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The Significance of Soil Erosion on Soil Fertility Under Different Tillage Systems and Granitic Sandy Soils in Semi-Arid Zimbabwe: A Comparison of Nutrient Losses Due to Sheet Erosion, Leaching and Plant Uptake

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1. Introduction

The plant nutrient status in the soils is dynamic and subject to a variety of transformations, gains and losses, depending on a number of factors including soil type, farming system and climate. Generally, soils lose plant nutrients in more ways than they gain them. The very common and obvious way is through the removal of crop harvests and residues. However, it is also known that erosion and leaching contribute immensely to the total nutrient loss from a field. In the case of nitrogen, denitrification/ volatilisation also contributes to the N loss (Stoorvogel and Smalling, 1990). For a sustainable management of nutrient systems some consideration has to be given to these losses and a balance struck between the losses and the possible gains that may occur in the field.

The components of a nutrient balance with regards to nutrient losses and possible nutrient gains are shown in Figure 1. As can be seen from this figure, the main losses of nutrients from the soil are through plant uptake, leaching and soil erosion. Volatilisation only involves nitrogen and is common under anaerobic conditions making it less important when compared to the first three forms of nutrient loss. Wind erosion in Zimbabwe is minimal and confined to a few areas to justify its exclusion from the components of nutrient balance. It is however, not clear as to what percentage of total nutrient loss is lost with each of the three major components, i.e. plant uptake, soil erosion and leaching.

Many investigations have shown that soil erosion results in loss of productivity, due to the modifications of the soil physical, chemical and biological composition. The degree to which these changes take place varies for the different soil types and from one agro-ecology to another (Kaihura, *et al.*, 1998). Given the very diverse agro-climatic conditions, results from one area cannot be successfully applied to the next. However, due to limited research findings in Sub-Saharan Africa, general estimations have been made and then extended to the whole region (van Reuler and Prins, 1992). In these countries soil is an essential input to farming as agricultural production is crucial to development and the livelihoods of the majority of the population depend on this sector (Barbier and Bishop, 1995). Yet inappropriate farming systems and overgrazing are rampant, nutrient budget is generally negative as soils are mined for nutrients resulting in negative environmental consequences of soil erosion and land degradation (van Reuler and Prins, 1992). Soil erosion - although considered as one of the many possible facets of land degradation (Biot, 1986) - constitutes a serious ecological and economic problem, which threatens agricultural production in Sub-Saharan Africa (Anderson and Thampapillai, 1990). Once initiated the process of erosion is self perpetuating in that fine soil particles that bind the soil particles together are lost and the soil becomes loose and more vulnerable to erosion, so erosion increases (Lowery and Larson, 1995).

In the case of nutrient uptake by the crop, many factors are involved, e.g. the light, temperature, air humidity, carbon dioxide, oxygen, water, macro- and micro-nutrients as well as the pH value of the soil solution and plant sap (Hekstra, 1996). According to Wrigley (1992), the nutrient uptake capacity is more closely related to root volume. What is important in nutrient loss studies however, is the availability of nutrients to the crop. This refers to the availability of a nutrient at the right time and in the right form and quantity. If the nutrients are not in the right form or quantity they may be fixed or leached. This reduces the amount of nutrients taken up by the crop, the rest being susceptible to leaching and fixation. Leaching of nutrients, therefore takes place at any time during crop growth when more soluble nutrients are found in the soil solution than can be taken up by the crop (Hekstra, 1996). These processes in turn deplete the soil of its nutrients and pollute the under-ground water. Fixation on the other hand is dependent on the pH, clay and organic matter content. Applied nutrients may be taken out of the soil solution and become immobilised or fixed on the soil's solids. This process counters leaching of applied fertilisers and thus adds to the soil's solid nutrient reserves (Singer and Munns, 1987).

The nutrient losses of concern for this study are the macro-nutrients, Nitrogen, Phosphorus and Potassium that are applied as fertilizers, even in low input agriculture. These are found in different forms in the soil. Some nutrients are more dynamic than the others, while some are more prone to fixation, leaching and/or washing away (Fitzpatrick, 1986). The macro-nutrients are also found in different concentrations in the soil solution. However, since soil erosion does not only render the soil of its available forms of nutrients, but also of its fixed and organic forms, it is important that total nutrients be considered when dealing with nutrient losses due to erosion, as this has a bearing on the productivity of the soil in the long term.

Nitrogen (N) in soils, unlike other nutrients does not originate from the soil mineralogy but a substantial amount of it originates from the air - through atmospheric deposition and symbiotic fixation (Singer and Munn, 1987). Fertilizer application is very important too as nitrogen is one of the most yield limiting nutrients (Brady, 1984; Stevenson, 1985). Nitrogen is a highly dynamic nutrient in the soil thus its status is very variable. It undergoes a wide variety of transformations in the soil, most of which involve the organic fraction. This makes the interpretation of available nitrogen content in the soil highly inconclusive as it changes within a short period. The common forms of nitrogen in the soil are (i) organic N, (ii) available N and (iii) fixed N (Stevenson, 1985). Only a small fraction of nitrogen in soils, generally between 1 - 2%, exists in available mineral compounds at any one time, i.e. as ammonium (NH_4^+) and nitrate (NO_3^-) forms (Brady, 1984). The main losses of N are as a result of (i) leaching, (ii) fixation, (iii) volatilization and (iv) erosion (Brady, 1984; Stevenson, 1985 Singer and Munns, 1987). While NH_4^+ ions are prone to fixation within the clay layers as well as volatilization as NH_3, NO_3^- ions are prone to denitrification.

