 2000–1000 μm classes accounted for 55–73% variation in soil organic carbon stock among the treatments. The transmission and storage pores (0.5–300 μm pore size) together constituted 52.5–63.1% of the total pore space with the largest pores obtained under 10VGS + VM_4. The mean SH_{phy} varied significantly ($p \leq 0.05$) among the treatments, and it was highest for 10VGS + VM_4 (0.79) and least for NV (0.49). Changes in SH_{phy} over 3 years ranged from –10.9% to 33.1%. The highest maize grain yield was obtained under 10VGS + VM_4 (1.82 t/ha), closely followed by VM_6 (1.79 t/ha), and the least yield recorded under NV (0.89 t/ha). Positive and significant relationship ($r = 0.93$; $p < 0.01$) was established between SH_{phy} and maize grain yield. However, the significant beneficial of vetiver mulch alone in improving soil physical health was dwarfed by the potential danger of high soil loss beneath the mulch cover in the absence of vegetative strips.

1. Introduction

In recent decades, land conversion from forest to farmlandhas exacerbated soil erosion hazards in many tropical countries; often in an unchecked fashion. Although, there are other competing non-agricultural uses which also led to large deforestation and increasing encroachment on marginal lands whose resilience is limited for crop production (Lal, 1995). Soil erosion is a selective process that removes soil components and consequently exposes the soil to all kinds of physical degradation. Oyedele and Aina (1998) reported that erosion by water has more devastating effects than other land degradation processes that influence soil productivity and crop yield. On steep lands, erosion accentuates low water holding capacity, poor aeration, soil structural degradation, surface sealing and hard-setting, and reduction in soil infiltrability (Pla, 1997).

Soil health, synonymous to soil quality, is the key factor of sustainable agriculture, which influences the quality of the ecosystem as air and water quality do. Soil physical health is the ability of a given soil to meet plant and ecosystem requirements for water, aeration, and strength over time and to resist and recover from processes that might diminish that ability (McKenzie et al., 2011). However, protection of soil physical health under intensive land use and fast economic development is a major challenge for sustainable resource use in the developing world. In sub-Sahara Africa (SSA), particularly in Nigeria, most farmers engage heavy machinery for land preparation without any guiding principle (Babalola, 2000). This process inadvertently removes the fertile topsoil freely and further exposes the subsoils so left, after being bulldozed, to soil erosion. Large number of farmers are, however,

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not convinced that a sound erosion control system brings about improvement in soil physical health and increased crop productivity, even in short term. This is partly because of the self-reliance on replacing the eroded soil nutrients with chemical fertilizers (Mbagwu, 1984). Meanwhile, Aina, (1979) and Meyer et al. (1985) demonstrated that a physically degraded soil possibly will not respond to fertilizer inputs if the top soils have been removed.

There are three recognizable but interdependent aspects of soil health identified by Doran and Parkin (1994). They include biological, chemical and physical health but often time, the soil physical health is given little consideration while much attention is on the chemical and biological indices in several soil health studies. Whereas the suitability of soil for sustaining plant growth and biological activity is a function of its physical properties (Hillel, 2004). In an attempt to curb erosion in Nigeria, several studies have documented soil, water and nutrient losses (Lal, 1976, 1986; Obi and Salako, 1995; Lal, 1997a,b; Oyedele and Aina, 1998; Salako et al., 2006; Babalola et al., 2007; Are et al., 2011), but few (Obi and Nnabude, 1988; Dada et al., 2016) have focussed on the soil physical health of eroded land.

In recent years, the use of vegetative strips and mulch, especially those of vetiver grass, has attracted scientific interest because of their effectiveness in reducing soil, water and nutrient losses. Considerable number of studies (Borin et al., 2005; Babalola et al., 2007; Are et al., 2011; Oshunsanya et al., 2014) have highlighted the flow-resistive capacity of vetiver grass strips and its ability modify the hydrology of overland flow, while only few studies (Babalola et al., 2007; Are et al., 2012; Donjadee and Tingsanchali, 2016) assessed the efficacy of vetiver grass mulch in reducing soil erosion in the tropics. The influence of vetiver grass strips and mulch on soil physical health of an eroded land has been of little concern in most of these studies. Though, the important role of vetiver grass strips in preventing water erosion and soil mass movement has been recognized in recent years, only few studies (Babalola et al., 2007; Jordán et al., 2010; Bhattacharyya et al., 2011) have attempted to verify changes in some soil physical properties of eroded land with either vegetative strips or mulch materials. However, there is scant information on the effectiveness of integrated use of vegetative strips and mulch in improving soil physical health of eroded land. Therefore, the basic assessment of soil physical health in this study was to investigate the potential of combined application of vegetative grass strips and mulch of vetiver grass in controlling soil loss and modifying soil physical health indicators of an eroded land during a three-year study.

2. Materials and methods

2.1. Experimental site and soil

The trial was conducted at a research station of the Institute of Agricultural Research and Training (IAR&T.), Ikenne (6° 51'N, 3° 42'E), Nigeria, between 2011 and 2014. The site is characterized by a tropical climate with marked wet and dry seasons. The mean annual rainfall recorded for a period of 10 years at Ikenne was 1441 mm (IAR&T, 2016). Rainfall peaks occur mostly in June and September while annual temperature ranges between 21.3 °C and 33.2 °C. There are two cropping seasons: early (March/April to early August) and late (mid-August to November) seasons. The site had been under continuous maize (*Zea mays* L.) cultivation managed with NPK-20-10-10 for more than 15 years before it was opened up for this study. The site was characterized by the presence of rills created by water erosion. Previous erosion control measure was by making contour bunds, which often break during heavy rainstorm. The soil was deep, well drained with red (2.5YR 4/8) to brownish-red (5YR 5/4) in colour. It has a sandy loam texture at the surface (0–15 cm depth) and belongs to Ultisol, classified as Rhodic Kanhaplustult (Okusami et al., 1997; Soil Survey Staff, 2010). The soil was locally classified as Alagba series (Moss, 1957).

Table 1
Experimental treatments and their description.

Treatment	Description
NV	Control (non-vetiver)
10VGS	Vetiver grass strips at 10 m interval
20VGS	Vetiver grass strips at 20 m interval
VM_2	2 t ha^{-1} vetiver mulch
VM_4	4 t ha^{-1} vetiver mulch
VM_6	6 t ha^{-1} vetiver mulch
20VGS + VM_2	Vetiver grass strips at 20 m interval + 2 t ha^{-1} vetiver mulch
20VGS + VM_4	Vetiver grass strips at 20 m interval + 4 t ha^{-1} vetiver mulch
10VGS + VM_2	Vetiver grass strips at 10 m interval + 2 t ha^{-1} vetiver mulch
10VGS + VM_4	Vetiver grass strips at 10 m interval + 4 t ha^{-1} vetiver mulch

2.2. Experimental setup and treatments

The experiment comprised 10 treatments, arranged in a randomized complete block design (RCBD) with three replications. Details of treatments are illustrated in Table 1. The field (0.5 ha) was initially prepared by conventional tillage by disc ploughing twice and thereafter harrowed before partitioning the land into three blocks with each block having 10 experimental plots. Each of the plots measured 40 m long and 3 m wide uniformly laid on 7% slope. Spacing of 0.5 m was maintained between plots within each block and 1.0 m buffer between blocks. Borders around each runoff plot were made with earthen bunds of about 15 cm high around the plot to prevent run-on of the runoff.

