Chapter 7

Quantifying Nutrient Losses with Different Sediment Fractions Under Four Tillage Systems and Granitic Sandy Soils of Zimbabwe

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Additional information is available at the end of the chapter

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1. Introduction

In soil erosion studies too much emphasis has been placed on the weight of soil loss (t/ha), while the real issue is not only about the amount of soil lost or the area of land degraded, but the effect of soil erosion on the productivity of the land. Soil erosion is rated as one of the major threats of sustainable land management, but the research data on the impact of erosion on soil properties and its effect on crop yield is grossly missing (Hudson, 1993), especially in tropical Africa (Kaihura, *et.al.*, 1998). While the process of erosion is somewhat better understood, the resultant changes in the soil properties, the decline in yield and evaluating the loss in productivity should be of concern to the researchers in this region.

On arable land, soil erosion is initiated through tillage. Tillage is the mechanical manipulation of soil for any purpose (Gill and Vanden Berg, 1967). It is an important part of the overall farming system. The primary objectives of tillage, as given by Godwin (1990) and Lobb (1995) are to prepare a desirable seedbed, to control weeds, enhance soil and water storage and retention, manage crop residues and reduce erosion. Tillage can however, either conserve or damage the soil depending on the intensity of inversion and the degree of exposure of the soil to weather conditions. The intensity of soil inversion also influences surface roughness, which in turn determines the sealing tendency of uncovered soil. The rougher the surface, the smaller the raindrop density per unit time and the lower the tendency to seal (Frede and Gaeth, 1995).

Conventional tillage or ploughing promotes soil organic matter loss through disruption of soil aggregates and increased aeration (Angers, N'dayegamiye and Cote, 1993; Beare, Hendrix and Coleman, 1994; Reicosky, *et al.*, 1996; Salinas-Garcia, Hons and Matocha, 1997). Also through ploughing, the crop residues are buried there-by enhancing organic matter decomposition and transformations. Where ploughing is practiced, it is practically impossible to increase organic matter content, even when huge amounts of fertilizer are applied. Reduced tillage intensity on the other hand can result in the maintenance/ increase of more labile fractions of soil organic matter (Angers, N'dayegamiye and Cote, 1993). Combining reduced tillage with surface crop residues not only inhibits the loss of soil organic matter but also improves soil aggregation.

In Zimbabwe soil tillage can be divided into three broad categories namely: Conventional Tillage, Reduced Tillage and Strip Tillage (Willcocks and Twomlow, 1992). Ploughing with a single furrow ox-drawn mould-board plough (conventional tillage) is the most widely used tillage practice in the communal areas of Zimbabwe and is estimated to be practiced on 73 - 90% of the cultivated area. The remainder of the land is ploughed using hired tractor (5 - 25%) and by hand (1 - 15%). Less than 1% is under tillage systems, which conserve soil, moisture, nutrients and/or energy inputs (Working Document, 1990). Reduced tillage involves mainly tied ridging, ripping and hand-hoeing. The tied ridging system is a useful compromise between drainage and storage (Hudson, 1992). Rainwater is retained in the basins to soak into the soil, so very little run-off occurs (Elwell, 1986). The hand-hoeing system is labour intensive and practiced mainly in areas infested with tsetse flies or in cases of extreme lack of draft power (Working document, 1990). Under this treatment, the ground usually has poor cover, the soil tends to compact and no significant soil conservation potential over conventional tillage has been observed (Vogel, 1992).

The ripping system saves on draft power as only the crop rows are opened and no tillage takes place between the crop rows. This means that the timeliness of operations is improved and yields may be improved as according to Oliver and Norton, (1988), low yields in the communal areas are also largely a result of late ploughing/ planting. Two types of ripping systems are currently under research in Zimbabwe, namely ripping into residues and clean ripping, where all crop residues are removed after crop harvest. Clean ripping reduces tillage and draft power requirement, however, the soil and water conservation potential of this system is low. Vogel, (1992) found no significant differences between this system and conventional tillage in terms of run-off and soil loss.

Mulch ripping has a lot of potential in conserving soil and water. Mulching has not yet been promoted in the communal areas as most of the stover is fed to cattle; however, the advantages of the system have been observed. When mulch is left on the soil surface, the soil is protected from high intensity raindrops (Adams, 1966; Elwell, 1986). Run-off, soil loss and subsequent nutrient loss are reduced (Elwell, 1986; Reicosky*et al.*, 1996). The underlying soil retains its high infiltration rate and most of this infiltrated moisture is protected from evaporation (Adams, 1966). The disadvantages are mainly weeds and the carryover of pests and diseases (Braithwaite, 1976; Elwell, 1986).

The effects of conventional tillage on the soil are generally known and can be summed up in a cause/effect relationship as shown in Figure 1. The conservation tillage systems ideally have to be designed in such a way that they reduce the effects of conventional tillage by generally protecting the land and sustaining crop production. Figure 1 tries to summarize the effect of tillage on soil productivity, giving the desired effect should conservation tillage systems be used.

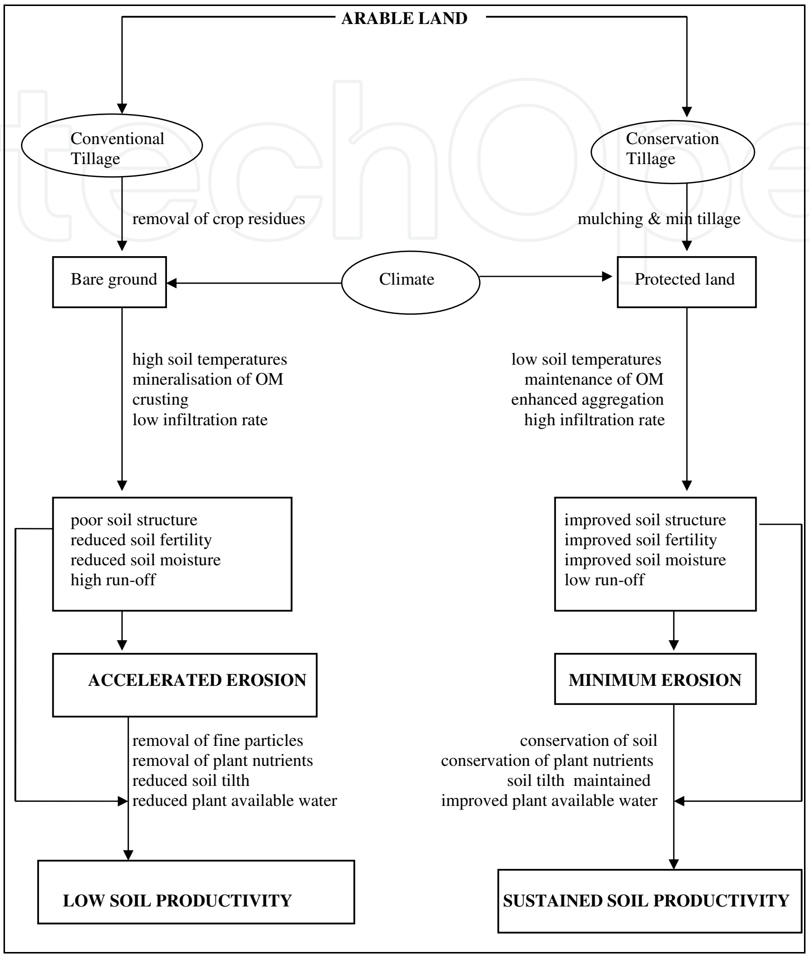

Figure 1. Soil erosion as affected by tillage and climate and its impact on soil productivity

Appropriate tillage systems should therefore, aim to maintain/ increase soil organic matter as it is the key to the productivity of the soils, as will be highlighted shortly. Organic matter content in most agricultural soils has been found to be highly correlated with their tilth, fertility and potential productivity. This soil constituent has positive effects on soil chemical, physical and biological properties that in turn contribute to improved crop yields (Bauer and Black, 1994; Gerzabek, Kirchmann and Pichlmayer, 1995). It facilitates soil aggregation and provides structural stability - improving air and water relationship - and protects soils from wind and water erosion (Godwin, 1990; Hunt, *et al.*, 1996). It is the source of plant nutrients and Carbon source for micro-flora. Its loss results in reduced infiltration rates, increased crusting, decreased water holding capacity, increased resistance to root penetration, decreased nutrient availability and subsequent degradation of soil structure (Godwin, 1990). Small changes in soil organic matter of soils with low soil organic matter contents - as is the case with the soils under study - are highly significant to the environmental and agricultural potential of these soils (Hunt *et al.*, 1996).

An ideal tillage system should also promote soil water storage, reduce erosion, increase crop yield and be straight forward enough to be adopted by farmers (Cassel, Raczkowski and Denton, 1995). Tillage intensity should be reduced and mulching promoted so that erosion susceptible soils are not exposed to weather conditions (Sauerbeck, 1994). Research has shown that the most cost effective erosion control practices involve keeping crop residues on the surface and reducing tillage as much as possible (Reicosky*et al.*, 1996).

The consequence of inappropriate land-use management is accelerated soil erosion leading to soil degradation and eventually to decreased soil productivity. On-site loss of potential crop production due to eroding away of productive organic-enriched topsoil has always been considered a major threat to sustained food production (Lowery and Larson, 1995). On arable land, the process of sheet erosion is insidious and is usually irreversible. Sheet erosion depletes soil productivity through alteration of soil physical and chemical properties. The extent to which these changes take place greatly depends on the soil type, crop and eco-region (Kaihura*et al.*, 1998).

Sheet erosion is a selective process that deprives the soil of its fine particles, i.e. particle size separation often takes place when soil material is eroded by water. Sediments generally contain a larger amount of the lighter elements, such as humus and higher proportions of finer soil particles than the original soil (Aylen, 1939; Massey and Jackson, 1952; Cormack, 1953; Hudson and Jackson, 1962; Shaxson, 1975; Hanotiaux, 1980; Young, 1980; Elwell and Stocking, 1984 ; Biot, 1986; Elwell, 1987). The finest particles are easily splashed out and/or carried in suspension, while the heavier particles are left behind (Poesen and Savat 1980). The soils are thus impoverished as these nutrient reservoirs are lost together with inherent and applied plant nutrients. The bulk density of the soils is increased and plant available water is decreased. The degree with which particle size separation takes place is higher on sandy soils than on clay soils (Hudson, 1958; 1959).

The major significance of soil erosion therefore, lies in the movement of plant nutrients both inherent and applied (Shaxson, 1975). As a result, the eroded material is enriched with nutrients, organic matter and clay particles. The enrichment ratio, defined as the concentration level of each factor (nutrient element, organic matter, clay) in eroded soil material compared to its level in the soil before erosion (Kejela, 1991), is an important parameter for the assessment of nutrient loss through erosion as well as assessing the impact of erosion on crop productivity. To this end therefore, this chapter seeks to assess the selective process of soil erosion and quantify the nutrient losses with each sediment fraction and the significance of each sediment fraction in carrying plant nutrients during an erosion process.