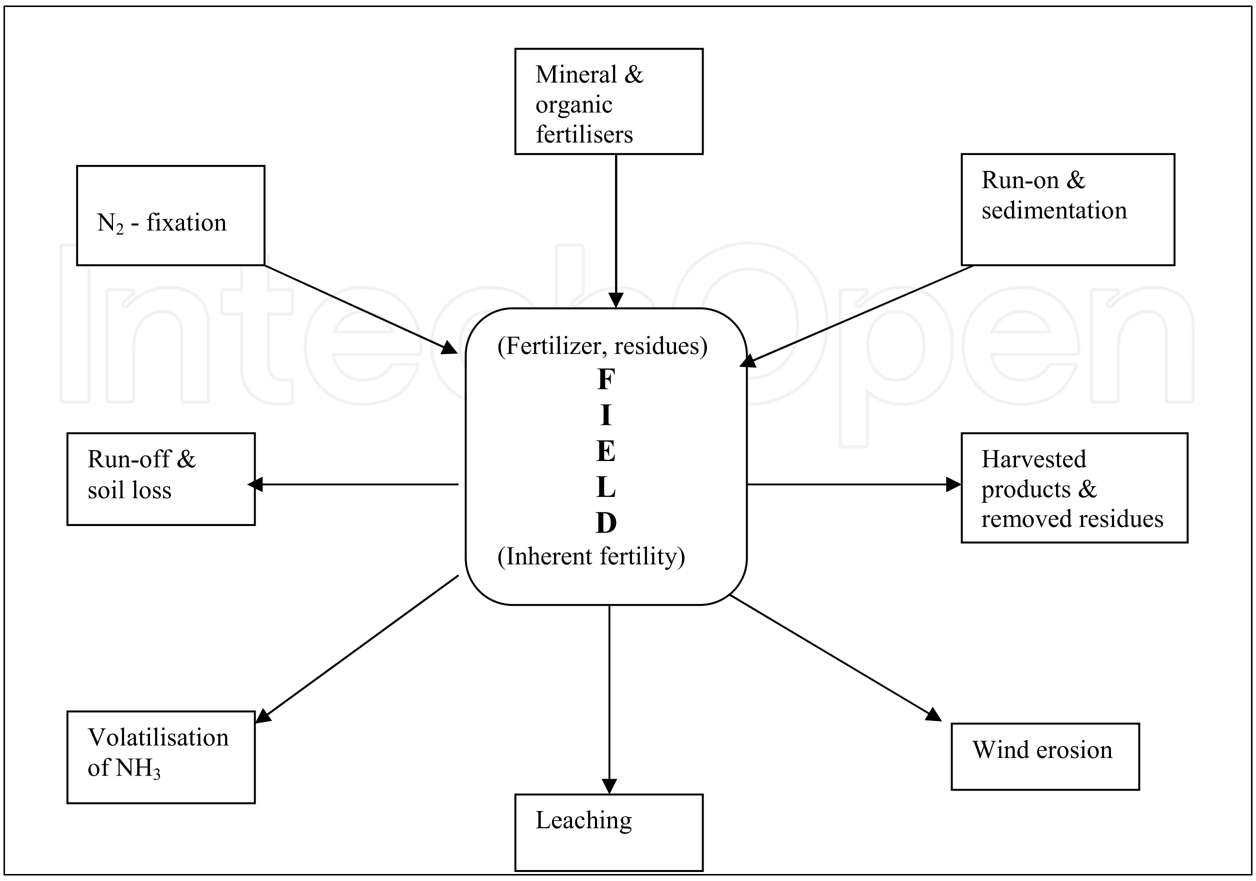

Fig. 1. External components of nutrient balance (Source: *modified from Hekstra, 1996*)

Phosphorus (P) originates from the parent material and soils formed from acid igneous rocks are generally low in phosphorus (Stevenson, 1985). The P cycle is complex and involves the storage of P in living organisms, dead organic matter and inorganic forms. There are comparatively low levels of total P in the soils compared to other elements. Organic P in the soil comprises more than half of the total soil P (Brady, 1984). Microbial activity simultaneously consumes and releases P to the soil solution, while the native P is not easily available and any P applied as fertilizer is prone to fixation. Soil pH also controls the fixation rate. In acid soils, as is the case with the Makoholi 5G soils, phosphate is readily precipitated as the highly insoluble Fe- and Al-phosphates or absorbed to oxide surfaces. This makes the available P in soils very low.

The original sources of potassium (K) are primary minerals such as micas and potash feldspars. The total quantity of potassium is generally greater than that of any other major nutrient element. Most of the potassium is in the primary mineral and non-exchangeable forms (Brady, 1984; Stevenson, 1985). Organic matter constitutes only a small amount and is not as important in determining the potassium content and its availability as is the case with nitrogen and phosphorus. The three main forms of potassium according to Brady (1984) are: unavailable K, which is found in primary minerals (90 - 98% of total K); slowly available K, which is the non-exchangeable (fixed) form (1 - 10% of total K) and readily available K, which is exchangeable including the amount in the soil solution (1 - 2% of total K).

In Zimbabwe, as is the case with many Sub-Saharan countries, soil nutrient losses as a result of erosion and leaching have not been given much consideration in the past. While data may be available on nutrient losses due to plant uptake, the relative significance of one type of loss to the other losses is not known. The information on the different forms of individual nutrients and their amounts in the soil serves to show how important it is to evaluate total nutrient losses as compared to the available/ exchangeable forms (sheet erosion). It is a fact that for annual soil fertility interpretation, the total quantity of a nutrient in a soil is much less important than the amount that is available or that can be made readily available for plant uptake. However, the degree to which the soil is impoverished may remain masked if only the available/ exchangeable forms of nutrients are considered. The nutrient losses through sheet erosion can mainly be reduced through conservation tillage. The main advantages of conservation tillage are the reduction of run-off and soil loss from a field by increasing infiltration. However, when infiltration is increased, it invariably increases drainage, which may lead to increased leaching of the nutrients. It is, therefore, of utmost importance to evaluate the different tillage systems on their nutrient losses with leachate and to ascertain whether in fact the systems that conserve soil and water also lead to more leaching of available nutrients than conventional tillage systems. This Chapter, therefore, focuses on the quantification and comparison of nutrients lost with sheet erosion (sediments and run-off), plant uptake and leaching under different tillage systems.

2. Materials and methods

2.1 Site characteristics

The research work was carried out at Makoholi Research Station, situated 30 km north of Masvingo town, Zimbabwe. It 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 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. 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 fertilisers or animal manure (MNRT, 1987).

2.2 Experimental design and tillage treatments

The treatments were laid out in a randomised complete block design replicated three times. The blocks were located at different positions along the slope (Down-slope, Middle-slope and Up-slope), which could differ in fertility, erodibility as well as moisture levels. At the beginning of the nutrient loss study, all trial plots had been under cultivation and the same treatment for a period of five years. All tillage operations were carried out soon after harvest before the soil dried out.

2.2.1 Conventional tillage

The land was ox-ploughed to 23 cm depth, using a single-furrow mouldboard plough and thereafter harrowed with a spike harrow. All crop residues were removed from the plots (Plate 1), 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, including this treatment provides a baseline for assessing the merits of other treatments.

Plate 1. Conventional tillage system

2.2.2 Mulch ripping

The land was ploughed to the recommended depth of 23 cm in the first year and rip lines were opened. During the subsequent seasons, 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 (Plate 2). The rip lines acted as crop rows and were alternated every year, to allow roots ample time to decay. Two basic conservation tillage components – minimum tillage and mulching - are realised here. The main aim was to maximise infiltration through rainfall interception provided by the mulch, thus minimising run-off. These parameters are the most important in the semi-arid regions, where soil moisture is the most limiting factor in agricultural production (Hudson, 1992). This treatment is one of the basic conservation tillage systems, which has shown great potential in protecting the soils, without compromising the production.

Plate 2. Mulch ripping system

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 (Plate 3). These ties were between one half to two thirds the height of the crop ridges allowing for run-off 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 to satisfactorily low level.

Plate 3. Tied ridging system

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 modelling purposes, as it gives the highest possible soil loss values and will probably give the lowest nutrient loss values as no fertilisers are applied.

2.3 Collection of run-off and sediments

Soil loss and run-off measurements were from 30 m x 10 m run-off plots, with 5 m border strips on either side. All treatments were laid out at 4.5% slope. The length of the plots was orientated up-slope. Tillage operations were done across the slope. 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. Polythene strips were dug in to form the boundary around each 30 m x 10 m and 150 m x 4.5 m plot. This is the standard soil erosion methodology for Zimbabwe – Soil Estimation Model for Southern Africa (SLEMSA).

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 channelled 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 channelled 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. 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. The sludge was transferred into 50 liter 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):

$$M_o = 1.7 \times (M_s - M_w) \quad (1)$$

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

2.4 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 communal areas. Due to the dry conditions prevailing at Makoholi, maize variety R 201, which tolerates moisture stress and is short seasoned, was used. 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 minimise the influence of factors other than those imposed by treatments. On all plots, except the Bare fallow, planting holes of about 10 cm depth and diameter were opened before the onset of the rains. 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. 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 fertiliser 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 fertiliser 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.