Vetiver grass (*Chrsopogon zizanioides* (L.), Roberty) strips were established immediately after field preparation by planting multiple grass slips (about 40 slips, ~7.5 cm intra-row spaced) into 2.5 cm deep trenches across 3 m wide of the selected plots assigned for vetiver grass strips (10VGS or 20VGS). The roots of the grass slips were pre-treated with cow dung slurry while 150 kg ha^{-1} of NPK-20-10-10 was also applied at planting for faster establishment and tillering. Two calibrated metal rods (erosion pins) were installed at 15 cm away from the vetiver grass strips to measure soil accumulation by the grass strips (Fig. 1). The rods were installed six months after the establishment of vetiver grass strips. At this time, the vetiver grass strips is well established. Each rod (30 cm long and 0.5 cm thick) was driven vertically into 15 cm soil depth using mallet for firmness of the rod while 15 cm remained above the soil surface. For other plots with no vetiver grass strips, erosion pins were positioned at every 10 m interval down the slope to measure changes in the soil surface level.

In each cropping season, vetiver mulch was usually applied at every 3 weeks after sowing on selected plots (VM_2, VM_4, VM_6, 10VGS + VM_2, 10VGS + VM_4, 20VGS + VM_2 and 20VGS + VM_4). Maize (*Zea mays* var. SUWAN-1-SR-Y) was planted as test crop in each season. The recommended rate of NPK 20-10-10 fertilizer applications for maize production in the region ranges between 200 and 300 kg ha^{-1}, depending on the soil nutrient status. However, NPK 20-10-10 fertilizer was only applied in the second year at the rate of 150 kg ha^{-1} to boost the initial growth. The maize crop was harvested by hand at physiological maturity to determine total above-ground biomass and grain yield on each plot at 15% moisture content.

2.3. Soil sampling and laboratory analyses

Soil samples were collected before land preparation to quantify the baseline status of the soil before the trial. The initial soil status is presented in Table 2. Subsequent soil sampling and data collection were carried out after 2, 4 and 6 cropping seasons to evaluate the effects of various treatments on selected soil physical health indicators. The surface soil layer, i.e. the top centimetres (0–10 cm) of the soil profile, was sampled because this layer controls many critical and environmental processes, including seed germination and early seedling growth, surface crusting, infiltration and runoff, erosion (Reynolds

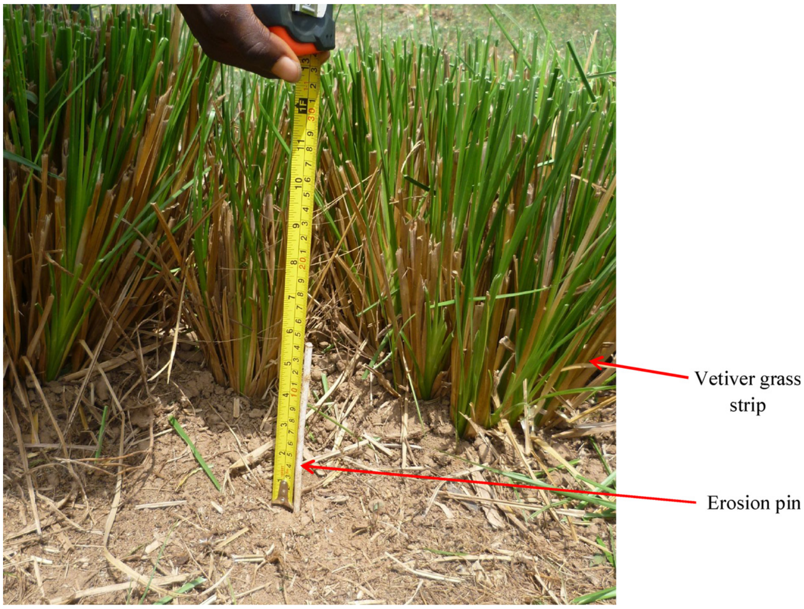

Fig. 1. Measurement of soil loss with erosion pin.

Table 2
Minimum data set (MDS) assessment of soil physical processes.

Soil processes relating to crop productivity	Relative Weight	Selected soil health indicators relating to soil processes	Relative Weight
Root penetration	0.15	Bulk density	0.40
		Total Porosity	0.20
		Soil strength	0.40
Ability to resist degradation	0.50	Water stable aggregates	0.50
		Particle size distribution	0.15
		Organic matter content	0.35
Ability to reduce soil erodibility	0.15	Organic matter content	0.30
		Permeability	0.10
		Water stable aggregates	0.35
		Erodibility factor	0.15
		Surface roughness	0.10
Water retention	0.20	Hydraulic conductivity (K_{sat})	0.15
		Particle size distribution	0.20
		Surface roughness	0.20
		Available water content	0.35
		Macroporosity	0.15

et al., 2009). To ensure representative sampling, bulk soil samples were composite of 10 samples (one sample/ ~4 m interval, down the slope) taken from 0 to 10 cm depth within a replicated plot. Soil loss was computed by considering the changes that occur in the above ground height of erosion pins following the relationship described by Hudson (1993) and Schuller et al. (2007), as expressed in Eq. (1):

$$S_L = [L(t) - L_0\delta, \tag{1}$$

where S_L (kg m^{-2}) is the amount of soil loss at that point, L_0 (m) is the initial length of erosion pin at the time of insertion, L(t) (m) is the exposed length of erosion pin after a defined period t (yr.) and δ (kg m^{-3}) is the density of the surface soil. In case $[L(t) - L_0]$ is less than zero, soil attrition (removal) has taken place during the observation period and if $[L(t) - L_0]$ is greater than zero, soil accretion (deposition) has occurred at the measuring point during the observation period. The soil loss values were expressed in absolute values ($/S_L/$) to obtain positive values.

Particle size distribution of the soil of each plot was carried using a modified Bouyoucos hydrometer method as described by Gee and Or (2002). A cylindrical core of 5 cm diameter and 5 cm in height was used to take undisturbed soil samples from 0 to 10 cm depth at 5 different sampling points (one core sample/ ~8 m interval, down the slope) for soil bulk density (ρ_b) determination as described by Grossman and Reinsch (2002). Cone penetration test, as described by Bradford (1986), was carried out from 5 sampling points at ~8 m interval, down the slope for soil strength determination at 0.05-m depth increments up to 0.2 m depth, using a gauge penetrometer (FARNELL Testing Machines, Hatfield, England). Soil strength was measured twice in year: during a dry spell and wet period, to reflect temporal changes (effects of treatments over time) in relation to soil moisture content. Gravimetric moisture content of the soil was also determined in each time the cone penetration test was being carried out.

Soil moisture retention within 0–10 cm depth was determined in the laboratory using cylindrical core of 5 cm diameter and 5 cm height and tension table assembly (Topp and Zebchuk, 1979) for lower suctions (0–6 kPa) and pressure plate apparatus for higher matric suctions (10, 50, 100, 500, and 1500 kPa), following Dane and Hopmans (2002) procedures.

Pore size distributions were calculated using the water retention data and capillary rise equation (Eq. (2)) as described by Flint and Flint (2002):

$$r = -\rho wgh = -\frac{(2\gamma cos\alpha}{\psi} \tag{2}$$

where r is the mean equivalent radius of pores (m) at a given matric potential ψ (kPa); γ is the surface tension of the water against the wetting surface (mJ m^{-2}) at the laboratory temperature; α is the contact angle between solid and water interface, assumed to be zero; *h* matric suction or pressure head (cm water) applied to drain the water; ρ_w is the density of water (Mg m^{-3}), and g is the acceleration due to gravity (m s^{-2}). In this study, the pores were grouped as suggested by Greenland (1981) into transmission pores (P_T) (50–500 μm equivalent cylindrical radius (ECR) corresponding to 20–100 cm of water), storage pores (P_S) (0.5–50 μm ECR corresponding to 100–15,000 cm of water) and residual pores (P_R) (0.5 μm ECR corresponding to > 15,000 cm matric suction). Total porosity was calculated as the saturated weight of sample minus the dry weight of the sample divided by sample volume.

Soil samples were also taken from 5 points per plot with cylindrical cores (5 cm diameter and 5 cm height), at 0–10 cm depth, to determine saturated hydraulic conductivity (K_{sat}) in the laboratory using a constant head permeameter (Reynolds and Elrick, 2002).