2. Materials and methods

2.1. Study site

Zimbabwe's climate is moderated by altitude and although the country lies within the tropics its climate is sub-tropical. According to the Koeppen climate classification system, the

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country is thus classified as temperate Cwb, i.e. mild mid-latitude, with dry winters and hot summers (Roesenberg, 2007). The average temperatures rarely exceed 33^0C in summer or drop beyond 7^0C in winter (MNTR, 1987). The country has been classified into five agro-ecological regions, namely Natural Regions I, II, III, IV and V. Only Natural Regions I and II have relatively high effective rainfall and are suitable for intensive agricultural production. Natural Regions III, IV and V constitute 83% of the total land area and are not suitable for intensive, high input agriculture (Moyo et al., 1991). Zimbabwe's soils are predominantly derived from granite and the geological complexity of the granites leads to the complexity of the soils (Thompson and Purves, 1978; Nyamapfene, 1991). The clay content of these soils varies according to the degree of weathering (influenced by rainfall) and catenal position (Thompson and Purves, 1978; Nyamapfene, 1991). From among all the soils derived from granite, the sandy soils, of the fersiallitic group, comprise the majority (Thompson and Purves, 1978) and are dominant in the small-holder farming areas (Vogel, 1993). These soils are generally light to medium textured and characterized by the presence of significant amounts of coarse sands (MNRT, 1987; Nyamapfene, 1991). The agricultural potential of these soils is fair (Grant, 1981; MNRT, 1987) and their productivity is likely to decline under intensive continuous cropping (Thompson and Purves, 1978). Therefore increased production can only be achieved through good management as well as application of fertilizers or animal manure (MNRT, 1987).

The research work was carried out at Makoholi Research Station, situated 30 km North of Masvingo town and is the regional agricultural research centre for the sandveld soils in the medium to low rainfall areas. The station lies within Natural Region IV at an altitude of about 1200 m (Thompson, 1967; Anon, 1969). Characteristic of this region is the erratic and unreliable rainfall both between and within seasons (Anon, 1969). Average annual rainfall is between 450 and 650 mm (Thompson and Purves, 1981). The soils at Makoholi are also inherently infertile, pale, coarse-grained, granite-derived sands, (Makoholi 5G) of the fersiallitic group, Ferralic Arenosols (Thompson, 1967; Thompson and Purves, 1978). Arable topsoil averages between 82 and 93% sand, 1 and 12% silt and 4 and 6% clay (Thompson and Purves, 1981; Vogel, 1993). The small amount of clay present is in a highly dispersed form and contains a mixture of 2:1 lattice minerals and kaolinite (Thompson, 1967). The organic matter content is also very low, about 0.8%, while pH ($CaCl_2$) is as low as 4.5. The soils are generally well drained with no distinct structure (Thompson and Purves, 1981), but some sites have a stone line between 50 and 80 cm depth. The low infiltration rates and water holding capacities are due to the soil texture characteristics.

2.2. Experimental design and tillage treatments

The treatments were laid out in a randomized block design replicated three times. The blocks were located at different positions along the slope (Down-slope, Middle-slope and Up-slope). Four different tillage systems were considered namely: conventional tillage, mulch ripping, tied ridging and a bare fallow.

2.2.1. Conventional tillage

The land was ox-ploughed to 23 cm depth, soon after harvest (winter ploughing), using a single-furrow mould-board plough and thereafter harrowed with a spike harrow in spring. All crop residues were removed from the plots, as is the practice in the communal areas. This tillage system is the most commonly used tillage system in the communal areas and was chosen as a standard primary tillage method, i.e. including this treatment provides a baseline for assessing the merits of other treatments (Working Document, 1990).

2.2.2. Mulch ripping

Crop residues from the previous season were left to cover the ground and only rip lines, 23 cm deep, were opened between the mulch rows, using a ripper tine. The rip lines acted as crop rows and were alternated every year, to allow roots ample time to decay. Two basic conservation tillage components were used here, i.e. minimum tillage and mulching. The main aim was to maximize infiltration through rainfall interception provided by the mulch, thus minimizing run-off. According to Hudson (1992), this parameter is the most important in the semi-arid regions, where soil moisture is the most limiting factor in agricultural production. This treatment is one of the basic conservation tillage systems, which has shown great potential in protecting the soils, without compromising the production potential and is currently being promoted by the Institute of Agricultural Engineering.

2.2.3. Tied ridging

The land was ploughed to the recommended depth of 23 cm in the first year and crop ridges constructed at 1 in 250 grade, using a ridger. The ridges were about 900 mm apart and small ties were put at about 700-1000 mm along the furrows between the crop ridges. These ties were between one half to two thirds the height of the crop ridges allowing for the water to flow over the ties and not over the ridges (Elwell and Norton, 1988). The ridges were maintained several years through re-ridging so as to maintain their correct size and shape. This treatment has been found to reduce run-off, and the soil losses are also reduced to satisfactorily low levels of 0.1 to 0.3 t/ha, much less than the tolerable limit of 5 t/ha/yr. (Elwell and Norton, 1988).

2.2.4. Bare fallow

Ploughing, up to 23 cm depth, was done using a tractor disc plough and disc harrow. The plots were kept bare and weed free, by spraying the germinating weeds during the season. This treatment is important for soil erodibility assessment and modeling purposes, as it gives the highest possible soil loss values and will probably give the lowest nutrient loss values as no fertilizers are applied.

At the beginning of this study, all trial plots had been under cultivation and the same treatment for a period of five years, having been opened up from virgin woodland. All tillage operations were carried out soon after harvest before the soil dried out. Shortly before the on-set of the rains, planting holes were made on all crop treatments, using a hand-hoe. Thereafter basal fertilizer and a nematicide were applied into the planting holes.

2.3. Agronomic details

Maize (*Zea mays* L.) is the staple food in Zimbabwe. For this reason, maize was chosen as a trial crop, so as to make the research project relevant to the small holder areas. Due to the dry conditions prevailing at Makoholi, maize variety R 201, which tolerates moisture stress and is short seasoned, was used. The crop spacing of 900 mm inter-row and 310 mm in-row were used resulting in a plant population of about 36 000 plants/ha. All weeding operations were done using a hand-hoe. The problems of nematodes, very common in the sandy soils and that of maize stalk borer were controlled, so as to minimize the influence of factors other than those imposed by treatments. Carbofuran, a nematicide was applied into the planting holes before the on-set of the rains, while Thiodan (against maize stalk borer) was applied six weeks after planting.

On all plots planting holes of about 10 cm depth and diameter were opened before the onset of the rains. Thereafter Carbofuran, was applied into these planting holes at a rate of 20 kg/ha. Compound D (N:P:K = 8:14:7) was also applied into the planting holes at a rate of 200 kg/ha to give a final ratio of 16 kg N: 12 kg P: 12 kg K. The nematicide and fertilizer were then slightly covered with soil and left until adequate rainfall had been received.

Once the profile of the ridges was wet throughout, maize was planted, two seeds per station. Ten days after planting, crop emergence count was carried out followed by weeding. The crop was then thinned out to one plant per station. When the crop was about six weeks, ammonium nitrate top-dressing fertilizer was applied at 100 kg/ha, amounting to 34.5 kg N/ha. The ammonium nitrate application coincided with the second weeding and the application of Thiodan, to control maize stalk borer.

2.4. Soil loss assessment

The standard soil erosion methodology for Zimbabwe (Wendelaar and Purkis, 1979) was used, where the plots were laid out at 4.5% slope. Soil loss and run-off measurements were from 30 m x 10 m run-off plots, with 5 m border strips on either side. The length of the plots was orientated up-slope. Tillage operations were done across the slope. Polythene strips were dug in to form the boundary around each 300 m^2 plot (Working Document, 1990). For the tied ridging treatment, the collection area was 150 m long and 5 crop rows wide (4.5 m), with 2 guard rows above and below. The crop ridges were laid at 1% slope and the length of the plots was orientated across the slope. Surface run-off and soil loss from each plot were allowed to collect in a gutter at the bottom of the plot. From the gutter these were channeled through a PVC delivery pipe into the first 1500 litre conical tank. The collection tanks were calibrated and run-off was measured using a metre-stick. Once the first tank was full its overflow passed through a divisor box with ten slots, which channeled only one tenth of the overflow into the second tank. Nine tenths of this overflow was allowed to drain away, thus increasing the capacity of the second tank. Due to the larger net plots of the tied ridging treatment, three tanks were installed, so as to capture the anticipated larger volume of sediments.

2.5. Sampling eroded material

Tanks were emptied at the end of each storm unless the interval between storms was too short to allow emptying. Sediments and run-off (including the suspended material) collected from run-off plots were treated as two different entities. Suspension was pumped out and sub-sampled for the determination of soil concentration in run-off, using the Hach spectrophotometer DL/2000. Later the sludge was transferred into 50 l milk churns, topped up with water to a volume of 50 litres and weighed. The mass of oven dry soil, M_o (kg) was calculated using the following equation (Wendelaar and Purkis, 1979; Vogel, 1993):

$$M_o = 1.7\, x\left(M_s - M_w\right) \tag{1}$$

Where M_s = mass of fixed volume of sludge (kg)

M_w = mass of the same volume full of water (kg)

1.7 = constant for the soil type

For clay, organic matter and plant nutrient assessment of the eroded soil, the collected sediments were thoroughly mixed and a sample taken by driving a hollow plastic tube into the sludge "profile" in the churn. Suspension was pumped out into 55 litre plastic containers, left to stand for 3 days, a water sample taken and the settled material at the bottom of the container sampled. Both soil samples were then air dried and analyzed individually i.e. for each storm, thus the averages given for the different treatments refer to twenty-one effective storms recorded during the season 1; nine storms during season 2 and twenty-two storms in season 3.

2.6. Soil sampling

Soil sampling on trial plots was carried out at the end of each season. Composite soil samples were taken (8-10 samples per plot) within the plough depth of 0-250 mm, using a split auger. They were then air dried and sieved.

2.7. Laboratory analysis

An analysis of the sediments for macro-nutrients was carried out, where the different sediment fractions (water, suspended material and sludge) were treated as different entities. The main aim being to quantify nutrient losses as a result of erosion and to ascertain which sediment component carries the most nutrients. Total nutrients were determined in an effort to capture all forms of nutrients and therefore give a clear picture of how much was lost with erosion, rather than giving a mere fraction of the available form. Soil samples from the trial plots, as well as eroded material, were analyzed using the following methods:

2.7.1. Texture

Texture was determined using the hydrometer method as described by Gee and Bauder (1986), where 100g of air dried soil in 15 ml of calgon and 500 ml of water were stirred for 15 minutes using an electrical stirrer. The mixture was then transferred into 1 litre cylinders and diluted with water to 1 litre. After shaking the cylinder, time and temperature readings were taken and hydrometer readings were taken after 5 minutes (clay and silt) and five hours (clay). The sand fraction was determined by transferring the contents of the cylinder on a 50 micron sieve and washing away all the silt and clay fractions and then drying.

2.7.2. Organic carbon

The Walkley and Black method as described by Nelson and Sommers (1982) was used. One g of soil was digested with 10 ml of 1N potassium dichromate solution and 20 ml of concentrated sulphuric acid. After ten minutes 100 ml of water were added, the mixture shaken and then read on a spectrophotometer.

2.7.3. Total nitrogen

Nitrogen was determined using the microkjeldahl method as described by Bremner and Mulvaney (1982). The methodology, in brief, was as follows: The soil was digested with concentrated sulfuric acid and hydrogen peroxide in the presence of a selenium catalyst. Organic nitrogen was converted into ammonium sulfate. The solution was made alkaline and the liberated ammonia (NH_3) was distilled and trapped in boric acid. The boric acid was titrated with a standard mineral acid.