Plant growth parameters (plant height, number of leaves, tasselling and silking) were recorded on selected twenty plants per plot and an average taken to indicate plant growth for the different tillage systems. The measurements started at two weeks after planting and continued up to physiological maturity, about 18 weeks after planting. Sub-plots of 3.6 m x 6 m were marked out with each plot having two subplots for all treatments except for tied ridging, which had four sub-plots per plot. The crop within this area was harvested, grain samples weighed and dried at 105^0 for 16 hours, while the stover samples were weighed and dried at 65^0 for 24 hours in the Memmert Universal ovens (Model UL 80). The yield was calculated at 12% grain moisture, while stover was given as dry matter. On all trial plots, soil samples were taken at 0-250 mm using a split auger. The soil samples were air dried and passed through a 2 mm sieve.

2.5 Leachate measurement

A technically simple and cheap methodology, as described by Hagmann (1994) was used for the collection of leachate. Nine percolation lysimeters were installed on a 4.5% slope under the three tillage systems. For each tillage system, two lysimeters were installed in plots, which were later cropped and one in a bare plot. The percolation lysimeters were made out of galvanised metal sheets and were 1.5 m long, 0.9 m wide and 0.5 m deep. They were installed at a depth of 0.25 m below the soil surface to allow for undisturbed tillage and weeding operations as well as undisturbed inter-flow. The 0.25 m above the lysimeter box together with the depth of the percolation lysimeter ensured that the base of the lysimeter was below the rooting depth, which has been found to be 0.70 m (Moyo and Hagmann, 1994). Thus the water, which reached the bottom of the lysimeters could well be defined as drainage water, as it would have left the rooting zone and would not benefit the crop. Soil was excavated and piled according to soil horizon. Lysimeter boxes were installed in the pits, filter packages inserted at the outlets and drainage pipes were connected to the outlets. A layer of 50 mm of fine gravel was added at the bottom of the boxes to allow for better percolation. The excavated soil was refilled in layers corresponding to the soil horizon. To regain the natural bulk density (1.4 - 1.5 Mg/m^3) the refilled soil was slightly compacted. The pipes from the outlets were laid out at a gentle slope to enable drainage water to gravitate into the collection pit. Leachate was collected daily.

2.6 Laboratory analyses

An analysis of the sediments for macro-nutrients was carried out, where the different sediment components (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. The soil samples and sediments were air dried and passed through a 2 mm sieve, while the plant material (stover and maize grain) were oven dried at 35^0C and ground before they were analyzed for the macro nutrients N, P and K. Nitrogen was determined using the microkjeldahl method as described by Bremner and Mulvaney (1982) and the ignition method as described by Olsen and Sommers (1982) was used to quantify phosphorous. Potassium content was determined using the wet digestion method using perchloric acid as described by Knusden, *et. al.*, (1982).

Run-off was filtered and as with leachate, the aliquot treated as soil extract. Run-off and leachate were analysed for the dissolved nutrients, 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 flame-photometer in the case of K. It should be noted that only NO_3^-- N was quantified during this study, as very low levels of NH_4^+-N are lost due to leaching, even under intensive maize production systems (Kladivko, *et. al.*, 1991; Prunty and Montgomery, 1991; Drury, *et. al.*, 1993).

2.7 Soil nutrient balance

A method that was developed by Stoorvogel and Smaling (1990) on balancing of nutrients was used. This method looks at balancing the inputs and outputs as the sum of the inputs versus the sum of the outputs in a given system as follows:

$$\text{Nutrient balance} = [IN1 + IN2 + IN3 + IN4 + IN5 + IN6] - [OUT1 + OUT2 + OUT3 + OUT4 + OUT5 + OUT6] \quad (2)$$

Where: IN1 = mineral fertilisers; IN2 = animal manure; IN3 = atmospheric deposition; IN4 = biological nitrogen fixation; IN5 = sedimentation; IN6 = uptake by deep rooted plants; and OUT1 = harvested products; OUT2 = crop residues; OUT3 = leaching; OUT4 = gaseous losses; OUT5 = soil erosion OUT6 = losses in deep pit latrines.

According to Scoones and Toulmin (1999), some of the parameters may relatively be easy to assess, e.g. fertiliser and manure inputs and crop outputs, while leaching, volatilisation and erosion present more measurement difficulties. The trend has been that the leaching, volatilisation and erosion losses were estimated. In this study however, these, with the exception of volatilisation, have been quantified. Volatilisation presents negligible losses under these conditions, as it is most prevalent in anaerobic and mainly alkaline conditions (Stoorvogel and Smaling, 1990). The biological N fixation in maize production systems is also negligible. Atmospheric deposition of N is the only worthwhile input that could have been considered in the balancing of N, however that data was not available and as such the N balance may be slightly inaccurate. No manures were used in this study and the only inputs into the system were limited to inorganic fertilisers.

Thus the equation was modified as follows:

$$\text{Nutrient balance} = [IN1] - [OUT1 + OUT2 + OUT3] \quad (3)$$

Where: IN1 = mineral fertilisers; OUT1 = plant uptake; OUT2 = soil erosion; OUT3 = leaching

The differences in soil loss, run-off, plant growth parameters, yield and nutrient losses attributed to treatment were analysed 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 Plant nutrient losses with sheet erosion

Soil erosion removes topsoil enriched in nutrients by natural formation processes and fertilization. To be able to quantify the nutrient losses with sheet erosion one has to measure run-off and the rate of soil erosion. Previous research has put much emphasis on the importance of N and P in plant nutrition. For example Barisas *et. al.* (1978), Sherwood and Fanning (1981) and Arnimelech and McHenry (1984) also examined N and P and disregarded other nutrients. N is without doubt the most significant nutrient for high maize yields and its deficiency limits production more than any other nutrient (de Gues, 1973). A maize crop uses N throughout its growing period, unlike P which mainly promotes root development and is an important part of the proteins. Thus P application is only confined to basal application, while N can be applied up to three times during the growing season. P deficiency also has drastic effects on the maize yields. Singer and Munns (1987) reported that the loss of phosphorus and nitrogen is most serious, because they are often deficient. Elwell and Stocking (1988) also quantified the loss of N and P with erosion, while disregarding cations, especially K, which is always applied as a basal fertilizer (together with N and P) in all maize production systems in Zimbabwe. The importance of N and P may well be emphasized if only plant nutrition is of importance, but no consideration is given to the soil condition after erosion (erosion effect). It is arguable that the loss of cations is also equally important as it leads to soil acidification and consequently to soil degradation. Potassium is relatively abundant in the soil, especially when compared to P (Stevenson, 1985) and if its loss is left unabated, the soils become impoverished and this enhances soil degradation. K, classified as a primary nutrient with N and P, is essential for crop growth (de Geus, 1973). Assessing its loss is important, as it has a role in plant nutrition and is also implicated in soil degradation studies.

