Soil Fertility Erosion under Different Soil and Residue Management Systems: A Case Study in the Semi-Deciduous Forest Zone of Ghana.

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ABSTRACT

Two experiments were carried out at the University of Science and Technology, Kumasi, Ghana to study the effects of tillage and mulching on soil fertility erosion. In Experiment 1, tillage treatments studied were: Hand tillage, Plough-plant, Plough-harrow-plant, and Excessive tillage (double ploughing + 3 times harrowing + 3 times spike-tooth harrowing and planting). In Experiment 2, the mulching treatments using dry *Panicum maximum* were Bare plot (T_0), no mulch + maize (T_1), 2t ha^{-1} mulch + maize (T_2), 4t ha^{-1} mulch + maize (T_3), 6t ha^{-1} mulch + maize (T_4). The test crop in both experiments was maize (*Zea mays*, L). Both studies were carried out on runoff plots on a slope of 3.5 per cent. Eroded sediments were analysed for N, P, K and organic matter. Enrichment ratios for the nutrients were calculated to give indices of fertility erosion.

In Experiment 1, hand tillage and all tillage in excess of plough-plant caused significant losses of N, P, K and organic matter. In all cases, the excessive tillage recorded the highest losses of nutrients whilst plough-plant had the least. Enrichment ratios (E.R.) differed for the various nutrients. In the case of organic matter and K, E.R for all the tillage treatments exceeded 1.0, indicating that the eroded sediments were richer in organic matter and K than the parent soil from which the sediments were eroded. The E.R for organic matter was in the decreasing order of excessive > hand > plough-plant > plough-harrow-plant. For K, the trend was hand > excessive > plough-harrow-plant > plough-plant. In the case of available P, the trend was hand > excessive > plough-plant > plough-harrow plant. The analysis for N showed that only the eroded sediments from the excessive and hand tillage treatments had E.R. values greater than 1. Maize grain yield was highest under plough-plant. All tillage in excess of plough-plant reduced grain yield.

In Experiment 2, mulching significantly reduced nutrient and organic matter losses with the magnitude of reduction being greater as mulch rate increased. In all cases nutrient losses were in the decreasing order of bare (T_0) > no mulch + maize (T_1) > 2t ha^{-1} mulch (T_2) > 4t ha^{-1} mulch (T_3) > 6t ha^{-1} mulch (T_4). The enrichment ratios showed that, with a few exceptions, most of the eroded sediments were richer in nutrients and organic matter than the parent soil. Enrichment ratios ranged from 0.9 to 2.3 with a trend of $T_0 > T_1 > T_4 > T_2 = T_3$ for organic matter; 0.9 to 1.8 and $T_0 > T_1 > T_2 > T_3 > T_4$ for total N; 1.5 to 4.3 and $T_0 > T_1 > T_2 > T_3 > T_4$ for available P and 1.5 to 2.9 and $T_1 > T_0 > T_2 > T_3 = T_4$ for K. The results further showed that although losses of soil may be small, the concentration of nutrients could be high. Although low quality mulching material may be effective in controlling erosion maize grain yield may be reduced in the short-term.

Keywords: Fertility erosion; mulching, tillage, enrichment ratios.

INTRODUCTION

The production of food, fibre, shelter, and to some extent, energy for the sustenance of our ever-increasing population and feeding our agro-based industries depends directly or indirectly on soil and water (Bonsu and Quansah, 1992).

The use of inappropriate soil and crop management techniques in producing these basic necessities required in our daily life leads to serious accelerated soil erosion which is the most potent degradative process responsible for the loss of soil productivity (FAO, 1965; Kelly, 1987; Dudal, 1981; Quansah, 1990).

The loss of soil and water through erosion by water is almost always accompanied by losses of plant nutrients. The process, termed fertility erosion (Ellison, 1950), is selective in that finer particles relatively high in plant nutrients and organic matter are the most susceptible to erosion. Consequently, the eroded sediment is usually the most fertile. It contains higher concentrations of organic matter and plant nutrients in available form than the soil from which it was eroded and any fertilizers the farmer has applied (Massey and Jackson, 1952; Ellison, 1950). In the long term, these losses adversely affect soil productivity. In spite of these adverse effects, soil fertility erosion has not received much research attention within the West African sub-region in general and Ghana in particular. Yet such studies are pertinent to the development of strategies for controlling the increasing losses of soil nutrients through erosion.