Water-stable aggregates and mean weight-diameter of undisturbed soils collected from 0 to 10 cm depth with hand trowel were determined at the end of each year (every 2 cropping seasons) using a modified Kemper and Rosenau (1986) wet sieving method, as described by Nimmo and Perkins (2002). Three hundred grams (300 g) fresh soil were sieved using 5 mm sieve while the retained soil aggregates (> 5.0 mm) were collected and air-dried. Fifty grams (50 g) of the air-dried soil aggregates were placed on a set of sieves: 2000, 1000, 250, 53 μm in that order and then attached to a dipping machine. A pan of the same size was attached with the set of sieves below the 53 μm to account for aggregates < 53 μm. The set of sieves was cycled through a column of water for 10 min (30 cycles per min, 4.0 cm stroke length). All visible plant residues, fauna and stones were removed before the sieving procedure. Each fraction of the retained soil was oven dried at 105 °C to a constant mass and made sand corrections.

Soil organic carbon (SOC) from the whole soil and carbon distribution within the aggregate classes (Agg-C) at the end of year 3 were measured by loss-on-ignition method as described by Cambardella et al. (2001). Meanwhile, 5-g subsamples from the aggregate classes (< 2000, 1000–2000, 250–1000, 53–250 and < 53 μm) and whole soil were sampled, dried at 65 °C to constant mass and further dried at 450 °C in electric furnace to determine the carbon contents

2.4. Soil physical health assessment and temporal changes

A Soil Management Assessment Framework (SMAF) as described by Andrews et al. (2004) was adopted in quantifying soil physical quality in this study. The soil physical health indicators including organic matter content were selected based on their sensitivities to cause changes in soil function under water erosion process and integrated into quality index based on different soil processes relating to crop productivity (Table 2). In this framework, the integration was based on the transformation of the observed physical indicators using non-linear scoring curves (Andrews et al., 2004) and standard scoring functions (Wymore, 1993). The measured values of indicators were transformed into dimensionless values (ranging between 0 and 1) based on the critical values of the indicators (Lal, 1994) for easy combination into single value. Relative weights were assigned to the indicators and the identified soil processes according to their level of importance to crop production function (Table 2). The soil physical health indicators and their processes were integrated into a quality index value. All indicators affecting a particular process were grouped together, given scores and relative weights based on importance. The score for each indicator was multiplied by the appropriate weight and summed to provide soil quality rating for each process. The soil quality (sq) rating of each process was also multiplied by the appropriate weight, producing a matrix that was summed to provide soil physical health index for crop production as follows in Eq. (4):

$$SQ_{phy} = \sum_{i=1}^{n} WS = q.\ rp\ x\ wt + q.\ rd\ x\ wt + q.\ wr\ x\ wt + q.\ re\ x\ wt \tag{3}$$

where SQ_{phy} is the soil physical quality index; W is the total weighted average of the soil physical processes, S is the relative scores of the factors; q.rp is the soil quality rating for root penetration process; q.rd is the soil quality rating for ability to resist structural degradation process; q.wr is the soil quality rating for water retention; and q.re is the soil quality rating for reduction in soil erodibility.

In quantifying the temporal changes in soil physical quality (dSQ_{phy}/dt) over the 3-year period, a modified model developed by Larson and Pierce (1994) was used as described in Eq. (4):

$$dSQ_{phy/dt} = f\left[\frac{\frac{sq_{it}-sq_{t0}}{sq_{t0}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \frac{sq_{nt}-sq_{t0}}{sq_{t0}}}{dt}\right] \tag{4}$$

where dSQ_{phy}/dt = dynamic change in soil physical health over the study period

sq = soil physical quality index

sq_{it} = soil physical quality index of the year under measurement

sq_{t0} = initial soil physical quality index of the experimental plots before the study.

sq_{nt} = soil physical quality index of the nth year

dt = change in time (years)

An aggrading soil physical quality would have a positive dSQ_{phy}/dt and a degrading soil physical quality would have negative dSQ_{phy}/dt.

2.5. Statistical analysis

The statistical analyses were performed using the general linear model procedures (GLM Proc) of the statistical analysis software (SAS Institute, 2002). Analysis of variance (ANOVA) test was carried out to assess whether the ratings of soil physical health under a particular year and over the years differed among treatments, while assuming a randomized complete block design (RCBD). Separation of means was subjected to a Duncan Multiple Range Test (DMRT) at 0.05 probability level, unless otherwise stated. Data for soil loss in case of negative values were transformed to meet assumptions of normality and for easy comparison with positive values. The relationships between soil physical health and maize grain yield, and Agg-C and aggregate-class distribution were evaluated using Pearson correlation analysis to determine whether there are significant correlations between the pairs.

3. Results and discussion

3.1. Soil loss

The soil losses for 3-year study are presented in Fig. 2. On average, the soil loss varied from 0.71 to 4.72 t ha^{-1} yr^{-1} among the treatments. The soil losses from different plots for the 3-year study showed that vetiver-managed (whether VGS, VM or combined VGS + VM) plots had better and significant ($p \le 0.05$) control of soil loss than unamended control (NV). In comparison, 10VGS had significant reduction in soil loss than for 20VGS and VM_2 but not differed significantly from VM_4 and VM_6. However, among the integrated VGS + VM, 10VGS + VM_4 appeared more effective in reducing soil loss and significantly different from other amendments. Generally, it was obvious that soil sediment was better trapped by 10VGS in those erosion plots that had 10VGS (i.e. 10VGS, 10VGS + VM_2 and 10VGS + VM_4) than the 20VGS (i.e. 20VGS 20VGS + VM_2 and 20VGS + VM_4) and mulch only (VM_2, VM_4 and VM_6). The short spacing (10 m interval) between vetiver grass strips (VGS) coupled with the stiff structure of the grass, increased the sediment trapping efficiency of 10VGS treated plots than either those of 20VGS or vetiver mulch (VM) alone (Are et al., 2011). In this study, the higher vetiver mulch rates (such as 6 t ha^{-1} vetiver mulch) that protected the soil surface limited particle detachment and it reduced soil loss than 4 t ha^{-1} mulch by 10.5%. Study by Jordán et al. (2010) linked application of mulch to increase in surface roughness and interception of raindrops by the large quantity of mulch (such as 6 t ha^{-1} vetiver mulch), which delayed runoff generation. However, the higher vetiver mulch rates were less effective in reducing soil loss compared to VGS at 10 m interval (i.e. 10VGS). Despite the soil surface shielding by the imposed vetiver mulch, the soil losses under vetiver mulch-managed plots were higher than the VGS-managed at 10 m interval. Babalola et al. (2007) demonstrated that vetiver grass “standing”, as in a strip, was more effective than vetiver grass “prostrate” as in a mulch in controlling soil loss of an alfisol in Nigeria. Similar observation was made by Are et al. (2012) where 15% increase in soil loss was recorded

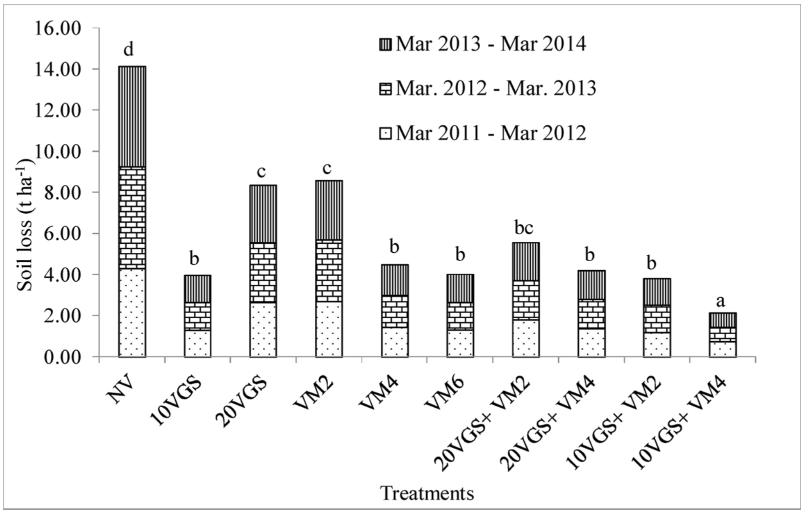

Fig. 2. Soil loss distribution for three consecutive years.
Means across the bars, for soil loss distribution across the three years, containing a common letter are not significantly different ($p \le 0.05$).

under VM_6 as against 10VGS. Elsewhere, Cogle et al. (2002) observed that the removal of finer fractions accounted for large part of eroded sediments recorded under rice straw on erosion plots in India. From the standpoint of soil conservation, the integration of 10VGS and VM_4 (10VGS + VM_4) took the full advantages of interception of sediment by grass strips and surface soil protection by mulch which perhaps modified the hydrology of the overland flow in terms of sediment settling velocity and deposition, and consequently reduced soil loss than other treatments.