3.1.1 Run-off and soil loss

Run-off and soil losses were highest under the bare fallow followed by the conventional tillage while mulch ripping and tied ridging recorded low run-off volumes and soil losses (Table 1). These differences among the different tillage treatments were significant at P < 0.001. To properly evaluate the effectiveness of the conservation tillage treatments (MR and TR), the mean of conventional tillage and that of the two conservation tillage treatments were compared using an independent t-test. The results showed that conventional tillage differed significantly from the mean of the two conservation tillage systems (at P < 0.001), while the two treatments did not differ significantly from one another.

In the semi-arid conditions, rainfall is a very important parameter in agricultural production. It is not only the amount that matters but also the nature of rainfall received, i.e. its distribution and intensity. High intensity rainfall of up to 132 mm/h was received mainly during the months of October and November. During this period the soils in the communal areas would mainly be bare due to the nature of the predominant farming system here, where all crop residues are removed from the fields or left for the livestock to graze on during the winter months (Hudson, 1964; Elwell and Stocking, 1974). Most soils are said to best absorb rainfall of 12 mm/h intensity (Wrigley, 1992) and the very high intensities measured during this study show that the erosion potential is very high. The potential damage is aggravated by the absence of crop cover (Hudson, 1964) during this period. According to Wrigley (1992) heavy intensity of tropical storms is frequently in excess of the receptive capacity of the soil and the beating of soil by raindrops seals the soil surface thus hindering infiltration. Run-off is initiated, which is the initial stage of erosion. These findings imply that high intensity rains are received at the beginning of the season, before enough crop cover has been attained and the soils would be most vulnerable to erosion.

Treatment	Run-off (mm)	Soil loss (kg/ha)
CT	104.4	33.7
MR	39.8	1.7
TR	34.1	2.2
BF	161.1	93.4
Signif. level	***	***
s.e.d.	8.07	4.00

Table 1. Run-off (mm) and soil loss (kg/ha) as affected by tillage at Makoholi Contill site during three seasons

Run-off was dependent on seasonal rainfall and it differed significantly among the three years as follows: Year 1 received 483 mm of rainfall and had an overall mean run-off of 60 mm; Year 2 received 384 mm and recorded 31 mm of run-off while rainfall recorded in Year 3 was 765 mm, with 165 mm of run-off. Another factor, which influenced run-off, was the tillage system. The conservation tillage treatments reduced run-off drastically when compared to the conventional systems, ranging from <1 - 15% under mulch ripping; 1 - 11% under tied ridging; 13 - 22% under conventional tillage and 17 - 39% under the bare fallow. Overall the treatments recorded annual averages of 40 mm (MR); 34 mm (TR); 104 mm (CT) and 161 mm (BF). The month of January, during Year 3 received 419 mm of rainfall, (55% of total seasonal rainfall), which increased run-off drastically, especially under mulch ripping treatment, as the soil was saturated and water logging was experienced. Run-off decreases with the increase in soil moisture up to saturation point, after which it increases drastically (Le Bissonnais and Singer, 1992; Olsen, 1994). For this reason run-off from mulch ripping rose steeply to 15% of total seasonal rainfall, tied ridging recorded 11%, while under conventional tillage run-off rose slightly to 22%.

The natural equilibrium of the soil under the bare fallow was disturbed through cultivation and the lack of crop, weed or mulch cover further aggravated the situation. This practice accelerates the rate of organic matter mineralisation through disruption of soil aggregates and increased aeration (Schroeder, 1984; Salinas-Garcia, Hons and Matocha, 1997; Angers, N'dayegamiye and Cote, 1993). Organic matter improves water infiltration and storage (Follet *et al.*, 1987) thus its reduction results in high run-off. Furthermore, when there is no soil protection and rainfall energy is not intercepted surface crusting is promoted (Troeh *et al.*, 1980), which further accelerates run-off. According to Le Bissonnais and Singer (1992), soil crusts reduce water infiltration rate and induce the erosion process by increasing run-off. The cropped treatments recorded lower average percentages of run-off due to the crop cover effect. Continuous inversion of the soil (through ploughing and harrowing), as has been highlighted for the bare fallow and conventional tillage, increase organic matter mineralisation resulting in the reduction of water stable aggregates (Beare, Hendrix and Coleman, 1994). The soil structure therefore, deteriorates and enhances run-off (Elwell, 1990), which increases as the number of years of cultivation increase. Effective reduction of run-off was realised under mulch ripping and tied ridging. The mulch under mulch ripping intercepts rainfall energy, thus increasing infiltration (Adams, 1966; Braithwaite 1976; Elwell 1986). The rotting stover adds organic matter to the soil, which contributes to improved water infiltration and storage and generally to the maintenance of a good soil structure (Hargrove, 1991; Reicosky *et al.,* 1996). The lower run-off under tied ridging was a result of water ponding in the micro-dams, which increased infiltration drastically. The tied ridging treatment was described by Hudson (1992), as a useful compromise between water storage and drainage, as water is retained in the basins to soak into the soil, resulting in very little water leaving the system.

The soil losses in sandy soils were, as expected, very high (Table 1) as these soils are much more susceptible to erosion as compared to other soils with higher contents of clay and/or organic matter. As soil erosion is a function of run-off, soil loss was also dependent on seasonal rainfall and tillage treatment. The very high losses under the bare fallow (93t/ha/yr) were a result of continuous ploughing of the soil and leaving the soil bare throughout the year. Aeration was high leading to mineralisation of organic matter and there was no ground cover to protect the soil from the impact of climatic factors (rainfall, solar radiation). No impediments were constructed to slow down the velocity of run-off at any given time during the growing seasons. The combination of all these factors is a deteriorated soil structure, low organic matter content, few water stable aggregates and accelerated soil loss. Gerzabek, Kirchmann and Pichlmayer (1995) found that bare fallow plots had lower soil stable aggregates compared to other treatments. Since the water stable aggregates are a measure of the resistance of soil particles against disruptive forces of water (Beare *et al*., 1994), it therefore follows that the lower the water stable aggregates the higher the soil loss as soils would not be able to resist erosion.

The soil losses under conventional tillage were very high and averaged 34t/ha/yr. Although this value is low when compared to the 50 - 75 t/ha/yr estimated by Elwell (1975), it must be noted that his estimation may still be valid for some seasons characterised by high rainfall amount and intensities, e.g. the 54 t/ha soil losses recorded during Year 3. One other factor, which influences the amount of soil loss is the period of cultivation, as these results are from fairly new fields, having only been cultivated for a period of nine years, while some soils in the communal areas have been under cultivation for over fifty years. Continuous ploughing and removal of crop residues under this treatment has led to the deteriorating soil structure. Elwell, (1990) reported that cultivation leads to mineralisation of organic matter, which is important in the soil aggregation and that the removal of crop residues together with organic matter mineralisation leads to poor soil structure. Poor soil structure profoundly increases run-off and soil loss. The very high topsoil losses with conventional tillage will eventually result in reduced plant available water and nutrients and thus productivity, as the soil depth is limited due to the presence of a stone line at around 50 - 80 cm depth (Vogel, 1993). This suggests that the soils become shallower, have less organic matter and become relatively less permeable to air, water and roots. Although plant nutrients can be compensated by additions of fertiliser or manure, in

rain-fed agriculture, plant available water cannot be ameliorated. The physical properties therefore, altered (e.g. water holding capacity) by soil erosion, are the most long term yield limiting factors (Lowery & Larson, 1995).
The most effective systems in reducing soil erosion were mulch ripping and tied ridging, which recorded 1.7 t/ha/yr and 2.2 t/ha/yr respectively. Under these treatments the soil losses were maintained at very low levels even during seasons with extremely high rainfall amounts and intensities. The observed conservation potentials of these two systems are through (a) the reduction of run-off and enhancement of rainfall infiltration; (b) minimum disturbance of the soil, meaning less aeration and thus reduced mineralisation of organic matter and maintenance of soil structure; (c) the soil protection provided by mulch which reduced the impact of rainfall energy and solar radiation. The negligible soil losses under mulch ripping and tied ridging, guarantee the maintenance of soil tilth, organic matter content, plant nutrients and thus soil productivity.