The control of fertility erosion would require the development and adoption of landuse systems that are capable of replenishing or maintaining the nutrient status of the soil in addition to controlling erosion (Sanchez et al., 1997; Ofori and Fianu, 1996; Quansah, 1996; Quansah et al., 1997a; Lal and Stewart, 1992; Syers, 1997). Until these prerequisites are satisfied at every stage of our agricultural production, the goal of sustainable agricultural production advocated by the World Commission on Environment and Development (1987) will continue to be a mirage to the present and future generations of the country. It is in the light of this that the results of two earlier studies on the effects of tillage and mulching on erosion in Ghana (Quansah and Baffoe-Bonnie, 1981; Quansah et al., 1997b) are presented with emphasis on the role of these practices in the control of fertility erosion.

MATERIALS AND METHODS

Location

The experiments were carried out at the Experimental Fields of the Department of Crop Science, University of Science and Technology, Kumasi, Ghana.

Characteristics of the Experimental Sites

The experimental sites fall within the semi-deciduous forest zone with a mean annual rainfall of 1302 mm. A twenty-year average rainfall amounts for the major (March – July) and minor (September – November) wet seasons are 748 mm and 371 mm, respectively. Rainfall intensities of 25 to 75 mm h^{-1} sustained for 15 minutes are common. Median drop size, by the flour pellet method, ranges between 0.9 and 2.6 mm with about 58% in the range 2.0 to 2.6 mm. Annual kinetic energy loads calculated from autographic rainfall charts vary between 14466 and 26197 J m^{-2} with a mean of 17866 J m^{-2}. The mean annual erosivity index - KE $\geq$ 1 is 13467 J m^{-2}. About 61% of this is obtained in the major wet season (March to July) and 26% in the minor wet season (September to November). The soils at the sites belong to the Akroso series (Haplic Acrisol) and Bomso series (Ferric Acrisol) for experiments 1 and 2 respectively. The Akroso series consists of loamy sand and Bomso series is a sandy loam. The soils are generally low in nutrients (Table1).

Table 1. Characteristics of the soil at the experimental sites (0 -15 cm of soil profile)

Parameter	Haplic Acrisol (Experiment 1)	Ferric Acrisol (Experiment 2)
pH 1:2.5 (H_2O)	6.0	5.3
Total N (%)	0.09	0.15
Available P (mg kg^{-1})	3.5	2.5
Exchangeable K (cmol kg^{-1})	0.08	0.14
Carbon (%)	0.62	1.46
Organic matter (%)	1.07	2.52
Sand	72.6	57.6
Silt	17.2	18.2
Clay	10.2	24.2

Experimental Design

In Experiment 1, a complete randomized design (CRD) with four replications was used in studying the effect of the following tillage treatments on erosion:

- Hand tillage consisted of cultivating the land with a hoe and cutlass as practised by the local farmers.
- Plough-plant (a reduced tillage) comprised ploughing with a disk plough followed by planting.
- Plough-harrow-plant (conventional tillage) consisted of ploughing with a disk plough, harrowing and planting.
- Excessive tillage consisted of double ploughing + 3 times harrowing + 3 times spike-tooth harrowing and planting

In Experiment 2, the effects of the following mulching treatments on erosion were studied in a randomized complete block design (RCBD) with three replications:

- T_0 - bare plot
- T_1 - no mulch + maize

- T_2 - 2t ha^{-1} mulch + maize
- T_3 - 4t ha^{-1} mulch + maize
- T_4 - 6t ha^{-1} mulch + maize.

The mulching material consisted of Guinea grass (*Panicum maximum*) which is a common weed on most continuously tilled farms in the semi-deciduous forest zone. The percentage carbon, nitrogen, phosphorus and potassium contents of the mulch were 41.5, 0.47, 0.02 and 0.45, respectively. The C/N ratio was 88.3. Before the application of the mulch, the experimental field was ploughed and harrowed. The test crop in both experiments was maize (*Zea mays*, L.).

Soil Loss and Runoff.

The two experiments were carried out on runoff plots with sediment and runoff measuring devices on a slope of 3.5 per cent. Plot sizes were 27.4 m x 3.1 m and 10 m x 5 m for Experiments 1 and 2, respectively. Plot boundaries consisted of 30 cm-wide strips of galvanized iron roofing sheets. These were driven 20 cm into the soil leaving 10 cm above the soil surface. Each plot was bounded at the upslope end by an earth bund and a diversion channel to protect the plot from off-site runoff. At the lower ends of the plots were the measuring equipment. These consisted of collecting troughs to contain eroded sediments, and sedimentation tanks to collect the runoff with its fine sediment load. The overflow-sampling device consisted of 11 drainage tubes arranged around the top section of the sedimentation tank. Anytime the tank is full, the tubes drain the excess runoff and one is tapped through a rubber tubing into an overflow tank. Thus $1/11^{th}$ of the runoff is retained. The volume of runoff retained multiplied by 11 gives the total volume of overflow.