2.7.4. Total phosphorous

The ignition method as described by Olsen and Sommers (1982)was used. Air dried soil was weighed into a crucible and the crucible placed into a muffle oven. The sample was ignited at 500 - 600 ^{0}C for three hours after which it was allowed to cool. Sulfuric acid was added and the mixture shaken on a reciprocating shaker for three hours. The mixture was filtered and 0.5 ml of 3M sulphuric acid were added to 5 ml of the aliquot. Twenty ml of water were added together with 4 ml of Reagent P and ascorbic acid. After 20 minutes P absorbance was measured.

2.7.5. Total potassium

The wet digestion method using perchloric acid as described by Knusden, Peterson and Pratt, (1982) was used. The mixture of finely ground soil, hydrofluoric acid and perchloric acid was heated and cooled. Some more hydrofluoric acid was added and the contents were evaporated in a sand bath. After cooling, 6N HCl and water were added and the mixture further heated until it boiled gently. The contents were transferred to a flask, diluted to volume and filtered. K was read from a flamephotometer.

2.7.6. Nutrients dissolved in run-off

Run-off was filtered and the aliquot treated as soil extract, where the nutrient concentration was either titrated with boric acid, for N determination, read from an Atomic Absorption Spectrophotometer for the determination of P or read from a flamephotometer in the case of K.

2.8. Statistical analyses

The differences in soil loss, run-off, plant growth parameters and yield attributed to treatment were analyzed with the analysis of variance (ANOVA) procedure of Genstat 5 Release 1.3 statistical package. An independent t-test was used to compare the means of different populations. Unless otherwise indicated, significance is indicated at $P < 0.05$ (*), 0.01(**) to 0.001 (***).

3. Results

3.1. Run-off

As slope steepness and slope length are the same for all treatments, run-off is thus expected to be mainly dependent on the amount, distribution and intensity of seasonal rainfall, infiltration rate, which is directly influenced by tillage and ground cover. A tillage system that either maintains a good soil structure, or inhibits run-off velocity and raindrop impact, or forces water to pond, or has a good ground cover (mulch or crop) tends to have a higher infiltration rate and therefore, lower run-off.

The highest run-off was recorded under bare fallow, with a run-off range of 17 – 39% of total seasonal rainfall. Conventional tillage recorded the second highest average run-off ranging from 13 to 22% of total seasonal rainfall. This could be attributed to a somewhat better infiltration rate at the beginning of the season, as the soil would be loose. The best treatments in conserving water were mulch ripping and tied ridging, which had run-off ranges of 9 - 15% and 1 - 11% respectively. The mulch cover has all the positive attributes that have been highlighted, i.e., reducing raindrop impact thus inhibiting soil capping, reducing run-off velocity and increasing water infiltration. Under tied ridging, run-off is also contained at low levels by way of water ponding. The micro-dams force water to pond - thus increasing infiltration - until all the micro-dams are full and start overtopping along the ridges, allowing very little water to leave the system.

Table 1 shows ANOVA results between treatments and as influenced by year. Note that the year x treatment interaction was mainly due to the differences in rainfall amount. Run-off differed significantly between treatments at $P < 0.001$. To properly evaluate the effectiveness of the conservation tillage treatments, the mean of conventional tillage versus the mean of the two conservation tillage treatments was compared using an independent t-test. The results of this test are given in Table 1. Despite the overall high significant variation between the treatments, it was established that this difference was only between conventional tillage and the two conservation tillage treatments (mulch ripping and tied ridging). There was, however no significant difference between the two conservation tillage treatments. This finding confirms that both mulch ripping and tied ridging treatments are effective in reducing run-off when compared to conventional tillage.

Treat/Year (Rainfall)	Year 1 (483 mm)	Year 2 (384 mm)	Year 3 (765 mm)	Overall mean (mm)	Source of variation	Run-off
CT	94.9	48.7	169.5	104.4	Treat	***
MR	4.6	3.6	111.4	39.8	Year	***
TR	16.0	4.5	81.8	34.1	Treat x Year	NS
BF	122.7	65.3	295.3	161.1	MR vs TR	NS
Overall mean	59.5	30.5	164.5	84.9	CT vs (MR, TR)	***
n = 9 (Treatment)	s.e.d. = 8.07	s^2 = 340.4			Yr 1 vs Yr 2	*
n = 12 (Year)	s.e.d. = 7.53	df = 24			Yr 3 vs (Yrs 1, 2)	***
n = 3 (Treatment x Year)	s.e.d. = 15.06					

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 1. Run-off (mm) as affected by tillage and year (rainfall) and their interactions at MakoholiContill site during three seasons

The amount of run-off recorded during the different years also differed significantly at $P < 0.001$. This was due to the high variation in rainfall amounts received during the three seasons. Year 1 received close to twice the rainfall amount received during Year 2. Run-off increased by more than six times, due to the concentration of rainfall in January, inducing saturated conditions, which led to high run-off. As a result of this highly significant seasonal variation an independent t test was carried out on the means of the different years. The results showed that the 100 mm difference between Year 1 and Year 2 resulted in significantly different run-off levels, at $P < 0.05$, while run-off from Year 3 differed significantly ($P < 0.001$) from the mean of that of Year 1 and Year 2. There was no significant difference for the interaction between the treatment and the year ($P = 0.145$).

The significant difference between the years further prompted an analysis of variance to establish how treatments varied within the individual years (Table 1). The overall run-off treatment differences were significant at $P < 0.01$ for the Year 1 and Year 3. A higher overall significant treatment difference was found for Year 2 indicating that the differences in run-off become more pronounced if seasonal rainfall amount was low than during wetter seasons. During wet seasons, run-off was also higher under the conservation tillage systems as they reached saturation point faster due to the already high residual soil moisture. An independent t-test showed that conventional tillage differed highly significantly from the mean of conservation tillage treatments throughout the three seasons. Mulch ripping and tied ridging, however did not differ significantly in any one of the seasons. This finding further emphasizes the water conservation potential of mulch ripping and tied ridging and also shows that a lot more rain water is lost under conventional tillage.

3.2. Soil loss

Soil losses followed the same trend as rainfall, especially under the bare fallow, where there was no ground cover (Table 2). The highest soil losses were recorded under bare fallow, averaging 93 t/ha/yr. Soil losses under conventional tillage averaged 34 t/ha/yr, while mulch ripping and tied ridging recorded soil loss averages of 1.7 and 3.3 t/ha/yr respectively. The importance of crop cover on soil erosion is shown by the different cropped treatments, especially conventional tillage, where the reduction in erosion (34 t/ha/yr from that of bare fallow, 93 t/ha/yr) is attributed to cover alone and not tillage system. Overall, the treatments differed significantly at $P < 0.001$. Independent t-tests showed that conventional tillage differed highly significantly from the two conservation tillage treatments, while there was no significant difference between the conservation treatments. This finding, tallies with the run-off results and is in accordance with expectations as soil loss is a function of run-off.

Treat/Year (Rainfall)	Year 1 (483mm)	Year 2 (384mm)	Year 3 (765mm)	Overall mean (t/ha)	Source of variation	Soil loss
CT	40.2	6.8	54.0	33.7	Treat	***
MR	0.2	0.1	4.8	1.7	Year	***
TR	3.0	0.1	3.5	2.2	Treat x Year	***
BF	84.1	43.5	152.5	93.4	MR vs TR	NS
Overall mean	31.9	12.6	53.7	32.7	CT vs (MR, TR)	***
n = 9 (Treatment)	s.e.d. = 4.00	s^2 = 71.83			Yr 1 vs Yr 2	***
n = 12 (Year)	s.e.d. = 3.46	df = 24			Yr 3 vs (Yrs 1,2)	***
n = 3 (Treatment x Year)	s.e.d. = 6.92					

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 2. Soil losses (t/ha) as affected by tillage and year (rainfall) and their interactions at MakoholiContill site during three seasons

Year had a significant effect on soil loss ($P < 0.001$) due to the varied seasonal rainfall totals. The Years 1 and 2 varied significantly at $P < 0.001$. When the mean of these two seasons was compared with the mean of Year 3, the difference also varied significantly at $P < 0.001$. The influence of rainfall on soil loss is apparent, as the season with the highest rainfall also recorded the highest soil loss and vice versa. The analysis of variance during the individual years, gave a significant overall treatment difference at $P < 0.001$ across all years. A compari-

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son between the treatment means also confirmed a significant variation ($P < 0.001$), between conventional tillage and the mean of mulch ripping and tied ridging. There was no significant difference between mulch ripping and tied ridging. As soil loss is a function of run-off, the increase of soil loss with the increase in the number of years of cultivation was expected and the same range of factors that affected run-off should be responsible for these increases in soil loss.

3.3. Particle size distribution of the sediments

The average mechanical composition of the sediments collected over the three years is shown in Table 3. Only clay and silt fractions are given. The sediments from the conservation tillage treatments comprised of more clay, i.e. more suspended material as compared to sludge (coarse material), while under the conventional tillage systems more sludge was lost compared to suspended material. There was very little clay/ silt found in sludge, while the suspended material hardly contained any sand fraction, i.e. over 90% of the suspended material was found to be clay and silt fractions. It is clear that the suspended material comprises of the most reactive soil particles (clay, silt and organic matter) and thus its loss is most detrimental to the soils' productivity as compared to sludge. Furthermore, the total sediments (sludge + suspended material) had higher clay and silt contents when compared to the original soil.

The ratios between these two sediment components were worked out for the different tillage systems (Table 3). The results show that 10 - 17 times more sludge than suspended material was found under the bare fallow, while the ratio ranged between 1.5 and 5 under conventional tillage and below 1, under the conservation tillage treatments (mulch ripping and tied ridging). This is an indication that not so much soil is moved during erosion under these treatments, while under bare fallow, mass movement is realized. The impediments created under the two conservation tillage systems ensured that the run-off velocity was reduced thus allowing no sheet wash but only the suspended soil particles to leave the system.