3.2. *Soil physical quality indicators*

3.2.1. *Particle size distribution, bulk density and soil strength*

The soil particle size distribution is shown in Table 3. The sand fractions ranged from 737 g kg^{-1} to 780 g kg^{-1} among the treatments for three consecutive years (2 cropping seasons $year^{-1}$). The amount of sand particles on NV plot was consistently larger (though not significant, $p \le 0.05$) than other treatments for the entire study period. Similarly, the silt particles did not show any significant variation among the treatments. However, silt did not follow any discernible trends as observed in sand particles but its mean values under NV were consistently lower than other treatments. Clay particles, on the other hand, showed statistically significant differences ($p \le 0.05$) among the treatments with the highest clay content consistently recorded under 10VGS + VM_4 during the study period. Although, the particle size distribution of the eroded sediment was not determined per se, it is difficult to lay claim to the movement clay particles either in vertical movement or overland that accounted for the observed differences. In spite of the differences in soil clay contents, the textural classes of the soils for different treatments were the same (i.e. sandy loam). This confirms Hulugalle et al. (1985) assertion that changes in soil texture does not occur easily but takes place after a long period of time to occur irrespective of management practices put in place. It was evident from this study that erosion detached more smaller fractions easily as observed under NV treated soil. This is consistent with preferentially removal of fine soil particles by soil erosion reported by Blanco-Canqui and Lal (2007).

The soil bulk density (ρ_b) ranged from 1.25 to 1.49 Mg m^{-3} among the treatments (Table 3). In each year, ρ_b for VM_6 was consistently lower than other treatments (though not significantly different from 10VGS + VM_4). The control (NV) plots, on the other hand, had the highest bulk densities (1.42, 1.46 and 1.49 Mg m^{-3}) for the three consecutive years. However, it was evident from the study that bulk density reduction was more pronounced under vetiver mulch-managed plots, although the reduction was significantly ($p \le 0.05$) higher vetiver mulch rates (VM_4, VM_6, 20VGS + VM_4 and 10VGS + VM_4. The low bulk density recorded under mulch may be linked to greater earthworm activity, an indication of in-situ structural changes as suggested by Mupangwa et al. (2013). In contrast, the exposure of soil surface in plots without mulch perhaps allow raindrop impact to destroy aggregation while increasing the bulk density that was obvious on NV plots. The changes in the surface soil bulk densities, compared to the initial bulk density (1.41 Mg m^{-3}) before the study, were such that the bulk densities of vetiver mulch-managed soils reduced by 0–11.4% while those for NV increased by 0.7–5.7% over the years. However, the trends of change in bulk densities under 10VGS and other treatments without mulch were not consistent (Table 3). In previous studies, Babalola et al. (2007) reported 8.1% decrease in soil bulk density following application of 6 t ha^{-1} $year^{-1}$ mulch while Blanco-Canqui and Lal (2007) recorded 45 and 57% decreases in bulk density under 8 and 16 t ha^{-1} $year^{-1}$ wheat-straw mulch, respectively for 10-year duration. However, the trends were in contrast with observed increase in bulk density recorded by Bottenberg et al. (1999) while Acosta et al. (1999) found no linear relationship between mulch rate and soil bulk density. Perhaps the mixed results is attributed to difference in soil type (different from sandy loam) and the type of mulch material used.

A measure of soil strength (Table 3) under various treatments showed that penetration resistance (PR) values of surface soil, especially when the soil was wet, were significantly different from one another, though the PR values of all the treatments including unamended control (NV) were below the critical level (2 MPa) for plant root growth. The resistance offered to cone penetration when the soil was moist (PR_{wet}) still showed that vetiver mulch-managed soil offered less resistance with VM_6 having the least average resistance of 0.64 MPa and closely followed by 10VGS + VM_4 (0.66 MPa) after 3 years. On the other hand, the PR_{wet} (average of 1.28 MPa) of soil under unamended control (NV) treatment was consistently and significantly higher than other treatments for the 3-year study. Although, the resistance offered by the soils to cone penetration on dry soil (PR_{dry}) was not significantly ($p \le 0.05$) different irrespective of the treatments, VM_6 and NV consistently offered the least and highest resistances to cone penetration (Table 3). Despite the PR_{wet} values of the soils of all the treatments were below the critical level, the variation observed might be explained by the levels of protective covering volume of vetiver grass mulch and consequently the variation in percentage moisture retention. It was observed in this study that as low as 2 t ha^{-1} mulch, the resistance offered to cone penetration by the mulch-managed soil is less than for 20VGS or 10VGS that stands alone without mulch cover. Khurshid et al.

Table 3
Effects of integrating vetiver grass strips and vetiver mulch on soil physical health indicators.

Treatments	Sand g kg^{-1}	Silt	Clay	ρ_b Mg m^{-3}	TP %	†PR_{wet} MPa	††PR_{dry}	WSA > 250 µm (kg kg^{-1})	MWD (mm)	$^zK_{sat}$ (10^{-3} cm s^{-1})
	Soil physical health indicators after two cropping seasons – Year 1									
NV	779	118	103a	1.42de	46.4a	1.14e	2.08ns	0.530a	0.91a	13.4a
10VGS	766	119	115ab	1.38cd	47.9bc	0.95d	2.07	0.541a	1.02ab	22.7b
20VGS	762	122	116ab	1.41de	46.8ab	1.09e	2.07	0.537a	0.96a	19.4ab
VM_2	770	125	105ab	1.41de	46.8ab	0.93cd	2.07	0.532a	0.91a	15.4a
VM_4	754	124	122b	1.37bcd	48.3cd	0.79b	2.04	0.617c	1.45c	34.2c
VM_6	737	128	135c	1.32a	50.2e	0.68a	2.02	0.713d	2.05d	51.2d
20VGS + VM_2	758	128	114ab	1.40de	47.2abc	0.92c	2.05	0.540a	0.99a	24.2b
20VGS + VM_4	764	112	124b	1.36bc	48.7cd	0.78ab	2.03	0.620c	1.55c	37.6c
10VGS + VM_2	758	124	118ab	1.39cd	47.5ab	0.90c	2.04	0.603b	1.13b	25.7b
10VGS + VM_4	737	127	136c	1.34ab	49.4de	0.73a	2.03	0.715d	2.10d	47.8d
	Soil physical health indicators after four cropping seasons – Year 2									
NV	780ns	117ns	103a	1.46e	44.9a	1.34e	2.14ns	0.518a	0.89a	12.8a
10VGS	765	118	117b	1.40d	47.2ab	0.95cd	2.05	0.544ab	1.03ab	22.5b
20VGS	764	121	115ab	1.42de	46.4ab	1.05d	2.07	0.538a	0.96a	16.4a
VM_2	767	127	106ab	1.41de	46.8ab	0.91c	2.07	0.541ab	0.92a	17.2a
VM_4	751	125	124b	1.34bc	49.4bc	0.77b	2.02	0.634b	1.52c	37.2c
VM_6	741	122	137c	1.29a	51.3c	0.65a	1.98	0.779c	2.10d	53.1d
20VGS + VM_2	756	130	114ab	1.39cd	47.5ab	0.90c	2.02	0.554b	1.02ab	26.3b
20VGS + VM_4	750	126	124b	1.32ab	50.2bc	0.75ab	2.00	0.654b	1.63c	40.5c
10VGS + VM_2	757	125	118b	1.38bcd	47.9ab	0.89c	2.02	0.610b	1.16b	27.4b
10VGS + VM_4	737	126	137c	1.30a	50.9c	0.66a	1.99	0.786c	2.12d	53.4d
	Soil physical health indicators after six cropping seasons – Year 3									
NV	780ns	118ns	102a	1.49d	44.2a	1.36f	215.5ns	0.498a	0.79a	11.4a
10VGS	765	118	117b	1.39bc	47.2ab	0.94de	2.05	0.546ab	1.03ab	21.3b
20VGS	763	123	114ab	1.43bcd	46.0ab	1.02e	2.06	0.538a	0.97a	15.2a
VM_2	768	126	106a	1.41bcd	46.8ab	0.90cd	2.06	0.546ab	0.93a	17.8a
VM_4	755	122	123b	1.31ab	50.6c	0.68b	2.00	0.664b	1.58c	38.2c
VM_6	742	121	137c	1.25a	52.8c	0.59a	1.98	0.786c	2.14d	53.8d
20VGS + VM_2	755	130	115b	1.37bc	48.3b	0.87c	2.01	0.566b	1.08ab	26.9b
20VGS + VM_4	754	122	124b	1.29ab	51.3c	0.66a	1.99	0.675b	1.66c	42.4c
10VGS + VM_2	756	123	121b	1.36b	48.7bc	0.83c	2.01	0.625b	1.28b	28.1b
10VGS + VM_4	742	120	138c	1.27a	52.8c	0.59a	1.98	0.792c	2.19d	54.1d