3.1.2 Total Nitrogen, Phosphorus and Potassium losses with sheet erosion

The amounts of nutrients lost with erosion were found to vary greatly with each nutrient, as affected by tillage system and amounts of soil lost. The nutrient losses were calculated using the following equation:

$$Nut_{los} = Soil_{los} \times Nut_{conc} \quad (4)$$

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 %)

The nutrient status of the soils was determined before the assessment of nutrient losses through the three different ways. Table 2 shows the nutrient status of the soils and that the most abundant nutrient in the soil is potassium followed by nitrogen and the least abundant is phosphorus. It is also clear that these soils are inherently infertile. As 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.

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

Table 2. Nutrient content of the soils as at beginning of the study at Makoholi Contill site

Using equation 4 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 3. Total nitrogen loss differed significantly

($P < 0.001$) between the different treatments, different years and for the treatment * year interaction. These results follow the same trend that was established for soil loss (Table 1) and serve to confirm the dependence of nutrient losses on 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 because no fertilizers were applied and the sediments under this treatment comprised mainly the non-reactive coarse particles.

The overall phosphorus loss (of 0.5 kg/ha) was 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 3). This trend was to be expected, as nutrient losses are a function of soil loss. Despite the low losses, the treatments and years were significantly different at $P < 0.001$. The two conservation tillage treatments were not significantly different from one another. Potassium was 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 3), and this explains the high losses.

Treatment	N (kg/ha)	P (kg/ha)	K (kg/ha)
CT	15.81	0.750	24.5
MR	2.25	0.091	0.6
TR	2.70	0.169	4.3
BF	28.42	0.861	39.8
Signif. level	***	***	***
s.e.d.	1.341	0.0667	5.49

Table 3. Total N, P and K losses (kg/ha) as a result of erosion under different tillage systems over three years at Makoholi Contill site

The same trend that was established for N and P was also found for 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 3. The overall treatment differences were significant at $P < 0.001$ mainly due to significantly different soil losses between the treatments. The different years also gave rise to different K losses, which were significant at $P < 0.001$. These differences show the conservation merits of mulch ripping and tied ridging, implying that potassium is also conserved effectively through the ability of these treatments in reducing erosion.

Soil erosion is a selective process that renders the soil of its fine particles –clay and organic matter- leaving less productive coarse sand and gravel behind. Moyo (1998) found that the sediments contained between 2 and 4 times more clay and between 5 and 7 times more organic matter than the original soils. The affinity of the nutrients to the fine soil particles is well known and documented. The exchange sites on the clay minerals and organic matter are the basis for this affinity, as nutrients are held at these exchange sites and organic matter is also crucial in the cycle of P and N (Brady, 1984; Stevenson, 1985, Singer and Munns 1987). 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 mineralisation of organic matter. 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 their 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 Ca and Mg ions in clay minerals, erosion is the main source of nutrient and productivity loss in agricultural lands. 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 and clay a strong indicator of overall plant nutrients resulting from erosion (Follet *et al.*, 1987).

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 were important in determining the amount of nutrient loss (Table 4), especially on these sandy soils, where the amount of clay and organic matter are critical as sources of plant nutrients.

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/1t Susp.	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; Treat = Treatment;

Table 4. Nutrient loss as affected by soil loss, sludge and suspended material at Makoholi Contill site

Regression analysis was carried out to relate nutrient loss to the amount of soil lost for the different tillage systems. Firstly, a general regression analysis was carried out, where all the data collected was pooled, without specifying the treatments or the years and soil loss, suspended material and sludge were considered independently (Table 4). Data was then split according to the different treatments (disregarding years) and again the different elements were regressed with soil loss. From the regression output, each element was then calculated in relation to a tonne of lost soil. Correlation coefficients were also worked out for the relationship between each element and soil loss (Table 4 and 5). 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 when total sediments were considered and ranged from 0.01 for P to 0.7 kg for K. The amounts of the nutrient losses were somewhat 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 fraction also influenced the amount of nutrients per unit of soil loss, with more nutrients lost with suspended than with coarse material. Table 4 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 (8.5 times less), 12 times more P was lost with one tonne of suspended material than with sludge, while K loss was 11 times more in suspended material than in sludge. This finding 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 5), 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 were lost under tied ridging than under mulch ripping, though the differences were not significant.

The type of soil determines first and foremost the status of a particular nutrient in the soil, with the sandy soils having lower nutrient contents than the clay soils (Stoorvogel and Smaling, 1990). This therefore, means that for the same amount of eroded soil, the clay soils are bound to lose more nutrients than the sandy soils. One should not overlook the fact that sandy soils have higher enrichment ratios of clay and organic matter contents and thus higher nutrient enrichment ratios than clay soils, although nutrients lost on sandy soils may be less. The nutrient losses with erosion are closely associated with the rate of soil loss Elwell and Stocking (1988), Kejela (1991) and Zoebisch *et al.,* (1995). 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 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. Furthermore the more extensive loss of the topsoil under the conventional tillage systems results in fertility loss as the topsoil is rich in nutrients due to the high amount of the nutrient reserves like clay and organic matter (Troeh *et al*., 1980; Follet *et al*., 1987; Tanaka, 1995). The conservation of clay and organic matter under conservation tillage, therefore implies nutrient conservation (Barisas *et al.*, 1978; Tiessen, Cuevas and Salcedo, 1998). 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 and thus 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. By conserving the soil, nutrients are conserved and soil fertility sustained. It should be emphasized, however, that the loss of organic matter and clay and resultant physical degradation of the soil, also leads to poor tilth, low available water holding capacity and high bulk density (Munodawafa, 2007).

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

Table 5. The relationship between nutrient loss and soil loss under different tillage systems at Makoholi Contill site

3.1.3 Nutrient enrichment ratios

In this study the nutrient enrichment ratio is defined as the ratio of the nutrient concentration in the soil to the nutrient concentration in the sediments. Overall the enrichment ratios for the different nutrients were not very different from one another (Table 6). 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). 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 for all nutrients except P, which recorded a ratio of 2.7. 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.

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

Table 6. Nutrient concentrations in the sediments and enrichment ratios for different tillage systems at Makoholi Contill site

3.2 Nutrient losses as a result of leaching

For all the nutrients, treatment differences were first analysed as influenced by year and as influenced by month. The first option at times led to no significant differences between the treatments although the years were significantly different from each other. The rain months on the other hand often resulted in significant differences in nutrient losses implying that seasonal rainfall tended to mask the influence of rainfall on nutrient loss as a result of leaching.