Figure 2 shows the actual amount of clay lost with sludge, suspension and with sediments as a whole. Although there was a lower percentage of suspended material as compared to sludge, under the bare fallow and conventional tillage, the actual amount of clay lost with suspension exceeds that lost with sludge. The clay amount lost with sediments showed the following trends:

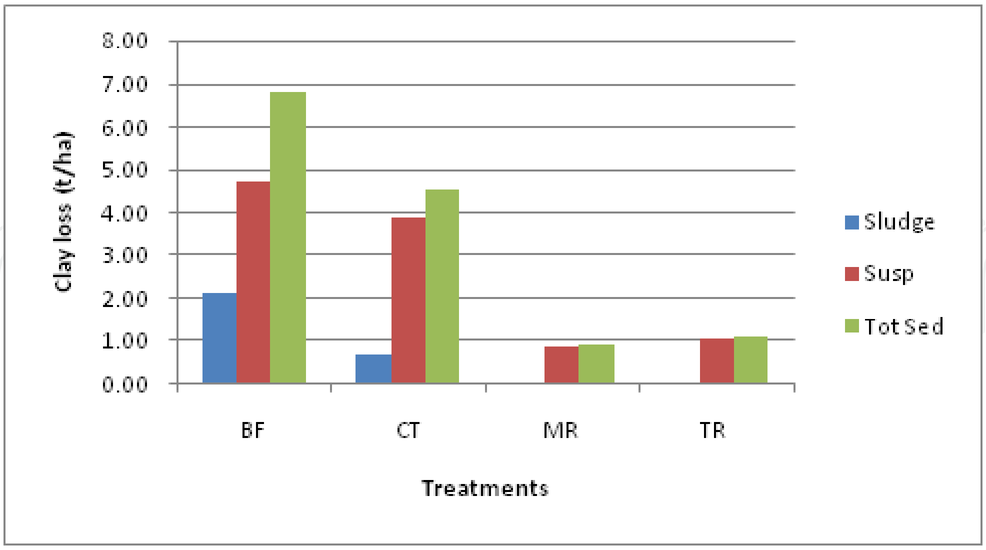
- the highest amount of clay was lost under the bare fallow (an average of 7 t/ha/yr.) followed by conventional tillage (5 t/ha/yr.) and only a negligible amount was lost under two conservation tillage treatments, i.e. 0.9 and 0.8 t/ha/yr. for mulch ripping and tied ridging respectively

- the amount of clay lost with suspension followed the same trend as that of the total sediments although the differences between bare fallow and conventional tillage were relatively smaller (Figure 1). The significant difference among the treatments was realized in the clay amount lost with sludge.

Year/Treat.	Soil loss (t/ha)		Ratio	Clay content (%)		Silt content (%)	
	Sludge	Susp	Slud:Susp	Sludge	Susp	Sludge	Susp
Year 1 (483 mm)							
BF	74.54	7.28	10.24	1.32	58.00	2.93	37.87
CT	27.97	6.33	4.42	1.22	57.69	3.21	34.40
MR	0.00	0.17	0.00	0.00	59.93	4.10	36.75
TR	0.38	1.16	0.33	0.81	66.68	4.59	33.32
Year 2 (384 mm)							
BF	41.09	2.37	17.34	2.78	52.56	1.58	29.55
CT	4.12	2.70	1.53	2.79	57.81	2.69	36.45
MR	0.00	0.08	0.00	0.00	59.75	0.00	38.02
TR	0.04	0.10	0.40	2.01	69.95	1.76	43.57
Year 3 (765 mm)							
BF	139.02	13.36	10.41	3.02	64.89	1.48	27.66
CT	45.66	8.44	5.41	3.15	76.97	2.22	34.27
MR	1.84	3.03	0.61	4.00	83.43	2.44	17.25
TR	0.65	2.88	0.23	4.02	83.40	4.12	6.05

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 3. Relationship between sludge and suspended material in erosion sediments from four tillage systems over three years at MakoholiContill site



Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Figure 2. Average clay loss with sediments during three years at MakoholiContill site with sludge, suspension and total sediments

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The clay enrichment ratios for the total sediments (clay content in soil: clay content in sediments) show that the sediments have distinctly more clay than the original soil (Table 4). In all cases the bare fallow had enrichment ratios of less than 2, while under conventional tillage the ratio ranged between 2.8 and 6.0. The two conservation tillage treatments recorded the highest enrichment ratios, as expected, of between 12.4 and 14.5 for mulch ripping and 13.8 - 19.0 for tied ridging. The very high clay enrichment ratios found under conservation tillage treatments indicate the very low run-off velocity which only carries suspended material but has not enough energy to erode and carry coarse particles, as is the case under conventional tillage and the bare fallow. Table 4 also shows that clay content in the sediments varied highly significantly between the treatments ($P < 0.001$), while there was no difference ($P = 0.966$) between the sediment composition over the years

Treat./Year	Clay in total sediments %	Clay t/ha	Clay Enrichment Ratio
Year 1			
BF	6.36	5.20	1.41
CT	11.63	3.99	2.78
MR	58.83	0.10	13.68
TR	50.00	0.77	13.81
Year 2			
BF	5.50	2.39	1.22
CT	25.07	1.67	5.98
MR	62.50	0.05	14.53
TR	50.00	0.07	13.81
Year 3			
BF	8.45	12.87	1.87
CT	14.68	7.94	3.50
MR	53.39	2.60	12.42
TR	68.84	1.43	19.02
Source of variation	Clay % in sediments	Clay (t/ha)	
Treatment	***	***	
s.e.d.	5.65	2.676	
Year	NS	***	
s.e.d.	19.23	2.320	

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 4. Clay loss with sediments and its enrichment ratios for the different tillage systems during three seasons at MakoholiContill site

3.4. Organic matter loss with sediments

The original organic matter content of the virgin soils averaged approximately 0.8%, (Table 5). After continuous cultivation for five years the organic matter content was found to have declined by 25% under the bare fallow; 19% under the conventional tillage; 6% under mulch ripping and 9% under tied ridging. This finding shows that with continuous cultivation the organic matter status of these soils decreases, more so if no plant residues are left in the field, e.g. bare fallow. The higher organic matter content under conventional tillage, compared to bare fallow, is a result of roots left behind after harvest. Tied ridging combines this effect with that of soil conservation to give an even better maintenance of organic matter. The best effect is, however, achieved under mulch ripping, where roots together with plant residues and soil conservation effects contribute to better organic matter maintenance, thus only 6% was lost. The mineralization of organic matter after cultivation is expected to take place but by further addition of mulch the depreciation rate is lowered drastically. Reduced tillage in the mulch ripping treatment, as compared to other treatments, further contributes to conservation of organic matter.

Treatment	Virgin land OM %	After five of cultivation OM %	OM reduction %
BF	0.72	0.53	24.9
CT	0.84	0.68	18.9
MR	0.85	0.80	5.7
TR	0.70	0.64	9.1

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 5. Soil organic matter content of the soils (0 - 25 cm depth) for different tillage systems as at opening from virgin land and five years later at MakoholiContill site

The concentration of organic matter in sediments was higher for conservation tillage systems than for conventional tillage and bare fallow. This resulted in higher enrichment ratios (organic matter content in soil: organic matter content in sediments) for conservation tillage systems. Mulch ripping and tied ridging recorded enrichment ratios of 4.6 and 3.4 respectively, while conventional tillage recorded an enrichment ratio of 2.8 and bare fallow 2.6 (Table 6). The total amount of organic matter lost with conservation tillage was, however, only a fraction of that lost from conventional tillage and bare fallow. Under bare fallow an annual average of 424 kg/ha was lost, while under conventional tillage 299 kg/ha were lost, mulch ripping lost only 55 kg/ha and tied ridging 61 kg/ha/yr (Table 7). It is quite obvious that although the organic matter concentrations in sediments of bare fallow and conventional tillage are quite low, the extensive losses of soil contributed to a tremendous total loss. Higher contents for conventional tillage as compared to bare fallow show the contribution of roots to the soil organic matter, thus a higher depreciation is apparent under bare fallow, where no crops are grown.

Under the conventional tillage treatments organic matter losses were much higher than with conservation tillage. Whereas most organic matter in conservation tillage was lost in suspension, losses with conventional tillage were more evenly distributed between suspension and sludge, because of the very high sludge losses, see Table 7.

Treatm.	OM content (%)		Enrichment ratio
	Soil	Sediments	
Year 1			
BF	0.54	1.63	3.02
CT	0.68	2.24	3.29
MR	0.80	5.36	6.70
TR	0.63	2.82	4.48
Year 2			
BF	0.54	1.05	1.94
CT	0.68	1.27	1.87
MR	0.80	2.88	3.60
TR	0.63	1.22	1.94
Year 3			
BF	0.54	1.49	2.76
CT	0.68	2.13	3.13
MR	0.80	2.69	3.36
TR	0.63	2.34	3.71

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 6. Organic matter contents of the soils and sediments and calculated enrichment ratios for four tillage treatments, over three seasons at MakoholiContill site

The amount of organic matter lost varied significantly ($P < 0.001$) among all treatments. Contrasting the different systems against one another showed that conventional tillage did not differ significantly from the bare fallow. The mean of conventional tillage and bare fallow, however, differed significantly at $P < 0.001$, with that of mulch ripping and tied ridging, indicating that the two conservation tillage treatments are very effective in conserving and/or maintaining soil organic matter. When conventional tillage was also compared to the mean of the conservation tillage treatments, the difference was significant, $P < 0.001$. Finally the two conservation treatments were compared within the group and they were not significantly different. As it is important to show which of the two conservation treatments performs better than the other, an independent t-test was carried out, i.e., disregarding the other two treatments altogether and comparing the two conservation treatments only. The results showed a significant difference at P < 0.05, where lower losses were found under the mulch ripping treatment.

Treatm.	OM content %		OM loss kg/ha		Enrichment ratio	
	Sludge	Susp.	Sludge	Susp.	Sludge	Susp.
Year 1						
BF	0.23	2.59	168.25	188.86	0.43	4.80
CT	0.35	3.27	99.15	206.78	0.51	4.81
MR	0.00	5.02	0.00	8.46	0.00	6.28
TR	0.42	4.56	1.58	52.74	0.67	7.24
Year 2						
BF	0.04	2.06	11.04	48.20	0.07	3.81
CT	0.10	2.44	4.60	70.15	0.15	3.59
MR	0.00	2.88	0.00	2.58	0.00	3.60
TR	0.15	2.29	0.06	2.11	0.24	3.63
Year 3						
BF	0.37	2.61	509.49	345.07	0.69	4.83
CT	0.45	3.81	208.55	307.09	0.66	5.60
MR	0.31	5.07	4.80	148.53	0.39	6.34
TR	0.55	4.12	4.24	121.30	0.87	6.54
ANOVA						
Treatment	***	***	***	***		
Year	***	***	***	***		

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 7. Differences in the organic matter contents of sludge and suspended soil over three seasons at MakoholiContill site

Soil organic matter is generally associated with the finer and more reactive clay and silt fractions of the soil (Follet*et al.,* 1987). It is, therefore as expected that more organic matter should be lost with suspended load than with sludge. Table 7 shows the two sediment parameters (sludge and suspended load), which were treated as different entities. In relation to this, organic matter contents, quantities and enrichment ratios for the different parameters are given.

Under the conventional tillage treatments relatively less soil was lost as suspended load. The amount of organic matter lost with this fraction was, however, substantial, i.e. 40 - 81%

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(BF) and 60 - 94% (CT) of the total organic matter lost. The soil lost under mulch ripping was almost entirely in suspended form. This resulted in almost all the organic matter (97 - 100%) being lost with suspended material. Under tied ridging most of the soil was also lost as suspension, 75% of the total soil loss, with 97% of total organic matter loss. The enrichment ratios are thus very high for the suspended soil consisting mainly of clay and silt. The sludge has lower enrichment ratios and the organic matter contents are even less than of the original soil.