Different letters indicate significant differences among treatments within a column at the end of each year at $P \leq 0.05$ according to Duncan multiple range test (DMRT). ns indicates non-significant differences within a column at the end of each cropping season at $P \leq 0.05$.

† Average moisture contents for PR_{wet} at the time of measurement in year 1, year 2 and year 3 were 20.3%, 20.1% and 21.2% respectively.

†† Average moisture contents for PR_{dry} at the time of measurement in year 1, year 2 and year 3 were 9.7%, 10.4% and 10.2% respectively. ^{z}Geometric mean value.

(2006) reported that surface mulch application contributes to improvement in ecological environment of the soil and increased soil water content, resulting in less root penetration resistance. Meanwhile, Lal (2000) adduced the decrease in penetration resistance with increase in mulch rate may partly be due to fairly high soil moisture content. This could have been a possible explanation for the significant reduction in soil PRs under VM_6 plots with higher moisture content (not reported).

3.2.2. Aggregate sizes and distribution

The soil aggregate distribution and sizes in terms of Water Stable Aggregates (WSA > 250 µm) and Mean Weight Diameter (MWD) are reported in Table 3. Water stable aggregates ranged from 0.530 to 0.715 kg aggregates kg^{-1} soil at the end of first year; 0.518 to 0.786 kg aggregates kg^{-1} soil in second year and 0.508 to 0.792 kg aggregates kg^{-1} soil in the third year. The soil managed with 10VGS + VM_4 had a marked increase in water stable aggregates and significantly higher than other treatments except VM_6. On the other hand, soil aggregation was poorly formed under no-vetiver grass (NV) plots with reduction in macroaggregates from 0.540 kg aggregates kg^{-1} soil before the trial to 0.498 kg aggregates kg^{-1} soil at the end of third year (after 6 cropping seasons). However, the differences in water stable aggregates between NV and 10VGS, 20VGS, VM2 and 20VGS + VM_2 treatments were not statistically significant ($p \leq 0.05$). Meanwhile, aggregate sizes in term of MWD, followed trends similar to WSA > 250 µm as shown in Table 3. Among the treatments, the MWD (2.10 mm) for 10VGS + VM_4 was the highest and larger than other treatments after the first two cropping seasons (i.e. after year 1). Continuous application of 10VGS + VM_4 in subsequent years increased the aggregate size to 2.19 mm at the end of year 3. However, the MWD for 10VGS + VM_4 did not differ significantly ($p \leq 0.05$) from VM_6 treatments throughout the study period. The unamended control (NV) consistently had the least MWDs with an average of 0.84 mm after 3 consecutive years. The least value obtained on the NV plot might be due to the absence of protective cover by mulch to surface during the entire study period. The positive influence of mulch cover on aggregate stability and size distribution is indirect and this may be due to the higher earthworm activity observed in mulched soil with large quantities of worm casts at sampling. Aggregate stability and size distribution are two physical measurements suggested as indicators for evaluating effects of soil and crop management practices on soil quality (Arshad and Coen, 1992). These measurements were suggested because they reflect resistance of soil to erosion (Luk, 1979; Tejada and Gonzalez, 2007). In this study however, vetiver grass mulch, especially those with high rates in VM_4, VM_6, 20VGS + VM_4 and 10VGS + VM_4, contributed more to the build-up of soil aggregation than other treatments without mulch or low mulch rates (NV, 10VGS, 20VGS, VM2, 20VGS + VM_2 and 10VGS + VM_2). The increase in soil aggregation under mulched plots suggested the contributive effect of organic matter in improving soil aggregation following mulch application. As the incorporated mulch is breaking down, the level of soil organic matter increased to strengthen macroaggregation. Previous studies (Sonnleitner et al., 2003; Babalola et al., 2007; Blanco-Canqui and Lal, 2007; Karami et al., 2012; Zhang et al., 2014) have established a close relationship between the soil aggregate

Table 4
Soil organic carbon for the whole soil and their distribution within aggregates sizes after six cropping seasons.

Treatments		Distribution of carbon within the aggregates				
	SOC for whole soil ($g\,C\,kg^{-1}$ soil)	> 2000 µm	2000–1000 µm	1000–250 µm	250–53 µm	< 53 µm
NV	8.95a	2.82ab	1.85a	1.48a	0.98ns	1.31ns
10VGS	9.95a	3.03b	2.28a	1.55a	0.91	1.28
20VGS	9.60a	2.86ab	2.13a	1.50a	0.93	1.28
VM_2	10.00ab	2.34a	3.22ab	1.62a	0.92	1.26
VM_4	15.50bc	3.86c	5.64bc	2.86c	0.89	1.27
VM_6	20.50d	5.92d	8.54d	3.42d	0.87	1.27
20VGS + VM_2	12.70b	3.03b	4.38b	2.36b	0.90	1.27
20VGS + VM_4	16.30c	4.11c	6.04c	2.92cd	0.89	1.26
10VGS + VM_2	13.00b	3.19b	4.42b	2.45b	0.91	1.25
10VGS + VM_4	20.10d	5.99d	8.44d	3.31d	0.87	1.26

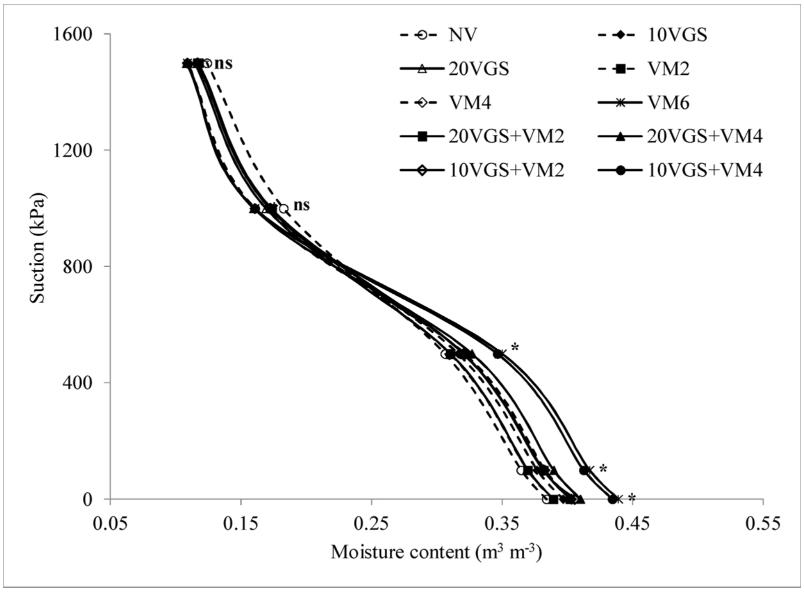

Fig. 3. Soil moisture retention as affected by vetiver grass strips and mulch after 3-year study.
The asterisk (*) indicates significant difference at $p \leq 0.05$. ns is non-significant.

stability index and SOM content.