At the end of each erosive rain, the eroded sediment on the trough is weighed. The runoff is thoroughly stirred and sampled for the determination of sediment concentration.
Total soil loss is the sum of the total dry sediment in the runoff and that on the collecting trough. Total runoff is the sum of the volume of runoff in the sedimentation tank and the total volume of overflow.

Chemical analysis of the eroded sediments

The original soil and eroded sediments were analysed for:

- Total nitrogen by a modified macro Kjeldahl method.
- Available phosphorus by the Bray P1 method with a dilute acid fluoride as the extractant.
- Exchangeable potassium by flame photometry using ammonium acetate as the extractant.
- Organic carbon content by the Walkley-Black wet combustion procedure (Nelson and Sommers, 1982). Per cent organic carbon was multiplied by 1.724, the van Bemmelen factor, to give per cent organic matter.
- pH was measured in 1:2.5 soil-water suspension by a glass electrode-calomel electrode pH meter (Mclean et al., 1982). Particle size distribution was determined by the Bouyoucos Hydrometer method.

Enrichment Ratio (E.R)

The enrichment ratios of the nutrients were calculated to give indices of fertility erosion. The E.R is given by:

$$E.R = \frac{\text{Concentration of nutrients in the eroded sediment}}{\text{Concentration of nutrients in soil from which eroded sediment originated (parent soil).}}$$

The data collected were statistically analysed using MSTATC (ver. 2.2). The results of the major wet season for both experiments are presented in this paper.

RESULTS

Organic Matter Losses

The losses of organic matter in Experiment 1 are presented in Table 1. The plough-plant and conventional tillage treatments lost significantly ($P< 0.05$) smaller amounts of organic matter than the excessive and hand tillage treatments. The respective amounts of organic matter losses from excessive, hand and conventional tillage treatments were 41, 18.5, and 4.2 times greater than that from the plough-plant.

In Experiment 2 (Table 2) the losses of organic matter was in the order of To > T1 > T2 > T3 > T4. The loss of organic matter from the bare soil was significantly higher than those from the cropped plots. Organic matter loss from T1, which was cropped with no-mulch was significantly higher than that from any of the mulched plots. Although the losses among the mulched plots were not significant ($P< 0.05$), organic matter losses decreased as mulching rate increased.

Total Nitrogen Losses

Table 1 shows the order of nitrogen losses in Experiment 1 as excessive > hand > conventional > plough-plant tillage treatments. The small losses recorded for the plough-plant is noteworthy. As one of the major nutrients for the proper growth of the crop, attempts should be made to conserve it by avoiding practices such as excessive tillage that tend to deplete it. The losses of total nitrogen in Experiment 2 were in the order of To > T1 > T2 > T3 > T4 (Table 2). Nitrogen losses under To were significantly higher than those of all the other treatments. The losses from the mulched plots were however significantly lower than T1. There was a considerable reduction in nitrogen losses by mulching with the rate of loss significantly decreasing as mulching increased. This suggests the importance of mulching as a simple agronomic measure in conserving and maintaining the fertility level of the soil.

Available Phosphorus Losses

Phosphorus losses (Tables 1 and 2) were generally lower than those of the other nutrients. This may be attributed to the rather lower mobility of soil phosphorus. The loss from excessive tillage (Table 1) was significantly ($P< 0.05$) greater than the other tillage treatments. The losses followed the trend of excessive > hand > conventional > plough-plant.