Many scientists have reported on the selective nature of soil erosion (Aylen, 1939; Hudson and Jackson, 1962; Shaxson, 1975; Elwell, 1987; Lal, 1988 among others), however the extent to which the soils have been impoverished or the sediments enriched have mainly been estimated. This study showed that sheet erosion is selective as sediments recorded higher contents of clay, silt and organic matter than the original soil. The particle size distribution of sludge was mainly coarse sand and had a maximum of 4% clay. Suspended material on the other hand had up to 83% clay, the rest mainly being the silt fraction. Sediments from conservation tillage systems comprised of more sand than the clay fraction, bare fallow had 13 times and conventional tillage 4 times less sludge than suspension. Due to the high losses of coarse material under the conventional tillage, the clay enrichment ratio of sediments was lower than under the conventional tillage systems. The bare fallow recorded only 1.5 and conventional tillage 4.1 times more clay in the sediments. Under the conservation tillage systems more soil was lost in suspension than as sludge. Mulch ripping recorded 0.2 times and tied ridging 0.3 times more sludge than suspension, resulting in higher clay enrichment ratios of 13.5 and 15.5 under mulch ripping and tied ridging respectively. However, these high enrichment ratios amounted to less amount of clay lost from conservation tillage compared to conventional tillage, due to the reduced total sediments lost under the conservation tillage systems. Under bare fallow an average of 7 t/ha of clay were lost, 5 t/ha under conventional tillage and 0.9 and 0.8 t/ha under mulch ripping and tied ridging respectively. The very high enrichment ratios under the conservation tillage systems are a reflection of the soil losses, which were lost mainly as suspended material, which constitutes fine soil particles, however the very low amount of soil led to negligible losses of total clay loss with sediments.

This selective nature of erosion manifested itself in the high enrichment ratios of the sediments as compared to the original soil. This means that soil fertility is affected severely by the soil lost in suspension, as it constitutes mainly of clay and organic matter fractions, which are the main sources of nutrients (Stocking, 1983). The soil structure and water holding capacity are also affected as these soil fractions are responsible for soil aggregation and influence the water dynamics of the soil (Follet*et al*., 1987; Stocking and Peake, 1987). The sludge fraction, however, affects mainly the soil productivity through reduction in soil tilth as it contains few reactive particles.

As was established for the clay loss, the organic matter enrichment ratios were higher under mulch ripping (4.6) and tied ridging (3.4) as compared to conventional tillage (2.8) and bare fallow (2.6). Exceptionally high organic matter losses were realized under conventional tillage systems as compared to conservation tillage systems, due to the high sediment losses.

The bare fallow lost an annual average of 424 kg/ha, while conventional tillage lost 299 kg/ha, mulch ripping lost only 55 kg/ha and tied ridging 61 kg/ha/yr and the treatments differed significantly from one another. The proximity and concentration of soil organic matter near the soil surface (< 250 mm) and its close association with plant nutrients in the soil makes erosion of soil organic matter a strong indicator of overall plant nutrient losses resulting from erosion (Follet*et al.*, 1987). Thus the effectiveness of the two conservation tillage treatments can be appreciated based upon the small amount of organic matter lost with eroded sediments, compared to the conventional tillage.

In situ measurement of organic matter as a measure of soil erosion yielded fruitful as the organic matter levels dropped drastically after five years of cultivation, especially under the conventional tillage systems. The bare fallow lost 25%, conventional tillage 19%, tied ridging 9% and mulch ripping 6% of total organic matter found on virgin land. This is in agreement with the very high losses of fine particles lost under the conventional tillage systems as compared to conservation tillage. It is apparent that through conservation of the soil under mulch ripping and tied ridging, the organic matter status in the soil is maintained, thus the soil structure and soil productivity.

As most of the soil fertility is associated with clay and humus and these also affect microbial activity, soil structure, permeability and water holding capacity (Troeh*et al.*, 1980), it is clear that through sheet erosion the land is degraded chemically, physically and biologically. Thus not only soil fertility is reduced, but also soil productivity, which unlike fertility cannot be addressed by mere fertilizer application.

3.5. Nutrient losses with sediments

Before the assessment of the nutrient losses with erosion, it was important to evaluate the nutrient (N, P, K) status of the soils. From Table 8, it is apparent that the most abundant nutrient in the soil is potassium, followed closely by nitrogen and the least abundant is phosphorus. Since total nutrients are considered it is expected that the nutrient with the highest concentration in the soil will also result in the highest losses and vice versa. Thus, comparing the amount of different nutrients lost with the sediments may not be very meaningful but a method of evaluating and comparing the loss of different nutrients should also be based relatively upon the status of that nutrient in the soil. This method involves the determination of nutrient concentration in the soil and in the sediments and calculating the enrichment ratios.

The nutrient losses were calculated using the following equation:

$$\mathrm{Nut}_{los} = \mathrm{Soil}_{los} \times \mathrm{Nut}_{conc} \tag{2}$$

where Nut_{los}= any nutrient lost with sediments (kg/ha)

Soil_{los}= mass of soil lost by erosion (kg/ha)

Nut_{conc}= the concentration of a nutrient in the sediment (ppm or %)

Treatment	Nutrient status of the soil		
	N %	P ppm	K ppm
BF	0.04	39.4	554.2
CT	0.05	52.0	616.7
MR	0.05	62.2	575.0
TR	0.05	91.8	487.5

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 8. Nutrient of the soils as at beginning of the study at Makoholi Contill site

3.5.1. Nutrient losses with total sediments

Nitrogen

Using Equation 2 to calculate the amount of N lost with erosion, the highest total nitrogen losses were realized under bare fallow, at 28 kg/ha followed by conventional tillage (16 kg/ha), while they were least under mulch ripping (2.3 kg/ha), which was also barely different from tied ridging (2.7 kg/ha), see Table 9. Total nitrogen loss differed significantly ($P < 0.001$) between the different treatments, different years and for the treatment x year interaction. These results follow, as expected, the same trend that was established for soil loss (Table 2) and serve to confirm the dependence of nutrient losses with the amount of soil lost from a field. The maintenance of soil under the two conservation tillage treatments is also directly related to the lower N losses. Although nitrogen losses were highest under the bare fallow, the actual nutrient concentration in the soil was least under this treatment (Table 12) because no fertilizer was applied and the sediments under this treatment comprised mainly the non-reactive coarse particles.

Treat/Year (Rainfall)	Year 1 (483 mm)	Year 2 (384 mm)	Year 3 (765 mm)	Overall mean	Source of variation	N loss
CT	17.40	6.82	23.22	15.81	Treat	***
MR	0.53	0.16	6.06	2.25	Year	***
TR	3.03	0.15	4.92	2.70	Treat x Year	***
BF	32.10	9.06	44.10	28.42	MR vs TR	NS
Overall mean	13.27	4.05	19.58	12.30	CT vs (MR, TR)	***
n = 9 (Treatment)	s.e.d. = 1.341	$s^2 = 8.097$				
n = 12 (Year)	s.e.d. = 1.162	df = 24				
n = 3 (Treatment x Year)	s.e.d. = 2.323					

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 9. Total nitrogen loss (kg/ha) as a result of erosion under different tillage systems over three years at MakoholiContill site

Phosphorus

The overall phosphorus loss of 0.5 kg/ha, was as expected, much lower than nitrogen loss (12.3 kg/ha), due to the generally low P status in the sandy soils. The bare fallow had the highest P loss of 0.9 kg/ha followed by conventional tillage with 0.8 kg/ha, tied ridging 0.2 kg/ha and the least P losses were recorded under mulch ripping (0.09 kg/ha) (Table 10). This trend was to be expected, as nutrient losses are a function of soil loss. Despite the low losses, the treatments and years gave highly significant differences at P < 0.001. The two conservation tillage treatments were not significantly different from one another.

Treat/Year (Rainfall)	Year 1 (483 mm)	Year 2 (384 mm)	Year 3 (765 mm)	Overall mean	Source of variation	P loss
CT	1.403	0.182	0.666	0.750	Treat	***
MR	0.057	0.009	0.208	0.091	Year	***
TR	0.282	0.008	0.218	0.169	Treat x Year	***
BF	1.269	0.245	1.069	0.861	MR vs TR	NS
Overall mean	0.753	0.111	0.540	0.468	CT vs (MR, TR)	***
n = 9 (Treatment)	s.e.d. = 0.0667	s^2 = 0.02004 df = 24				
n = 12 (Year)	s.e.d. = 0.0578					
n = 3 (Treatment x Year)	s.e.d. = 0.1156					

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 10. Total phosphorus (kg/ha) as a result of erosion under different tillage systems over three years at MakoholiContill site

Potassium

Potassium was, as expected, lost in greater quantities when compared to the other elements (overall 17.3 kg/ha). It has been highlighted that K is the most abundant element in the soils' mineralogy (Table 8) and this explains the high losses. The same trend that was established for N and P was also found with K, where more K was lost with bare fallow (40 kg/ha) and conventional tillage (25 kg/ha) as compared to the conservation tillage systems (0.6 and 4 kg/ha for mulch ripping and tied ridging respectively), see Table 11. The overall treatment differences were significant at P < 0.001 mainly, due to significantly higher soil losses between the treatments. The different years also gave rise to different K losses, which were sig-

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nificant at P < 0.001. These differences show the conservation merits of the conservation tillage treatments, implying that potassium is also conserved effectively through the ability of these treatments in reducing erosion.

Treat/Year (Rainfall)	Year 1 (483 mm)	Year 2 (384 mm)	Overall mean	Source of variation	K loss with erosion
CT	42.3	6.7	24.5	Treat	***
MR	1.0	0.2	0.6	Year	***
TR	8.3	0.2	4.3	Treat x Year	***
BF	66.7	12.9	39.8	MR vs TR	NS
Overall mean	29.6	5.0	17.3	CT vs (MR, TR)	***
n = 6 (Treatment)	s.e.d. = 5.49	$s^2 = 90.44$			
n = 12 (Year)	s.e.d. = 3.88	df = 16			
n = 3 (Treatment x Year)	s.e.d. = 7.76				

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 11. Total potassium loss (kg/ha) as a result of erosion under different tillage systems over three years at MakoholiContill site

Overall the enrichment ratios (soil nutrient concentration: sediment nutrient concentration) for the different nutrients were not very different from one another (Table 12). These were as follows: N: 4.3; P: 3.8 and K: 4.2. Although the amount of P lost with erosion was only a fraction of N and K amounts, it is clear that relative to the amount of P in the soil, all nutrients were lost in near equal proportions. The highest enrichment ratios were recorded under the conservation tillage systems, where the ratios ranged between 6.0 (P) and 7.3 (K), while under conventional tillage the sediments were enriched as follows: 2.0 for N, 1.9 for P and K. The bare fallow recorded the least nutrient enrichment ratios of about 1.0 N and K, while a ratio of 2.7 was recorded for P. The difference in enrichment ratios was only recorded for the different tillage systems and not for the plant nutrients, as these showed a similar trend within these tillage systems.

3.5.2. Nutrient losses with run-off

Nitrogen

The amount of nitrogen lost with run-off was very small, on average constituting less than 1% of total nitrogen lost under conventional tillage, bare fallow and tied ridging, while under mulch ripping an average of 2% was recorded over the three years, see Figure 3a. Tied ridging recorded the least N loss of 15 g/ha and conventional tillage the highest N loss of 64 g/ha, however, there was no significant difference between treatments (P = 0.076), see Table 13. A significant difference of P < 0.001 was found between the different years showing that the different rainfall regimes influence run-off amount and consequently nitrogen loss. As N loss with run-off is dissolved N, it is expected that this fraction would be more under cropped treatments where N fertilizer was applied and generally where the nutrient status in the soil is higher. The lower N loss under the bare fallow compared to conventional tillage and mulch ripping, despite higher run-off, is because of this fact. The reason for the low N concentration under the tied ridging treatment is mainly due to the fact that fertilizers are protected on the ridges, while run-off mainly takes place in the furrows.