3.2.3. *Soil organic carbon concentration and its distribution within the aggregate classes*

Soil organic carbon (SOC) concentration and the distribution of associated carbon within soil aggregates after 3-year period are presented in Table 4. The total SOC concentration prior to this study was 9.98 g C kg^{-1} soil. However, after 3 years, the SOC of vetiver mulch-managed soils differed significantly ($p \leq 0.05$) from non-mulched soils (VGS-managed and NV) with the highest and the least carbon concentrations recorded under VM_6 and NV treated soils, respectively. After 3-year study, SOC increased (from initial 9.98 g C kg^{-1}) by 2.0%, 58.2%, 109.2%, 29.6%, 66.3%, 32.6% and 105.1% under VM_2, VM_4, VM_6, 20VGS + VM_2, 20VGS + VM_4, 10VGS + VM_2 and 10VGS + VM_4, respectively, whereas there were reductions in SOC under NV, 10VGS and 20VGS by 10.3%, 0.3% and 3.8%, respectively. The higher amount of soil organic carbon is attached to higher lignin content and C/N ratio in the mulch which perhaps influenced the level of C accumulation in soils managed with vetiver mulch. The proximate analysis of vetiver shoot shows that it contains about 15% carbon, and increased the level of SOC when decomposed (Are et al., 2012). The aggregate-associated carbon (Agg-C) in < 2000 and 2000–1000 µm classes accounted for 55–73% variation in carbon stock in all treatments. More than 70% of the carbon stock within the aggregates was associated with macroaggregates (> 250 µm classes) with a larger proportion obtained under VM_6 closely followed by 10VGS + VM_4. On the other hand, the distribution of carbon associated with microaggregates and free-light fractions (< 250 µm) were not significantly different among the treatments and they ranged from 10.5 to 27.6% of the carbon pool within the aggregates. Generally, the Agg-C of macroaggregates of vetiver mulch-managed soils (especially VM_4, VM_6, 10VGS + VM_4 and 20VGS + VM_4) were significantly higher than for unmulched soils (10VGS, 20VGS and NV). On the other hand, carbon associated with microaggregates and free-light fractions (< 250 µm) were higher in unmulched soils than mulch-managed soils, though the differences were not significant. Various studies (Blanco-Canqui and Lal, 2007; Jordán et al., 2010; Li et al., 2012) had demonstrated the importance of mulch application in increasing SOC concentration, especially in the top layers of soil. In this study, the manural potential of vetiver mulch did not only reflect in the total SOC storage but also influenced the distribution of aggregate-associated carbon in various aggregate sizes. The observed increase in SOC under vetiver mulch-managed plots, especially those with higher mulch rates (4 and 6 t ha^{-1}) might be ascribed to increase in SOC pools during decomposition after 3 years. Blanco-Canqui and Lal (2007) made similar assertion as they recorded about 33% increase in SOC in their comparison of 8 to 16 t ha^{-1} of wheat straw mulch on silty-loam for a period of 10 years.

3.2.4. Soil moisture retention, pore size distribution and saturated hydraulic conductivity

The soil moisture retention as influenced by combined application of grass strips and mulch at the end of the 3-year study are presented in Fig. 3. Soils with application of vetiver mulch (VM solely or in combination with VGS) had higher moisture retention than the unmulched treatments. The 10VGS + VM$_4$ treatment had significant moisture retention at all suctions and closely followed by VM$_6$. However, the differences in moisture retention among the treatments became increasingly smaller with increase in suction. At lower suctions (0–500 kPa), effects of VM$_6$ and 10VGS + VM$_4$ were distinctly visible, and significantly higher ($p \leq 0.05$) than other treatments. Compared to other treatments, application of 4 and 6 Mg ha^{-1} vetiver mulch (in VM$_4$, VM$_6$, 10VGS + VM$_4$ and 20VGS + M$_4$) retained 11.6–32.3% more of water than other treatments at 0–500 kPa. However, at higher suctions (> 500 kPa), the soil moisture retention among the treatments did not differ significantly. The increased moisture retention, especially in the soils with higher mulch rates (4–6 Mg ha^{-1}), might be attributed to the manural capacity of mulch materials that enhanced organic matter build up, better soil structure, reduce runoff velocity and increased water retention during erosion process. Previous studies (Aina, 1984; Blanco-Canqui and Lal, 2007; Mulumba and Lal, 2008) showed that soil moisture storage could be attributed to improved organic C status associated with residues in the rhizosphere, especially at higher mulch rates (> 2 Mg ha^{-1} mulch).

The alteration in pore size distribution of the surface soil (0–10 cm depth) as influenced by vetiver grass strips and mulch is shown in Fig. 4. It was also observed that 10VGS + VM$_4$ and VM$_6$ had comparable total pore spaces that were higher than other treatments. The transmission and storage pores together constituted 52.5% to 63.1% of the total pore space. The results indicated that the soil under 10VGS + VM$_4$ treatment had significantly greater transmission (0.0740 m^3 m^{-3}) and storage (0.1999 m^3 m^{-3}) pores than the other treatments. The increased transmission and storage pore spaces recorded under 10VGS + VM$_4$ and VM$_6$ treatments may be ascribed to the higher surface soil shielding capacity of mulch rates ($\geq$4 Mg ha^{-1}) and the resistive potential of 10VGS that slowed down overland flow, which alter the ecological environment of the surface soil and pore size distribution. On the other hand, the soil pore space under NV had fewer transmission (0.0451 m^3 m^{-3}) and storage (0.1562 m^3 m^{-3}) pores, which were significantly smaller than the plots with 4 and 6 Mg ha^{-1} vetiver mulch (VM solely or in combination with VGS). However, the largest residual (0.1825 m^3 m^{-3}) pore was recorded under NV, which was significantly greater than those with 4 and 6 Mg ha^{-1} vetiver mulch (VM$_4$, VM$_6$, 10VGS + VM$_4$ and 20VGS + VM$_4$) but did not differ significantly from 10VGS, 20VGS, VM$_2$, 10VGS + VM$_2$ and 20VGS + VM$_2$. The reduction in intra-aggregate and inter-aggregate pore spaces perhaps resulted in the observed breakdown of transmission and storage pores, and an increase in residual pore under NV (Chakraborty et al., 2010). A similarly breakdown of transmission and storage pores was also observed for 20VGS and VM$_2$ treatments. The collapse of transmission and storage pores may have resulted in soil structural degradation and poor plant growth recorded under NV, 20VGS and VM$_2$ treatments.