Table 1. **The effect of tillage on nutrient losses on a Haplic Acrisol**
(Total rainfall amount for the experimental period was 452 mm)

Treatment	Organic matter (kg/ha)	Total Nitrogen (kg/ha)	Available P (kg/ha)	Exch. K (kg/ha)	Runoff (ha-mm)	Soil loss (t/ha)	Maize grain yield (t/ha)
Excessive tillage	234.89	6.99	0.56	1.67	31.2	4.01	2.14
Hand tillage	105.68	2.58	0.22	1.37	12.2	1.40	3.25
Plough-harrow-plant	24.11	0.85	0.11	0.24	8.1	0.91	3.15
Plough-plant	5.71	0.15	0.05	0.21	3.3	0.19	3.37
LSD (0.05)	32.37	1.38	0.08	0.51	3.8	0.56	0.75

Table 2. **The effect of mulch on nutrient losses on a Ferric Acrisol**
(Total rainfall amount for the experimental period was 245 mm)

Treatments	Available P	Available K	Total N	Organic Matter	Runoff ha mm	Soil loss t/ha	Maize grain yield (t/ha)
	kg/ha						
Bare (To)	0.019	0.677	8.694	165.375	59.42	2.835	-
No Mulch (T1)	0.011	0.559	5.188	70.144	39.287	2.192	2.16
2 t/ha (T2)	0.006	0.281	3.418	38.103	30.929	1.335	1.64
4 t/ha (T3)	0.005	0.240	2.799	36.607	29.01	1.615	1.88
6 t/ha (T4)	0.002	0.130	1.553	24.987	26.578	1.013	1.71
LSD (0.05)	0.0027	0.01	0.775	21.66	22.151	1.774	0.53

The results of Experiment 2 (Table 2) showed that as the rate of mulch application increased available phosphorus content in the eroded sediment decreased. The order of decrease was To > T1 > T2 > T3 > T4. The loss of phosphorus under To was significantly higher than all the cropped treatments ($P < 0.05$). Among the cropped treatments, the loss of available P from T1 was significantly higher than the others. Statistically, no significant differences existed among the various mulch levels, except between T2 (2t/ha) and T4 (6t/ha).

Available Potassium Losses

The losses of potassium in Experiment 1 (Table 1) were significantly smaller in the plough-plant and conventional tillage treatments than the excessive and hand tillage. In experiment 2 (Table 2) the ranked order of potassium loss was To > T1 > T2 > T3 > T4. The loss from the bare plot (To) was significantly higher than those from all the cropped treatments. The differences in the losses among the cropped treatments were significant ($P< 0.05$).

Enrichment Ratios

The ratio of the average concentration of the nutrients in the eroded sediment to that in the parent soil is presented in Tables 3 and 4. The results in Experiment 1 (Table 3) showed that the order of enrichment ratios differed for the various nutrients. In the case of organic matter enrichment ratios for all the tillage treatments exceeded 1. These indicate that the eroded sediments were richer in organic matter than the parent soil. Enrichment ratio for organic matter was in the order of excessive > hand > plough plant > plough-harrow-plant. For potassium the trend was hand > excessive > plough-harrow-plant > plough plant. The enrichment ratios for nitrogen showed that only the eroded sediments from the excessive and hand tillage were richer in N than the parent soil with a trend of hand > excessive > plough-harrow-plant > plough-plant treatments. The order of decreasing enrichment ratios for phosphorus was hand > excessive > plough-plant > plough-harrow plant.

In Experiment 2, the ranked order of the enrichment ratios of available potassium was T1 > To > T2 > T3 > T4. The values of total nitrogen followed the latter trend. However T4 recorded an enrichment ratio less than 1. The concentrations of organic matter of the eroded sediments from the mulched plots were lower than that of the parent soil (i.e. values were less than 1). However the eroded sediments from the unmulched treatments were richer in organic matter with a trend of To > T1 > T4 > T2 > T3.

Maize grain yield

Maize grain yield as affected by the tillage treatments is presented in Table 1. Plough-plant gave the highest yield, followed by hand tillage, plough-harrow-plant and excessive tillage. The differences in the mean grain yields for the plough-plant, plough-harrow-plant and hand tillage were not statistically significant. However these latter treatments significantly out-yielded excessive tillage. Maize grain yield under mulching (Table 2) was in the order of $T_1 > T_3 > T_4 > T_2$. The differences in yield were, however, not statistically significant. Unexpectedly, T_1 gave the highest yield.