Treat	**Nutrient concentration in the sediments**			**Enrichment ratios: nutrient in soil: nutrient in sediments**		
	N %	P ppm	K ppm	N	P	K
Year 1						
BF	0.05	39.8	803.9	1.3	1.0	1.5
CT	0.07	104.6	1351.1	1.4	2.0	2.2
MR	0.41	570.9	5397.7	8.2	9.2	9.39
TR	0.28	447.6	5110.6	5.7	4.9	10.5
Year 2						
BF	0.03	14.4	318.7	1.0	0.8	0.6
CT	0.12	61.9	961.5	3.0	2.5	1.6
MR	0.40	156.6	1875.0	8.0	5.2	4.0
TR	0.25	104.8	1813.5	5.06	2.5	4.0
Year 3						
BF	0.05	15.0	-	1.7	0.9	-
CT	0.06	33.4	-	1.5	1.2	-
MR	0.22	124.4	-	4.3	4.8	-
TR	0.52	326.1	-	10.3	10.3	-
-	= missing data					
Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow						

Table 12. Nutrient concentrations in the sediments and enrichment ratios for different tillage systems at MakoholiContill site

Phosphorus

The amount of P lost with run-off constituted a slightly higher percentage of total P loss with sediments than was the case with nitrogen. The conservation tillage treatments realized a higher ratio of dissolved P losses, averaging 4% under mulch ripping and 2% under tied ridging. An average of 1% was recorded under conventional tillage and the lowest percentage loss was found under the bare fallow, where P in run-off only constituted 0.6% of total P lost, (Figure 3b). As was the case with N, there were no significant differences between treatments as the amounts were generally very low (Table 14). However, the different years gave rise to significantly different P losses ($P < 0.001$), due to the different amounts of run-off realized during these years.

Treat/Year (Rainfall)	Year 1 (483 mm)	Year 2 (384 mm)	Year 3 (765 mm)	Overall mean	Source of variation	Nitrogen in run-off
CT	0.0469	0.0071	0.1377	0.0639	Treat	NS
MR	0.0042	0.0037	0.1789	0.0623	Year	***
TR	0.0030	0.0012	0.0421	0.0154	Treat x Year	NS
BF	0.0298	0.0058	0.1208	0.0522	MR vs TR	NS
Overall mean	0.0210	0.0045	0.1199	0.0484	CT vs (MR, TR)	NS
n = 9 (Treatment)	s.e.d. = 0.01986	$s^2 = 0.001775$				
n = 12 (Year)	s.e.d. = 0.01720	df = 24				
n = 3 (Treatment x Year)	s.e.d. = 0.03440					

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 13. Nitrogen loss (kg/ha) with run-off under different tillage systems over three years at MakoholiContill site

Treat/Year (Rainfall)	Year 1 (483 mm)	Year 2 (384 mm)	Year 3 (765 mm)	Overall mean	Source of variation	P with run-off
CT	0.0066	0.0028	0.0153	0.0083	Treat	NS
MR	0.0021	0.0003	0.0078	0.0034	Year	***
TR	0.0034	0.0004	0.0081	0.0040	Treat x Year	NS
BF	0.0041	0.0026	0.0089	0.0052	MR vs TR	NS
Overall mean	0.0040	0.0015	0.0100	0.0052	CT vs (MR, TR)	NS
n = 9 (Treatment)	s.e.d. = 0.000973	$s^2 = 0.00004259$				
n = 12 (Year)	s.e.d. = 0.000843	df = 24				
n = 3 (Treatment x Year)	s.e.d. = 0.001685					

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 14. Phosphorus loss (kg/ha) with run-off under different tillage systems over three years at MakoholiContill site

Potassium

Dissolved potassium loss with run-off, as was the case with the other elements, constituted a smaller percentage of the total K lost with erosion. The highest percentage was found under the mulch ripping treatment (15 - 20% of total K), followed by tied ridging (5%), then conventional tillage with 2 - 3% and the bare fallow had the least percentage averaging 1% of total K lost, (Figure 3c). The treatments however, did not differ significantly from one another but the different years differed significantly at P < 0.001 (Table 15). Unlike the other elements the loss of dissolved K was highest under the bare fallow, indicating that K is abundant in the soil and highly soluble in water. This also gives an indication on the availability of K in these soils.

Treat/Year (Rainfall)	Year 1 (483 mm)	Year 2 (384 mm)	Year 3 (765 mm)	Overall mean	Source of variation	K in run-off
CT	0.87	0.18	3.81	1.62	Treat	NS
MR	0.20	0.03	3.25	1.16	Year	***
TR	0.38	0.01	1.85	0.74	Treat x Year	NS
BF	0.91	0.02	6.19	2.38	MR vs TR	NS
Overall mean	0.59	0.06	3.77	1.47	CT vs (MR, TR)	NS
n = 9 (Treatment)	s.e.d. = 0.663	s^2 = 1.976				
n = 12 (Year)	s.e.d. = 0.574	df = 24				
n = 3 (Treatment x Year)	s.e.d. = 1.148					

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 15. Dissolved K loss (kg/ha) with run-off under different tillage systems over three years at MakoholiContill site

3.5.3. Nutrient losses with suspended material

Nitrogen

For all the cropped treatments, most of the N was lost with suspended material and ranged from 49 - 82% of total nitrogen loss under conventional tillage; 86 - 99% under mulch ripping and 93 - 97% under tied ridging. The percentage was lower under the bare fallow and ranged from 29 - 50%, due to the extra-ordinarily high losses of sludge as compared to suspended material (Figure 3a). Analysis of variance showed that nitrogen loss with suspended material differed significantly (P < 0.001) between the different treatments, as a result of the significant treatment differences in the loss of suspended material (Table 16). The conservation tillage treatments did not differ significantly from each other. The different years also gave significant differences in nitrogen loss (P < 0.001). This finding indicates that the suspended material is by far the most important medium for overland transport of nitrogen from arable lands, as a result of erosion. The nitrogen concentration in suspended material ranged from 0.2 - 0.65% compared to 0.04 – 0.05% in the soil.

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Phosphorus

Most of the P was also lost with suspended material under the cropped treatments (Table 17). Conventional tillage lost 62 - 83% of total P with suspended material, while the losses ranged between 93 and 97% under mulch ripping and between 91 and 97% under tied ridging. Under the bare fallow, this phenomenon was less pronounced, with the P lost with this fraction accounting for 27 - 61% of total P lost (Figure 3b).

Treat/Year (Rainfall)	**Year 1 (483 mm)**	**Year 2 (384 mm)**	**Year 3 (765 mm)**	**Overall mean**	**Source of variation**	**Nitrogen in susp.**
CT	10.16	5.62	11.38	9.05	Treat	***
MR	0.52	0.16	5.23	1.97	Year	***
TR	2.94	0.14	4.68	2.59	Treat x Year	***
BF	12.33	2.66	22.03	12.34	MR vs TR	NS
Overall mean	6.49	2.14	10.83	6.49	CT vs (MR, TR)	***
n = 9 (Treatment)	s.e.d. = 1.307	s^2 = 7.686				
n = 12 (Year)	s.e.d. = 1.132	df = 24				
n = 3 (Treatment x Year)	s.e.d. = 2.264					

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 16. Nitrogen loss (kg/ha) with suspended material under different tillage systems over three years at MakoholiContill site

Treat/Year (Rainfall)	**Year 1 (483 mm)**	**Year 2 (384 mm)**	**Year 3 (765 mm)**	**Overall mean**	**Source of variation**	**P in susp.**
CT	1.0541	0.1512	0.4157	0.540	Treat	***
MR	0.0549	0.0087	0.1939	0.086	Year	***
TR	0.2739	0.0073	0.2049	0.162	Treat x Year	***
BF	0.7739	0.0664	0.5244	0.455	MR vs TR	NS
Overall mean	0.539	0.058	0.335	0.311	CT vs (MR, TR)	***
n = 9 (Treatment)	s.e.d. = 0.0597	s^2 = 0.01602)				
n = 12 (Year)	s.e.d. = 0.0517	df = 24				
n = 3 (Treatment x Year)	s.e.d. = 0.1033					

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 17. Phosphorus loss (kg/ha) with suspended material under different tillage systems over three years at MakoholiContill site

Due to this variation in the different treatments, analysis of variance among the different treatments gave a significant difference at P < 0.001. The different years and the interaction between treatment and year were also significantly different. The finding also shows the significance of suspended material in transporting P from arable lands as a result of erosion.

Potassium

The suspended material accounted for most of the potassium losses under all the cropped treatments, see Table 18. The conservation tillage treatments realized the highest percentages that ranged between 80 and 85% for mulch ripping and 90 and 93% for tied ridging, while conventional tillage lost 66 - 79% of total potassium with this sediment fraction. The bare fallow was the only exception, with the losses as low as 28 - 51% (Figure 3c). Once again this is an indication of the ratio between suspended material and coarse material under the bare fallow. The analysis of variance gave highly significant differences (P < 0.001) between treatments and years and a significant difference of P < 0.01 for the treatment x year interaction. Although somewhat lower the relationship between K and fine soil particles is clearly indicated.

Treat/Year (Rainfall)	Year 1 (483 mm)	Year 2 (384 mm)	Overall mean	Source of variation	K in susp.
CT	28.1	5.3	16.7	Treat	***
MR	0.8	0.2	0.5	Year	***
TR	7.7	0.2	4.0	Treat x Year	**
BF	34.0	3.6	18.8	MR vs TR	NS
Overall mean	17.7	2.3	10.0	CT vs (MR, TR)	***
n = 6 (Treatment)	s.e.d. = 3.60	s^2 = 38.77			
n = 12 (Year)	s.e.d. = 2.54	df = 16			
n = 3 (Treatment x Year)	s.e.d. = 5.08				

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 18. Potassium loss (kg/ha) with suspended material under different tillage systems over three years at MakoholiContill site

The nutrient enrichment ratios for suspended material were generally higher than those recorded for the total sediments, due to the high proportion of fine soil particles (Table 19). The following overall enrichment ratios were found: N: 6.2; P: 5.9 and K: 6.8. Once again the enrichment ratios show that nutrients were lost, relative to their nutrient status in the soil. Although the conservation tillage systems generally had high enrichment ratios, the difference between the treatments was not as distinct as was the case with total sediments. This is as a result of the similar composition of the suspended material, regardless of tillage treatment. The nutrient enrichment ratios were similar across all the nutrients.

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3.5.4. Nutrient losses with sludge

Nitrogen

Under all the cropped treatments, the amount of nitrogen lost with sludge was significantly lower than that lost with suspended load (Figure 3a). This phenomenon was more pronounced under the conservation tillage treatments. Conventional tillage recorded 18 - 50%, while mulch ripping recorded 0 - 11% and tied ridging 3 - 7 % of total N loss with sludge. The bare fallow recorded more N loss with sludge (50 - 71%) due to the very high sludge loss. These findings indicate that less nitrogen is associated with coarse soil particles and this is further implicated by the less nitrogen concentration in sludge, ranging between 0.00 and 0.05% as compared to that in suspended material (0.2 - 0.65%). The amount of N lost with sludge differed highly significantly ($P < 0.001$) between the different treatments and it differed significantly at $P < 0.01$ among the different years. As expected, there was no significant difference between the two conservation tillage treatments (Table 20).