The geometric mean saturated hydraulic conductivity (K$_{sat}$) values ranged from 13.4 × 10^{-3} to 51.2 × 10^{-3} cm s^{-1}, 12.8 × 10^{-3} to 53.4 × 10^{-3} cms^{-1} and 11.4 10^{-3} to 54.1 × 10^{-3} cm s^{-1} in years 1, 2 and 3, consecutively (Table 3). However, the values of K$_s$ reciprocally followed the same trend in bulk densities. During the study, significant changes in K$_{sat}$ were observed for vetiver grass treated (strips, mulch or combined strips and mulch) soils compared with unamended control except 20VGS and VM$_2$. The VM$_6$ treatment had the highest K$_{sat}$ (51.2 × 10^{-3} cm s^{-1}) in year 1 but in subsequent years, there was a better conductivity of water through the soil column of 10VGS + VM$_4$ than those of VM$_6$ and other treatments. When compared with year 1, the soil hydraulic conductivities increased in the second and third years, especially those treatments with higher mulch rates (4 and 6 t ha^{-1}), with the highest increase (13.2%) recorded under 10VGS + VM$_4$ in year 3. High K$_{sat}$ has been reported under mulching in various environmental settings (Rees et al., 2002; Bhattacharyya et al., 2011; Chiroma et al., 2006). The increase in K$_{sat}$ values for mulched plots has been attributed to the improved SOC, increased effective pore volume and better pore connectivity and reduced surface sealing encouraged by mulch cover. In this study however, the significant large K$_{sat}$ measured under 10VGS + VMG$_4$ and VM$_6$ plots may be attributed to increased flow from preponderance of macropores (transmission pores) created by soil fauna beneath the mulch cover. Mixed results have however been reported in similar studies. For instance, the contribution of mulch to increase saturated hydraulic conductivity was reported on an Alfisol in Southwestern Nigeria by Franzen et al. (1994) and on an Entisol in China by Zhang et al. (2008). In contrast, K$_{sat}$ was not enhanced by mulch in the findings of Chiroma et al. (2006) on a sandy loam soil

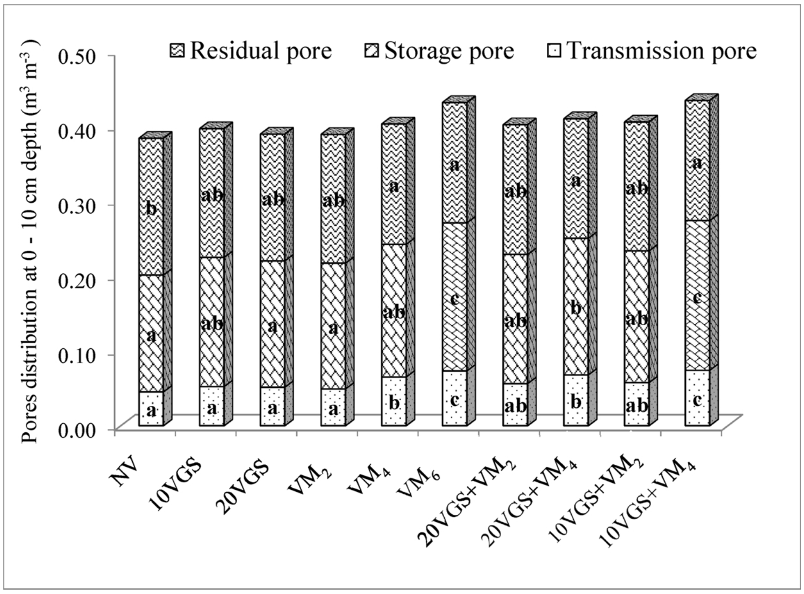

Fig. 4. Pore size distribution as affected by vetiver grass strips and mulch cover after 3-year study.
Means in bars for particular pore fraction containing the same letter (s) are not significantly different ($p \leq 0.05$).

Table 5
Effects of combined vetiver grass strips and mulch on changes in soil physical health under a continuous maize cultivation.

Treatment	Soil physical health index				Percentage change in SH_{phy} from initial 0.530			
	Year 1	Year 2	Year 3	Mean	Year 1	Year 2	Year 3	Mean
NV	0.478	0.489	0.484	0.483	−10.9	−8.5	−9.6	−9.6
10VGS	0.542	0.554	0.548	0.548	2.2	4.3	3.4	3.3
20VGS	0.518	0.529	0.524	0.524	−2.3	−0.1	−1.1	−1.2
VM_2	0.538	0.550	0.544	0.544	1.5	3.6	2.7	2.6
VM_4	0.636	0.650	0.644	0.643	16.7	18.5	17.7	17.6
VM_6	0.783	0.800	0.792	0.792	32.3	33.8	33.1	33.1
20VGS + VM_2	0.572	0.585	0.579	0.578	7.3	9.3	8.4	8.4
20VGS + VM_4	0.645	0.659	0.653	0.652	17.8	19.6	18.8	18.7
10VGS + VM_2	0.595	0.608	0.602	0.602	10.9	12.8	12.0	11.9
10VGS + VM_4	0.792	0.809	0.801	0.801	33.1	34.5	33.9	33.8

cropped with sorghum.

3.3. Soil physical health and its temporal change

The response of soil physical health of the surface soil (0–10 cm depth) to integration of vetiver grass strips and vetiver mulch were evaluated before the trial and at end of each year 1–3 of the trial (Table 5). The average soil physical health index (SH_{phy}) ranged from 0.483 to 0.801 after 3 years of consecutive maize cultivation with the highest and least index recorded under 10VGS + VM_4 and NV, respectively. We have a significant improvement in SH_{phy} where vetiver mulch was applied, either solely or integrated with vetiver grass strips. The results indicated that VGS, VM or combine VGS + VM, except for 20VGS, increased the soil physical health by 2.6%–33.8% compared with the control (NV). The soil with high rates of vetiver mulch application (VM_6, 10VGS + VM_4, 20VGS + VM_4 and VM_4) had their mean SH_{phy} increased by 17.6%–33.1%, and they were significantly ($p \leq 0.05$) different from those with low mulch rates or without mulch (NV, 10VGS, 20VGS, VM_2, 20VGS + VM_2 and 10VGS + VM_2) (Fig. 5). However, at the end of the year 3 study both positive and negative changes were recorded in soil physical health indices (Table 5). Compared with the initial index of 0.530 before the trial, SH_{phy} under NV and 20VGS reduced by 9.6% and 1.2%, respectively, thus showing a degradation of soil physical health after 3 years (6 cropping seasons) of continuous maize cultivation. The beneficial influence of vetiver mulch in increasing the SOC content perhaps increased soil structural stability, and effective pore volume, which consequently accounted for significant improvement in soil physical health under VM_6 and 10VGS + VM_4 than other treatments. Our results are consistent with a study by Dexter (2004) that drew a significant relationship between soil physical health and soil structure. Previous studies by Keller et al. (2007) also reported that the relationship between soil physical quality and soil structure was largely due to soil organic matter and soil water content. In our study, it was evident that SH_{phy} exhibited a pattern similar to those of SOC, aggregate size and distribution and pore size distribution.

3.4. Maize grain yield

The maize grain yields in early and late cropping seasons for 3 consecutive years and the pooled grain yields are presented in Table 6. The grain yields were significantly different among the treatments during the 6 cropping seasons. In year 1, the grain yields under NV plot (0.957 and 0.857 t ha^{-1} for early and late seasons, respectively) were consistently lower than other treatments by 0.6–52.1% and 4.5–52.1% in early and late seasons respectively. In comparison, the grain yield for VM_6 treatment was significantly ($p < 0.05$) higher than other treatments (except 10VGS + VM_4) in both early and late seasons of year 1. Relative to the maize yields obtained in early year 1, the yields in the late season. for NV, 20VGS and VM_2 reduced by 10.4, 2.7 and 9.4%, respectively, whereas the yields for 10VGS, VM4, VM6, 20VGS + VM2, 20VGS + VM4, 10VGS + VM2 and 10VGS + VM4 treatments increased by 0.9, 6.6, 42.8, 4.9, 14.2, 10.0 and 44.2%, respectively.