3.2.1 Drainage water

Before quantifying nutrient losses as a result of leaching, it is important to first of all examine the medium which transports these nutrients and that is drainage water. As nutrient losses with erosion were dependent on the amount of run-off and soil loss, it is expected that nutrient losses with leaching will be dependent on drainage. During the three years of data collection, no drainage was experienced during the months of October (beginning of the season) and March/April (end of the season). Drainage was collected as from November, with one or more lysimeters recording some drainage and continued up to February. The average drainage recorded over three seasons showed that for cropped treatments, more drainage was recorded under the conservation tillage treatments (78 mm under mulch ripping and 77 mm under tied ridging), when compared to conventional tillage with 64 mm (Figure 2). However, the bare fallows generally recorded more drainage than the cropped treatments due to crop transpiration under cropped treatments. Since three types of bare fallow were set up (under conventional tillage, mulch ripping and tied ridging), the data further showed that even under bare fallow, conservation tillage resulted in more drainage (136 mm under MR and 129 mm under TR) than conventional tillage (95 mm). This is a result of the little run-off, previously highlighted, under conservation tillage due to enhanced infiltration and therefore drainage.

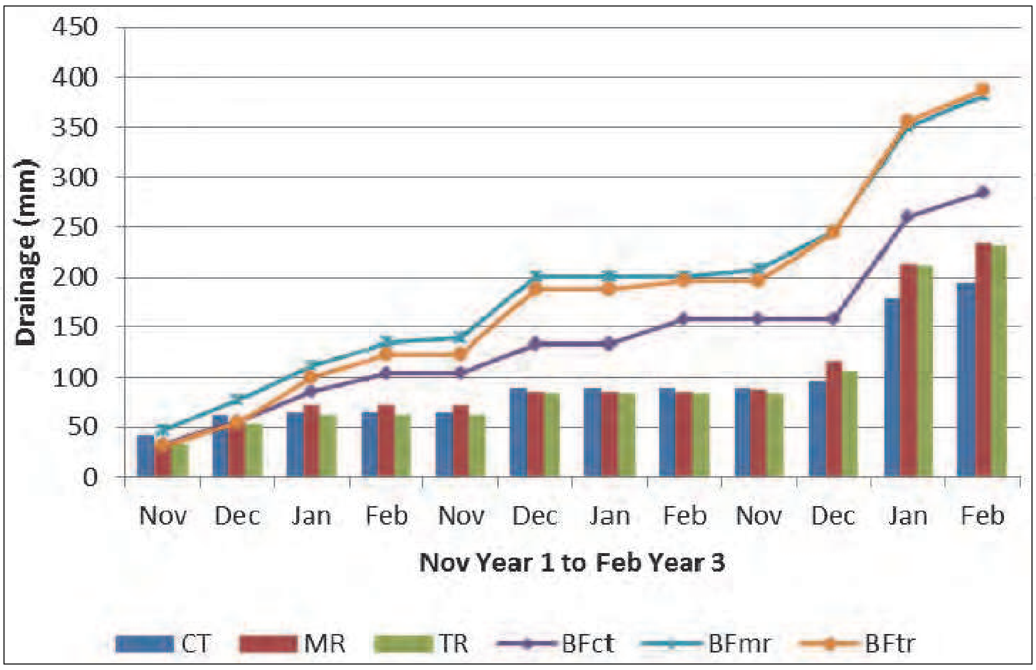

Fig. 2. Cumulative drainage from lysimeters under three treatments (cropped and bare) at Makoholi Contill site, over three seasons

The rainfall amount received during the effective 12 months of recording (November, December, January and February for three seasons) varied substantially among the different months, which differed significantly at $P < 0.001$. Drainage was highest (> 98 mm) in January of the third year, when the highest rainfall (419 mm) was recorded. Analysis of variance gave a significant difference ($P < 0.001$) between the different treatments, with conventional tillage recording the least drainage. There was however, no significant difference between the two conservation tillage treatments (cropped). The bare fallow under conventional tillage also differed significantly from bare fallow under conservation tillage, while there was also no significant difference between the bare fallows under conservation tillage. The different years differed significantly ($P < 0.001$) from one another, due to the different amounts of rainfall recorded during those years. Drainage was lowest when rainfall was also lowest and the highest drainage was recorded during the wettest season. A significant interaction between rainfall and treatment was found ($P < 0.009$), showing that different rainfall regimes resulted in significantly different drainage amounts from the different treatments. There was no interaction however, between treatment and year. This means that when the treatments are compared based on total seasonal rainfall, they show the same trend during the different years. The higher drainage under the bare plots compared to cropped treatments was obviously a result of transpiration by the crops, as Marshall (1967) reported that water in the soil was subject to removal by drainage, evaporation and transpiration by plants. As can be seen from these results, the conservation tillage systems recorded higher drainage than conventional tillage systems. This is a result of higher infiltration rates under mulch ripping and tied ridging, as evidenced by low run-off. The high run-off under conventional tillage translated into low drainage (Xu, Prato and Ma, 1995).

3.2.2 Nitrogen, Potassium and Phosphorus losses with leachate

The overall mean of nitrogen loss over the three seasons was highest under the three bare fallows, followed by cropped conventional tillage and was lowest under the cropped conservation tillage systems. Nitrogen losses among the different months ranged from 4.1 to 10.0 kg/ha. The month with the lowest mean nitrogen loss was November of the third year, which surprisingly did not have the lowest mean rainfall. Also the highest overall mean N loss was recorded in December of the second year, which had the second highest rainfall amount. This finding shows that nitrogen loss may not be directly dependent on drainage amount but also on the soil NO_3^- concentration at that time. The differences between the treatments were highly significant at $P < 0.001$, with the bare fallows recording almost the same amount of N (5.7 for CT; 5.3 for MR and 5.7 kg/ha/yr. for tied ridging). For the cropped treatments however, conventional tillage lost more N (3.1 kg/ha) than the conservation tillage systems (MR with 1.26 and TR with 2.77 kg/ha/yr.). The rain months also gave rise to significantly different nitrogen losses ($P < 0.001$). Furthermore, the significant interaction between treatment and rain that was found, serves to highlight that different treatments responded differently to monthly rainfall, as can be seen from Figure 3.

Very little amounts of phosphorus were lost with drainage, with a grand monthly mean of 4.1 g/ha. P lost over the three years ranged from 0.93 g/ha to 10.58 g/ha (Figure 4). Under the cropped treatments more P was lost under tied ridging (an average of 17 g/ha) followed by conventional tillage (14 g/ha) and least under mulch ripping (13 g/ha), however the differences were not significant.