Treat	**Nutrient concentration in suspension**			**Enrichment ratios: nutrient in soil: nutrient in suspension**		
	N %	P ppm	K ppm	N	P	K
Year 1						
BF	0.18	267.6	4634.8	4.5	6.8	8.4
CT	0.24	426.2	5233.2	4.8	8.2	8.5
MR	0.41	570.9	5397.7	8.2	9.2	9.4
TR	0.37	584.2	6660.3	7.4	6.4	13.7
Year 2						
BF	0.18	73.1	1671.2	6.0	4.3	3.0
CT	0.26	129.5	1922.5	6.5	5.2	3.1
MR	0.40	156.6	1875.0	8.0	5.3	3.3
TR	0.35	142.8	2505.6	7.0	3.4	5.1
Year 3						-
BF	0.16	73.5	-	5.3	4.6	-
CT	0.21	125.3	-	5.3	4.6	-
MR	0.32	192.2	-	6.4	7.4	-
TR	0.27	163.6	-	5.4	5.1	-

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 19. Nutrient concentration in the soil (0 - 25 cm) versus nutrient concentration in suspended material and enrichment ratios for different tillage systems at MakoholiContill site

Treat/Year (Rainfall)	Year 1 (483 mm)	Year 2 (384 mm)	Year 3 (765 mm)	Overall mean	Source of variation	N in sludge
CT	7.19	1.20	11.70	6.70	Treat	***
MR	0.00	0.00	0.65	0.22	Year	**
TR	0.09	0.01	0.20	0.10	Treat x Year	*
BF	19.75	6.39	21.95	16.03	MR vs TR	NS
Overall mean	6.76	1.90	8.62	5.76	CT vs (MR, TR)	***
n = 9 (Treatment)	s.e.d. = 1.962	s^2 = 17.32				
n = 12 (Year)	s.e.d. = 1.699	df = 24				
n = 3 (Treatment x Year)	s.e.d. = 3.398					

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 20. Nitrogen loss (kg/ha) with sludge under different tillage systems over three years at MakoholiContill site

Treat/Year (Rainfall)	Year 1 (483 mm)	Year 2 (384 mm)	Year 3 (765 mm)	Overall mean	Source of variation	P in sludge
CT	0.3423	0.0280	0.2350	0.4009	Treat	***
MR	0.0000	0.0000	0.0063	0.0033	Year	***
TR	0.0047	0.0003	0.0050	0.0021	Treat x Year	***
BF	0.4910	0.1760	0.5357	0.2018	MR vs TR	NS
Overall mean	0.2095	0.0511	0.1955	0.1520	CT vs (MR, TR)	***
n = 9 (Treatment)	s.e.d. = 0.02531	s^2 = 0.002883				
n = 12 (Year)	s.e.d. = 0.02192	df = 24				
n= 3 (Treatment x Year)	s.e.d. = 0.04384					

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 21. Phosphorus loss (kg/ha) with sludge under different tillage systems over three years at MakoholiContill site

Phosphorus

The amount of P lost with sludge was, as expected, lower than that lost with suspended material for all the cropped treatments (Figure 3b). During the two out of three seasons, there was no phosphorus loss with sludge under mulch ripping and during the last year, the P lost with this sediment fraction constituted only 3% of total P lost. Under tied ridging the losses were nearly the same, ranging from 2 - 4%. The conventional tillage treatment realized significantly higher losses between 16 and 35% of total P lost and once again the bare fallow recorded, during two of the three years, more than 50% of total P lost. The overall treatment and year differences were significant at P < 0.001 (Table 21). It is clear once again

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that P is associated with fine soil particles and not with the non-reactive coarse material as is evidenced by the low P concentrations in sludge, ranging from 0 - 34 ppm compared to 73 - 584 ppm in suspended material.

Potassium

The sludge fraction constituted the lowest losses of K under the cropped treatments, ranging from 0 - 5% under the conservation tillage treatments, a maximum of 32% under conventional tillage (Figure 3c). Under the bare fallow 48 - 72 % of total K was lost with this sediment fraction. These obvious differences between both treatment and year factors were significant at P < 0.001 (Table 22). K is therefore associated with the suspended material than with sludge, the somewhat higher percentages lost under conventional tillage and bare fallow are merely in relation to the very high coarse material lost under these treatments as the actual nutrient concentration in the sludge is very low compared to that in suspended material, a range of 0 - 472 ppm in sludge and 1671 - 6660 ppm in suspended material.

Treat/Year (Rainfall)	Year 1 (483 mm)	Year 2 (384 mm)	Overall mean	Source of variation	K in sludge
CT	13.35	1.17	7.26	Treat	***
MR	0.00	0.00	0.00	Year	***
TR	0.17	0.01	0.09	Treat x Year	***
BF	31.75	9.32	20.54	MR vs TR	NS
Overall mean	11.32	2.62	6.97	CT vs (MR, TR)	***
n = 6 (Treatment)	s.e.d. = 2.126	$s^2 = 13.56$			
n = 12 (Year)	s.e.d. = 1.503	df = 16			
n = 3 (Treatment x Year)	s.e.d. = 3.006				

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

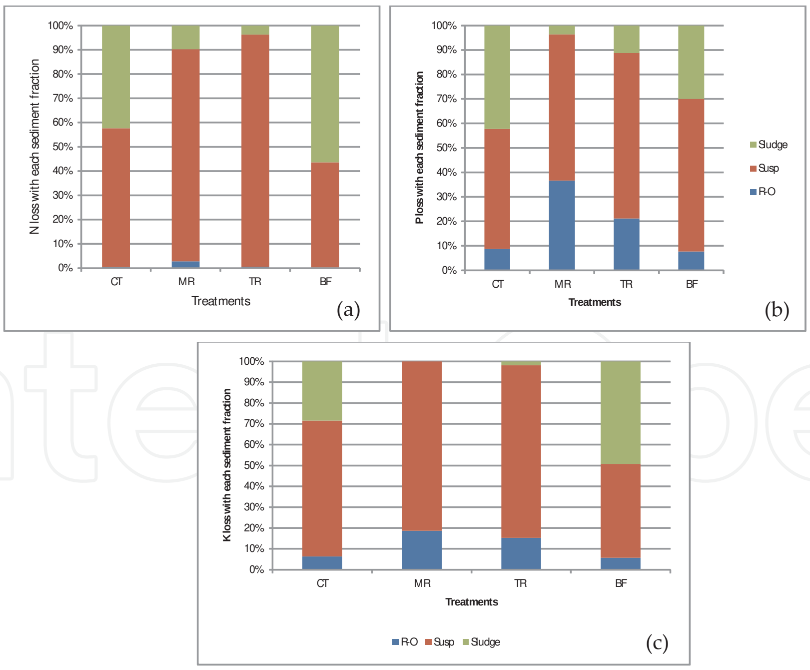
Table 22. Potassium loss (kg/ha) with sludge under different tillage systems over three years at MakoholiContill site

Due to the high proportion of non-reactive coarse particles in sludge, the nutrients concentration was low compared to total sediments and suspended material. Generally all the nutrients under all tillage systems recorded lower nutrient concentrations in the sludge compared to nutrient concentrations in the original soil, resulting in enrichment ratios less than 1.0, with the exception of N under bare fallow, which recorded 1.0. The overall nutrient enrichment ratios in sludge were as follows: N: 0.6; P: 0.5 and K: 0.5, an indication that this sediment fraction is impoverished in plant nutrients compared to the original soil (Table 23). Furthermore, there is no report on the association of coarse soil particles and the fertility of a soil, as is the case with fine soil particles. Generally, the sandier the soil the lower its nutrient status and/or soil productivity.

Treat	Nutrient concentration in sludge			Enrichment ratios: nutrient in soil: nutrient in sludge		
	N %	P ppm	K ppm	N	P	K
Year 1						
BF	0.04	17.5	429.8	1.0	0.4	0.8
CT	0.03	31.8	472.8	0.6	0.6	0.8
MR	0.00	0.0	0.0	0.0	0.0	0.0
TR	0.02	33.6	414.7	0.4	0.4	0.9
Year 2						
BF	0.02	11.0	240.8	0.7	0.6	0.4
CT	0.03	17.7	333.3	0.8	0.7	0.5
MR	0.00	0.0	0.0	0.0	0.0	0.0
TR	0.01	10.0	83.3	0.2	0.2	0.2
Year 3						
BF	0.04	9.3	-	1.3	0.6	-
CT	0.03	16.4	-	0.8	0.6	-
MR	0.05	13.2	-	1.0	0.5	-
TR	0.04	26.0	-	0.8	0.8	-

Key: CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 23. Nutrient concentrations in the soil (0 - 25 cm) versus nutrient concentrations in the sludge and enrichment ratios for different tillage systems at MakoholiContill site



Key: R-O = Run-off; Susp = Suspended material

Figure 3. (a) Nitrogen, (b) phosphorus and (c) potassium losses as influenced by different erosion fractions under four tillage systems at MakoholiContill site (averages over three years)

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3.5.5. Eroded nutrients versus soil loss and sediment fraction

Regression analysis was carried out to relate nutrient loss with the amount of soil lost and sediment fraction. Firstly, a general regression analysis was carried out, where all the data collected was pooled, i.e. without specifying the treatments or the years and soil loss, suspended material and sludge were considered independently (Table 24). Data was then split according to the different treatments (disregarding years) and again the different elements were regressed with soil loss and sediment fractions. From the regression output, each element was then calculated in relation to a tonne of lost soil and/ or sediment fraction. Correlation coefficients were also worked out for the relationship between each element and soil loss as well as sediment fraction (Tables 24 and 25).

Treat/Year	**Element**	**Element kg/1t SL**	**Standard error**	**% variance accounted for**	**P value**	**Correlation SL:Element**
Pooled	N	0.360	0.019700	94.5	***	0.980
Pooled	P	0.010	0.002090	38.3	***	0.719
Pooled	K	0.767	0.104000	80.0	***	0.908
Treat/Year	Element	Element kg/1tSusp.	Standard error	% variance accounted for	P value	Correlation Susp:Element
Pooled	N	1.589	0.0416	95.4	***	0.977
Pooled	P	0.058	0.00722	40.6	***	0.654
Pooled	K	4.201	0.271	86.5	***	0.932
Treat/Year	Element	Element kg/1t Sludge	Standard error	% variance accounted for	P value	Correlation Sludge:Element
Pooled	N	0.186	0.0137	76.5	***	0.879
Pooled	P	0.005	0.000302	80.0	***	0.904
Pooled	K	0.390	0.0198	92.1	***	0.960

SL = Soil loss; Susp = suspended material

Table 24. Nutrient loss as affected by soil loss, sludge and suspended material over three seasons at MakoholiContill site

The results of the regression analysis show that pooling the data gave moderate nutrient losses for every tonne of soil lost. All the nutrients were below 1 kg for every 1 tonne of soil lost, i.e., total sediments (ranging from 0.01 for P to 0.7 kg for K). The amounts of the nutrient losses were related to the losses under bare fallow but these amounts would under estimate the losses under cropped treatments. Generally for the pooled estimates, K was the most abundant element in the sediments and the sequence could be summed up as follows: K > N > P. The variance accounted for in the estimates was also very high for N and K and low for P.