In the subsequent years, the maize grain yields ranged from 0.903–1.900 t ha^{-1} and 0.915–2.020 t ha^{-1} early and late seasons of 2013, and 0.894–2.031 t ha^{-1} and 0.901–2.038 t ha^{-1} in 2014. Unlike year 1, the grain yields for 10VGS + VM_4 plot were consistently and significantly ($p \leq 0.05$) higher than other treatments in early and late seasons. In spite of application of 150 kg ha^{-1} of NPK–20–10–10 across board during the second year, the unamended control with no-vetiver grass consistently had the least grain yields in early and late seasons. The average (pooled) grain yields for six cropping seasons showed that 10VGS + VM_4 treatment had positive influence on the grain yield than other treatments. Although the difference between the treatment and VM_6 was not significant, the average grain yield of maize for 10VGS + VM_4 during the 6 cropping seasons was greater than those for NV, 10VGS, 20VGS, VM2, VM_4, VM_6, 20VGS + VM_2, 20VGS + VM_4 and 10VGS + VM_2 by 103.0, 65.6, 96.3, 91.4, 42.0, 1.0, 67.2, 33.6 and

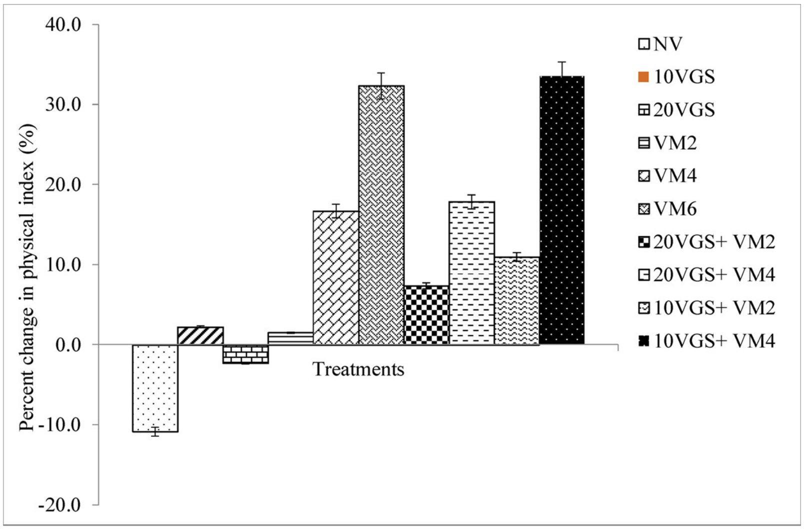

Fig. 5. Temporal changes in soil physical health index after 3-year of integrated use of vetiver grass strips and mulch. Error bars represent a 95% confidence interval of the mean values.

Table 6
Maize grain yields (t ha^{-1}) obtained in the six cropping seasons and average grain yields as influenced by integrated use of vetiver grass strips and mulch.

Treatment	Early 2012	Late 2012	Early 2013	Late 2013	Early 2014	Late 2014	Pooled
NV	0.957a	0.857a	0.903a	0.915a	0.894a	0.901a	0.905a
10VGS	1.070ab	1.080b	1.115b	1.127b	1.128c	1.130c	1.108b
20VGS	0.963a	0.937a	0.937a	0.952a	0.906ab	0.917ab	0.935a
VM$_2$	0.990a	0.897a	0.945a	0.967a	0.972b	0.983b	0.959a
VM$_4$	1.157c	1.233cd	1.307cd	1.324d	1.367e	1.368e	1.293c
VM$_6$	1.253d	1.789e	1.884e	1.927f	2.021g	2.030g	1.817e
20VGS + VM$_2$	1.010ab	1.061b	1.117b	1.132b	1.134c	1.133c	1.098b
20VGS + VM$_4$	1.153c	1.317d	1.396d	1.414e	1.482f	1.482f	1.374d
10VGS + VM$_2$	1.073b	1.182bc	1.245bc	1.258c	1.259d	1.268d	1.214c
10VGS + VM$_4$	1.239d	1.787e	1.900e	2.020f	2.031g	2.038g	1.836e

Values followed a common lowercase letter in the same column are not significantly different at $p \leq 0.05$.

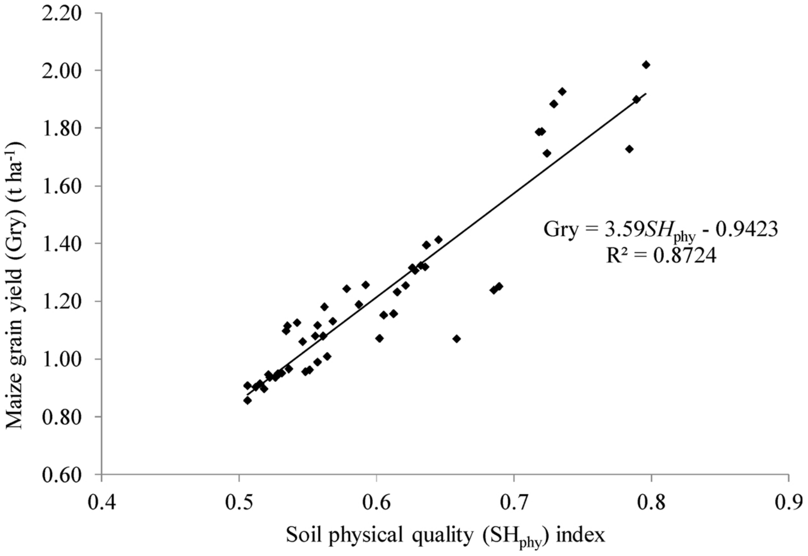

Fig. 6. Relationship between soil physical quality index and maize grain yield after six cropping seasons. GRY is the grain yield.

51.2%, respectively. It was evident from this study that maize grain yields were consistently higher on vetiver mulched plots, especially those with higher tonnage of mulch, than unmulched plots during the 6 cropping seasons (2 cropping seasons per year for 3 years). In comparison with the conventional yield on farmers field, only those with higher tonnage of vetiver mulch (≥4 t ha^{-1}) had higher yield than an averaged maize (var. SUWAN–1–SRY) grain yield of 1.25 t ha^{-1} recorded during the study in the area. Higher crop yield with vetiver mulch due to its manural effect had earlier been reported in Nigeria by Babalola et al. (2007) and Are et al. (2012). Similar report elsewhere (Xu et al., 2003) accounted the increase in the yield to the nutrient composition in vetiver grass shoots, which increased the fertility of the soil. It was reported by Xu et al. (2003) that 1 kg of dry vetiver shoots contains 422 g of C, 2.1 g of N, 0.5 g of P_2O_5, and 7.5 g of K_2O. In a 3-year experiment conducted by Lu and Zhong (1997) in India, application of 2.25 and 4.5 t ha^{-1} of vetiver grass mulch increased the production of corn seed from 2070 kg ha^{-1} of unmulched control to 2280 and 2790 kg ha^{-1}, respectively.

3.5. Relationship between soil physical health and maize yield

Evaluation of the Pearson product–moment correlation between maize grain yield and soil physical health at the end of 6 cropping seasons (Fig. 6) showed a significant and positive linear relationship ($r = 0.93$, $p \leq 0.01$). The correlation coefficient ($R^2 = 0.872$) indicated that 87.2% of the grain yield is accounted to changes in physical quality of the soil over the period of 3 consecutive years. The implication of this is that, a better management of soil physical properties and soil organic carbon (soil physical quality indicators) of an eroded land using vetiver grass, especially its clippings as mulch for erosion control, may enhance higher soil physical quality and concomitantly increase maize yield.

4. Conclusions

The influence of integrated use of vetiver grass strips and vetiver mulch as conservation-effective measure for improvement of soil physical health was examined on eroded land. Soil physical health indicators and their changes were measure for a period of three years (2 cropping seasons per annum). We have a significant improvement in soil physical health (SH_{phy}) where vetiver mulch was applied, either solely or integrated with vetiver grass strips. Although there was an improvement in soil physical health following addition of vetiver mulch especially those with high tonnage, nevertheless, the accrued soil loss over the three-year period was much on mulched plots than vetiver grass striped plots. However, at the end of the three-year study, both positive and negative changes were recorded in soil physical health indices, and this concomitantly influenced the maize grain yields. For sustainable crop production, application of 10VGS + VM$_4$ appeared to be most effective from the standpoint of soil and water conservation and improvement of maize grain yield.

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