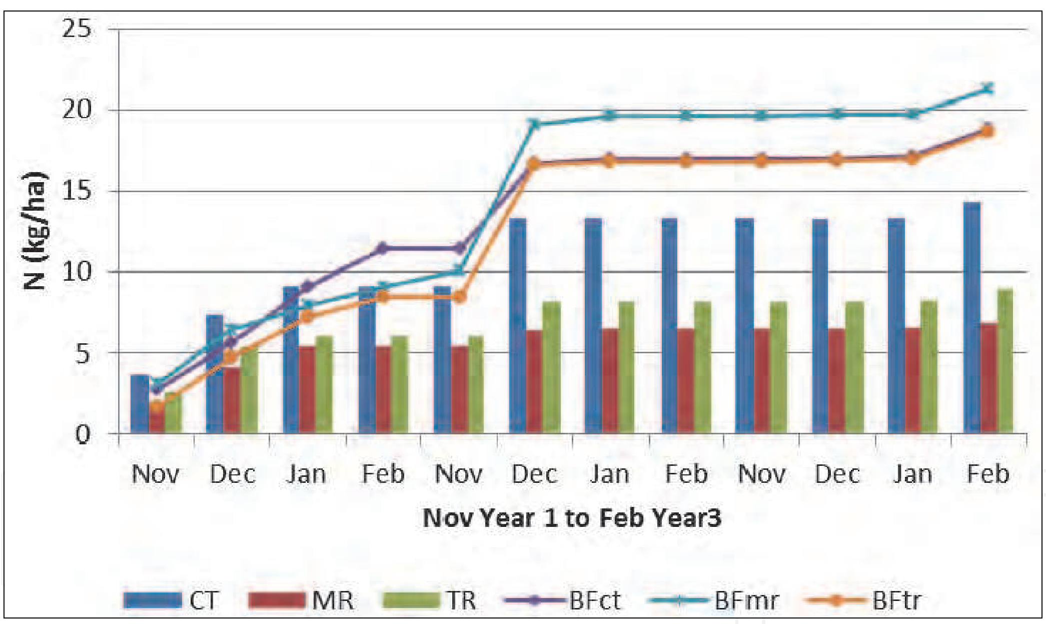

Fig. 3. Cumulative nitrogen loss with drainage water under three tillage systems (cropped and bare) at Makoholi Contill site, over three seasons

The bare treatments generally recorded more P loss than the cropped treatments, however, the trend was reversed as mulch ripping recorded highest loss (37 g/ha) followed by tied ridging (18 g/ha) and the least amount was lost under conventional tillage 15 g/ha). The higher P loss under mulch ripping may be due to high organic matter content and returned crop residues, thus also shifting the equilibrium towards soluble P, however the amounts and differences recorded are also small that they have no significant effects. Despite the little amounts of P lost, the treatment differences for the bare fallows were significant at $P < 0.001$, while the cropped treatments did not differ significantly from one another. The three years and the rain months each gave significantly different P losses at P < 0.001, with the wettest month recording the highest P loss. The different treatments reacted differently to rainfall amount received, thus resulting in highly significant interaction (P < 0.001) between treatment and rainfall.

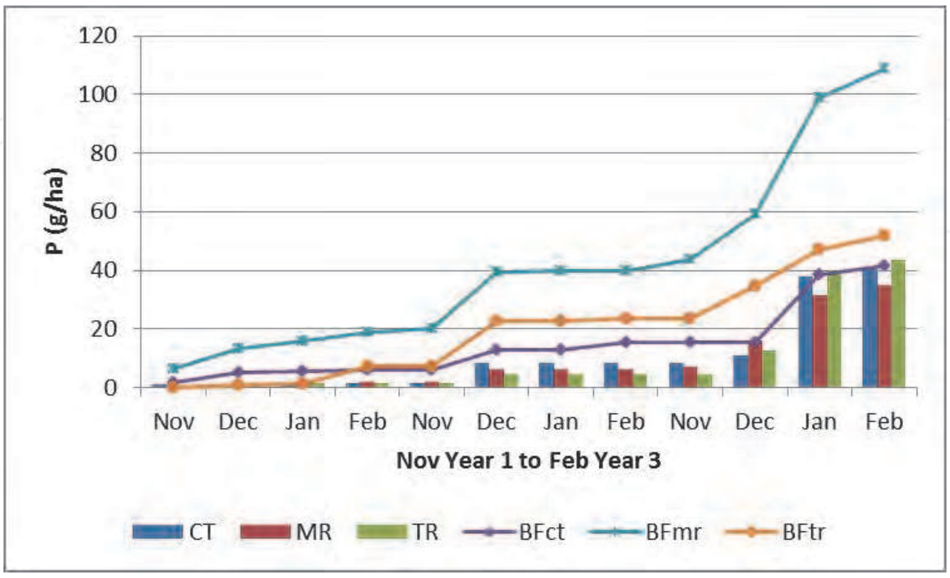

Fig. 4. Cumulative phosphorus loss with drainage water under three tillage systems (cropped and bare) at Makoholi Contill site, over three seasons

More potassium was lost with leachate as compared to nitrogen, a grand monthly mean of 2.1 kg/ha was recorded for potassium (Figure 5) compared to 1.1 kg/ha found for nitrogen. Among the cropped treatments more potassium was lost under conventional tillage (9 kg/ha) than under the two conservation tillage treatments (5 kg/ha under MR and 3 kg/ha/yr. under TR), which also differed significantly from each other, with mulch ripping losing more potassium than tied ridging.

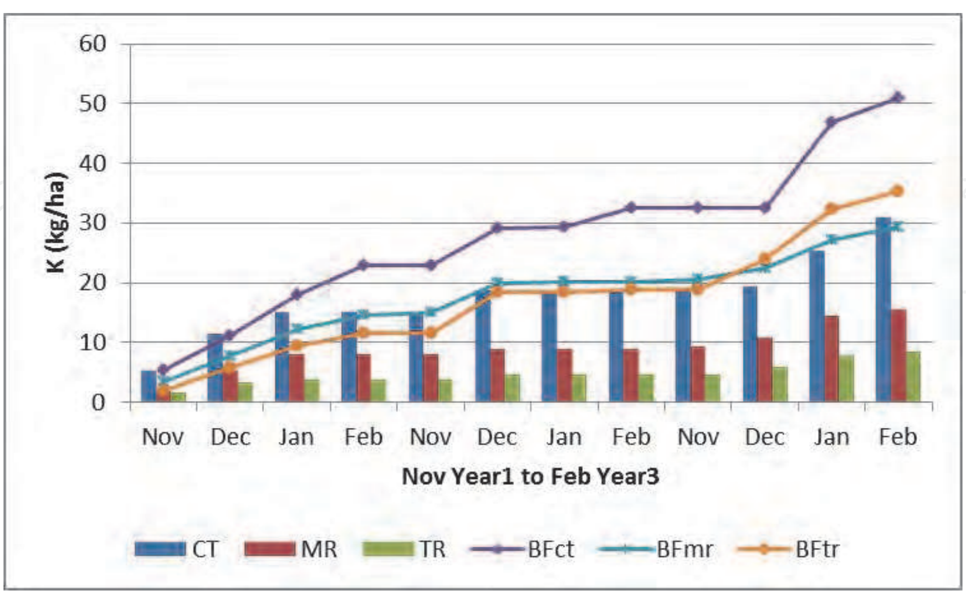

Fig. 5. Potassium loss with drainage water under three tillage systems (cropped and bare) at Makoholi Contill site, over three seasons

Due to lack of water and nutrient uptake by crops under the bare treatments, more drainage was realised and the nutrients that would otherwise be taken up by the crop were leached, leading to generally higher nutrient losses. Again the bare conventional tillage recorded the highest K loss (17 kg/ha) compared to uncropped mulch ripping (10 kg/ha) and tied ridging (12 kg/ha), which did not differ significantly from each other. The month with the highest rainfall amount also recorded the highest K loss and vice versa. It is clear therefore, that K loss was to a large extent influenced by the amount of rainfall received or drainage. Potassium loss differed significantly among the different treatments at $P < 0.001$, with the conservation tillage systems recording less K than conventional tillage. The different years differed significantly at $P = 0.003$, while the rain months were more significantly different at $P < 0.001$. The interactions between year and treatment and month and treatment were not significant.