The sediment composition also influenced the amount of nutrients per unit of soil loss, with more nutrients lost with suspended material than with coarse material (Table 24). This table shows that an average of 1.589 kg N was lost with one tonne of suspended material compared to 0.186 kg N lost with one tonne of sludge, i.e. (8.5 times). About 12 times more P was lost with one tonne of suspended material than with sludge, while K was 11 times more in suspended material than in sludge. This information further consolidates the fact that much more nutrients are lost with suspended material regardless of tillage treatment and plant element. The loss of coarse soil particles should have implications on soil productivity mainly due to the reduction of soil tilth and not soil fertility.

The different treatments also showed that the conservation tillage treatments lost more nutrients per unit soil loss than conventional tillage systems (Table 25), due to the low sludge: suspension ratio in the former. For the same reason, conventional tillage also lost more nutrients (all elements) per tonne of soil loss than the bare fallow. Between the two conservation tillage treatments, more nutrients (N, P and K) were lost under tied ridging than under mulch ripping. The differences though, were not significant. All the treatments showed a similar trend as that of pooled data. P losses were highly correlated to soil loss under mulch ripping, followed by bare fallow, whereas under conventional tillage and tied ridging the correlation was rather low, although still significant. The poor correlation may be as a result of the very low P losses, which may affect the accuracy of such measurements.

Treat.	Element	Element kg/1t SL	Standard error	% variance accounted for	P value	Correlation SL:Element
BF	N	0.305	0.030000	70.9	***	0.842
BF	P	0.008	0.001270	29.9	***	0.614
BF	K	0.700	0.105000	72.0	***	0.958
CT	N	0.434	0.044200	54.2	***	0.891
CT	P	0.017	0.005070	very low	**	0.339
CT	K	1.199	0.073400	95.1	***	0.977
MR	N	1.242	0.041400	98.7	***	0.994
MR	P	0.028	0.002420	89.5	***	0.966
MR	K	4.600	0.659000	80.1	***	0.951
TR	N	1.437	0.150000	79.0	***	0.900
TR	P	0.059	0.016700	11.7	*	0.496
TR	K	5.155	0.359000	95.7	***	0.981

SL = Soil loss; Susp = suspended material; CT = Conventional Tillage; MR = Mulch Ripping; TR = Tied Ridging; BF = Bare Fallow

Table 25. The relationship between nutrient loss and soil loss under different tillage systems at MakoholiContill site

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There is evidence that a substantial amount of nutrients is lost with erosion, as shown by the overall averages of 12.3 kg/ha N; 0.5 kg/ha P and 17.3 kg/ha K. The amount of nutrient lost was found to be strongly dependent on the nutrient status of the soil, i.e. the higher the status of a particular nutrient in the soil, the higher its loss with erosion. The nutrient status of the soils showed the following trend K > N > P and the overall nutrient loss with erosion also showed exactly the same trend. This explains why soils with higher fertility status lose much more nutrients relative to those with a lower fertility status (Stoorvogel and Smaling, 1990). According to Rose *et al.* (1988), the amount of a nutrient lost with erosion is dependent upon the soil type, tillage practice and the type of erosion. From this study it was found that the amount of soil loss and the sediment fraction − including run-off − were also important in determining the amount of nutrient loss, especially on sandy soils, where the amount of clay and organic matter are critical as sources of plant nutrients.

The sediment fraction on sandy soils is very important in determining the amount of nutrient loss due to the selective nature of sheet erosion on these soils. Nutrient losses in the water portion of the run-off were small, almost negligible compared to the losses with solid sediments, ranging from 1 – 2 % of total N; 0.6 – 4% of total P and 1 – 20% of total K. This was expected, as these nutrients have to be dissolved in water. Even in the original soil, the nutrients in the soil solution are only a small fraction of nutrients sorbed in the soil, ranging from 0.001% for P to 25% for Ca (Brady, 1984; Stevenson, 1985; Singer and Munns, 1987). The solid fraction is therefore, the major source of plant nutrient loss (Barisas et al., 1978; Kejela, 1991). Suspended material is the main source of nutrient loss from agricultural lands, as evidenced by the very high percentages of nutrient losses with this sediment fraction, especially under conservation tillage, > 90%. Although the ratio between sludge and suspension under the conventional tillage was between 1.5 and 5, about 25% of total sediments, it accounted for 63% of total N, 74% of total P and 73% of total K lost with erosion. With a sludge suspension ratio of between 10 and 17, the bare fallow also recorded proportionally higher nutrients with suspended than with sludge, shown by the following percentages: 39% of total N and K and 46% of total P being lost with this 8% suspended material. This finding certainly shows that much more nutrients are lost with suspended material than with any other sediment fraction.

Furthermore, the N concentration in sludge ranged from 0 – 0.5%, while in suspended material it ranged from 0.2 – 0.65 %, P concentration in sludge ranged from 0 – 34 ppm compared to 73 – 584 ppm and K recorded a concentration of 0 – 472 ppm in sludge and 1671 – 6660 ppm in suspended material. This is because clay and organic matter are the sorption sites for much of the nutrients and organic matter is also crucial in the cycle of P and N. Brady (1984) reported that organic matter was the major indigenous source of N while 65% of total P in the soil was found in the form of organic compounds. Clay more than organic matter, is the main source of fixed K and other cations and K losses are therefore associated with clay loss. Due to the selective nature of sheet erosion, high affinity of P to adsorption, fixation of K and ammonium ions, as well as the presence of K ions in clay minerals, erosion is the main source of nutrient and productivity loss in agricultural lands.

The affinity of the nutrients to the fine soil particles cannot be doubted. The exchange sites on the clay minerals and organic matter are the basis for this affinity, as nutrients are held at these exchange sites (Brady, 1984; Stevenson, 1985). According to Singer and Munns (1987), the different clay minerals and humus are most important in holding nutrients due to their specialized surface properties, capable of chemically retaining individual nutrients. Tiessen, Cuevas and Salcedo (1998) and Stocking (1984) also reported that soil organic matter provided plant nutrients in low-input agriculture and that N and P release depended on the mineralization of organic matter while cation exchange depended on the maintenance of organic matter. This is why the loss of top soil is detrimental to any soils' productivity as there is a close association between clay, organic and the plant nutrients. The proximity and concentration of organic matter near the soil surface and close association with plant nutrients, make the erosion of soil organic matter a strong indicator of overall plant nutrients resulting from erosion (Follet*et al.*, 1987).

The results across all cropped treatments and for all the elements show that most of the nutrients lost with erosion are associated with suspended material. Under conservation tillage systems it is arguable that the high percentages may be due to the fact that most of the soil lost was in suspended form, however, the high losses attributed to this fraction under conventional tillage indicate otherwise. This finding proves beyond doubt that although less suspended material may be lost from a field, it carries most of the soil nutrients with it. The conservation tillage systems obviously have higher percentages of nutrient losses with suspended material, however the quantities of nutrients lost are negligible when compared to those lost under conventional tillage and bare fallow because of reduced soil losses under conservation tillage.

The nutrient losses with sludge are minimal when compared to those lost with suspended material. While as high as 92% of total soil loss under bare fallow is sludge, the percentages of nutrients lost with this fraction are not as high (56% N; 23% P and 52% K). It should be noted also that there was no distinct separation of sludge and suspension, due to the fact that some suspended material would settle with the sludge, during a storm, before sampling was carried out. This explains the presence of 0.81 - 4.02% clay and 0.04 - 0.55% organic matter in the sludge. The nutrients in the sludge can be attributed to the fine soil particles and not the coarse material.

Nutrient losses (N, P and K) varied significantly among the different treatments. The conservation tillage treatments lost significantly less nutrients compared to the conventional tillage systems. Here, 2.3 and 2.7 kg/ha N; 0.09 and 0.2 kg/ha P; 0.6 and 4.3 kg/ha K were lost under mulch ripping and tied ridging respectively compared to 15.8 and 28.4 kg/ha N; 0.8 and 0.9 kg/ha P; 24.5 and 39.8 kg/ha K under conventional tillage and bare fallow respectively. As these treatments lost significantly different amounts of sediments, also following the same trend, this indicates that the nutrient losses with erosion are closely associated with the rate of soil loss (Elwell and Stocking 1988; Kejela 1991). The tillage systems in this study also showed their effect on the amount of nutrients lost by determining the amount of soil loss. Due to the fact that plant nutrients sorbed to the soil are transported with eroding sediments, the amount of soil lost with erosion becomes very important in determining the

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amount of nutrients lost. The conservation tillage systems dramatically reduced losses of soil and total nutrients when compared to conventional tillage systems, however the nutrient concentrations per unit soil loss are higher than for conventional tillage systems.

The concentration of nutrients in the sediments was much higher under the conservation tillage systems as compared to conventional tillage, obviously as a result of a high percentage of fine particles in the sediments compared to the later. Very high enrichment ratios of all nutrients were thus recorded in the sediments of the conservation tillage systems as a result of the high affinity of nutrients to fine soil particles (Barisas*et al.* 1978). However, the advantage of low amount of sediments in conservation tillage also resulted in lower average losses under this system.

The different years lost significantly different amounts of nutrients, which depended on the amount of rainfall received and amount of soil lost. For all the nutrients, nutrient losses increased with the increase in rainfall amount, i.e. with increased sediments. The regression analysis that was carried out to find the relationship between soil loss ad nutrient loss showed that nutrient losses are highly dependent on soil losses and that if soil losses are known, nutrient losses can be confidently predicted. The conservation tillage systems lose more nutrients per unit soil loss than conventional tillage systems because their sediments are predominantly fine particles, e.g., per tonne of soil lost 1.4 and 1.2 kg/ha of N were predicted to be lost under TR and MR respectively, while BF and CT were predicted to lose 0.3 and 0.4 kg/ha respectively. The point on the high affinity of all the nutrient elements to the fine soil particles has also been emphasized.

By conserving the soil, nutrients are conserved and nutrient replacement costs of erosion are drastically reduced, especially if the value of sustainable production is also taken into consideration. It should be emphasized, however, that the loss of organic matter and clay and resultant physical degradation of the soil, leading to poor tilth, low available water holding capacity and high bulk density, was not evaluated. This means that the value of nutrient losses is but a fraction of total loss (Kejela, 1991).

4. Conclusions

Sheet erosion is a selective process that robs the soil of its fine particles, i.e. clay and organic matter. The high enrichment ratios of clay and organic matter found in sediments as compared to the original soil, serve to support this fact. Of the two sediment fractions, the soil lost in suspension is the most detrimental as it comprises of clay and organic matter particles, which are known to be the soils' plant nutrient reservoirs. There is a very high association between nutrients and fine soil particles as shown by the high amount of nutrients lost with a unit mass of suspended material as compared to those lost with the same unit mass of sludge and/ or total sediments. This makes the suspended material the most detrimental sediment fraction, negatively affecting the soils' fertility status as well as impacting negatively on the soil's physical condition. The suspended material recorded high concentrations of clay, organic matter and nutrients when compared to sludge. However, the total loss of clay, organic matter and plant nutrients in the sediments is not dependent upon their concentrations in the eroded soil but rather on the total amount of soil lost. Thus mulch ripping and tied ridging proved to be effective in maintaining clay and organic matter levels and thus significantly reducing nutrient losses from agricultural lands due to their ability to reduce soil erosion.

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