Table 3. Effect of tillage on enrichment ratios on a Haplic Acrisol

Treatment	Organic Matter	Total Nitrogen	Available P	Exch. K
Excessive tillage	10.36	1.45	2.22	1.35
Hand tillage	6.67	2.11	3.27	3.95
Plough-harrow-plant	2.37	0.85	0.97	1.21
Plough-plant	2.98	0.15	1.29	1.03

Table 4. Effect of mulch on enrichment ratios on a Ferric Acrisol

Treatments	Organic Matter	Total N	Available P	Available K
Bare (To)	2.279	1.806	4.323	2.718
No Mulch (T1)	1.250	1.394	3.097	2.898
2 t/ha (T2)	0.886	1.194	2.344	1.902
4 t/ha (T3)	0.886	1.108	1.826	1.687
6 t/ha (T4)	0.964	0.900	1.505	1.461

DISCUSSION

Rainfall amounts during the period of experimentation were relatively low. As a result the losses of soil and nutrients were also low. However, the losses of NPK, and organic matter generally increased as tillage intensity increased. This may be due to the higher losses of soil and water as the soil is tilled intensively. Excessive tillage pulverised the soil and made it more susceptible to detachment and transport by rainfall and runoff. The higher losses of nutrients under hand tillage are noteworthy. Although hand tillage by the hoe is often regarded as a form of minimum tillage, the significant scraping and pulverisation of the surface soil could result in higher losses of soil and nutrients.

On the other hand the greater surface roughness provided by the plough-plant significantly reduced losses of soil, water and nutrients. The lower losses of nutrients recorded on the mulched plots may be due to the conservation attributes of mulch. The maintenance of mulch on the soil surface has been found to protect the soil against raindrop impact, impede the flow of runoff, reduce nutrient losses, soil detachment and dispersion and maintain high soil infiltration rate (Roose, 1975, Lawes, 1966; Lal, 1976).

Organic matter losses in both experiments were generally high. Because of its concentration in the surface soil and its low density, organic matter is one of the first soil constituents to be removed through erosion, yet it is among the hardest to replace. As the life-blood of tropical agriculture, organic matter is the main source of nitrogen, phosphorus and sulphur for plants in no-fertilizer peasant agriculture (Acquaye, 1990). It is estimated that in tropical soils, the humus content accounts for 90% of the cation exchange capacity under forest and about 80% under savannah conditions. The ability of the soil to hold nutrients and water also rests with the organic matter. Thus as organic matter is lost, the soil is not only depleted of one of its most valuable components, but significant quantities of nutrients such as nitrogen and phosphorus are removed with the organic matter. It is therefore not surprising that the losses of nitrogen and phosphorus followed the same trend as that of organic matter.

The high loses of organic matter are of particular concern because nutrients applied to the soil in the form of mineral fertilizers are far less effective on soils in which organic matter has been lost than those which contain adequate amounts of it (Barrows and Klimer, 1963; Swift, 1997). The implication is that if the losses of N, P and K recorded in these studies were to be replenished by applying mineral fertilizers, the desired effect on crop yield would hardly be attained because of the low soil organic matter content. It has therefore been advocated that soil fertility replenishment in Africa should aim at an integrated nutrient management. (Swift, 1997; Sanchez *et al.*, 1997; Quansah, 1996, Quansah *et al.*, 1997a). This involves the combined use of organic and inorganic inputs for sustaining soil fertility and crop yield.

A comparison made between the concentration of nutrients in the eroded sediments and that in the parent soil showed that, with a few exceptions, the eroded sediments were richer in nutrients. The degree of enrichment, expressed as enrichment ratios, is important not only from the soil fertility depletion viewpoint but for predicting the effects of soil erosion and erosion control on the quality of water (Menzel, 1980). It was further noted that although losses of soil may be small the concentration of nutrients in the sediments could be high. It is therefore apparent that smaller erosion losses such as those of the plough-plant treatment, which may seem unimportant with respect to volume of soil removed, may be very important as far as the depletion of soil fertility constituents is concerned. Therefore any soil management practice that reduces soil loss, runoff, nutrient loss and enrichment ratios has the potential to maintain the productive capacity of the soil for sustainable agricultural production.

CONCLUSIONS

The study indicates that hand tillage by the local hoe and all tillage in excesses of plough-plant increased the losses of NPK and organic matter. Nutrient losses were in the order of excessive > hand > plough-harrow-plant > plough-plant tillage. Mulching generally reduced nutrient loss. The magnitude of reduction increased as mulching rate increased at 2t/ha intervals from 0 to 6 t/ha. With a few exceptions, the eroded sediments were richer in plant nutrients than the parent soil. Mulching significantly conserved soil organic matter since the enrichment ratios for all the mulched treatments were less than 1. The traditional hand tillage should always be accompanied by a cover of vegetative residues to reduce soil loss, runoff and fertility erosion. Low quality mulching material (high C/N ratio) although effective in reducing losses of soil, runoff and nutrients may in the short-term reduce maize grain yield. This should be taken into account in recommendations involving residue management. Finally, sustainable production under mechanized agriculture should aim at reduced tillage.

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