Nutrient losses with leachate were generally highest under the bare plots, where there was no nutrient uptake by the crop. As nutrient losses are dependent on the nutrient concentration in the soil profile (Kolenbrander, 1981), this means that the concentration of nutrients in the soil solution was kept relatively high under the bare plots, thus leading to higher leaching losses. Under the cropped treatments, conventional tillage lost more nutrient than the conservation tillage systems. The higher drainage under the conservation tillage systems did not result, as was anticipated, in higher losses of nutrients. This is attributed to the improved soil structure, under the conservation tillage systems, leading to water percolation through macro-pores and thus lower nutrient losses (Kolenbrander, 1981). N and K presented the highest losses as they are mobile in the soil and their high concentrations make these elements susceptible to leaching (Stoovogel and Smaling, 1990; Drury *et al.*, 1993). N loss was not significantly dependent on the rainfall amount, showing that there are other factors that influence N leaching other than rainfall. Kolenbrander (1981) found that the amount of N lost through leaching depended on the nitrate concentration in the soil profile, while Stoorvogel and Smaling (1990) reported that the leaching of nutrients depended on rainfall amount and fertility of the soil. Rainfall intensity also affects the nutrient losses with leachate as according to Havis and Alberts (1993) low rainfall intensities produce higher leachate but lower release rates than high intensities. The contact time between the soil particles and thus nutrient desorption is lower during high intensity rainfall and higher during low intensity rainfall, thus affecting the concentration of nutrients in the leachate. There was a highly significant difference between the treatments, where the cropped treatments lost less N than bare plots and conservation tillage systems also lost less than conventional tillage. This finding also confirms the improved soil structure under the conservation tillage systems, which allows water to percolate through macro-pores or inter aggregate pore space (Follet *et al.*, 1987), thus reducing nutrient loss under conservation tillage.

Conventional tillage recorded higher K losses (9 kg/ha) compared to mulch ripping (5 kg/ha) and tied ridging (3 kg/ha). This, again, has a bearing on the improved soil structure under the conservation tillage treatments. The higher amount of K loss under MR compared to TR may be the result of K accumulation under this treatment, as according to Stoorvogel and Smaling (1990) the maize crop has a high amount of K in the stover than in the grain and according to Drury *et al.*, (1993), precipitation leaches nutrients from decomposing plant matter. P was lost in very small amounts (< 50 g/ha/yr.) as it is not mobile in the soil. The very low P status in the soil together with its high affinity for fixation in acidic tropical soils

(Stoorvogel and Smaling, 1990), were other reasons why P leaching was very low, as P in the soil solution is kept very low. Nitrogen and potassium thus presented the highest losses with grand seasonal means of 0.86 kg/ha and 2.02 kg/ha respectively, while negligible losses (< 50 g/ha) were recorded for phosphorus: K > N > P. This may be due to the abundance of labile nitrogen (nitrate) as a result of high fertiliser application as compared to the other elements and the abundance of potassium in the soils. However it is also important to consider that K^+ and NO_3^- ions are very mobile in the soil. Stoorvogel and Smaling (1990) reported that K and N were vulnerable to leaching, while P was tightly bound by the soil. This explains the negligible loss of phosphorus as it is generally immobile in the soil (Brady, 1984; Singer and Munns, 1987).

3.3 Maize grain yield and nutrient losses due to plant uptake

Generally yield is a function of many parameters including climate, soil productivity and management. In this study the climate parameter, rainfall and its effect on the quality of the season are discussed. It is assumed that the quality of the season should influence crop emergence, establishment, growth and yield. An optimal season should have no major mid-season droughts (the period during the growing season, when rainfall amount is less than half of the potential evapotranspiration, $P \leq 0.5$ PET) (FAO & Agritex, 1992). During this period there is definite moisture deficit and crop growth is negatively affected.

During Year 1 and Year 3, no mid-season droughts were experienced, although the typical dry spells (periods where none of the three consecutive five-day periods (15 days) have rainfall exceeding 20 mm) occurred. In Year 2, two mid-season droughts and a series of dry spells were experienced following low rainfall and poor rainfall distribution. Crop emergence was dependent on the amount and distribution of initial rainfall. Generally when rainfall distribution was good, good crop emergence was realised. Due to the higher evaporative losses and resultant moisture stress under tied ridging (Moyo and Hagmann, 1994), crop emergence was generally lower under this treatment than with the other treatments. Both emergence and plant population did not differ significantly between treatments. However, the different years gave rise to significant differences ($P < 0.05$) for both parameters, since the years were characterised by different rainfall (amount and distribution). Rainfall, rather than treatment is an important factor in determining emergence and plant population.

Although mulch ripping outperformed the other treatments during the drier year (2), overall, there were no significant treatment differences in yield ($P = 0.449$), see Table 7. Independent t-tests also showed no significant treatment differences. However, yields varied significantly during different years, ($P < 0.001$). As a result there was a significant interaction between year and treatment ($P < 0.05$), where conservation tillage treatments performed better when rainfall was less and conventional tillage was better when it was wet. Independent t-tests for the different years also confirmed this significant difference as the means of all treatments differed significantly at ($P < 0.001$). Rainfall, more than treatment, proved to be the most yield limiting factor in this region.

During Year 1, there were no significant differences in yield between the three treatments both within the group and independently. However, during Year 2, the treatments performed significantly different at $P < 0.01$ (Table 7). This season was characterised by low and poorly distributed rainfall, which brought about the advantages of mulch - reduction in evaporative losses and generally maintaining the soil moisture during the major dry spells.

Mulch ripping thus realised the highest yield. Conventional tillage had a significantly lower yield than the conservation tillage treatments (P < 0.001). The conservation and subsequent production merits of the conservation tillage treatments, especially mulch ripping, are apparent during drier seasons. Comparing the conservation treatments against each other showed that mulch ripping yielded almost twice as much as tied ridging resulting in a significant difference at P < 0.05. In Year 3 the overall treatment differences for yield were not significant. However, conventional tillage had the highest yield, which differed significantly from the mean of mulch ripping and tied ridging.

Treat/Year (Rainfall)	Year 1 (483mm)	Year 2 (384mm)	Year 3 (765mm)	Overall mean (kg/ha)	Source of variation	Yield
CT	2415	860	4642	2639	Treat	NS
MR	2623	2203	3923	2916	Year	***
TR	2969	1132	3736	2612	Treat x Year	*
Overall mean	2669	1398	4100	2722	MR vs TR	NS
n = 9 (Treatment)		s.e.d. = 259.8	s^2 = 303730		CT vs (MR, TR)	NS
n = 9 (Year)		s.e.d. = 259.8	df = 18		Year1 vs Year 2	***
n = 3 (Treatment x Year)		s.e.d. = 450.0			Year 3 vs (Years 1,2)	***

Table 7. Analysis of variance for yield (kg/ha) as affected by tillage and year (rainfall) and their interactions

Nutrient uptake of different elements was varied, with the highest uptake being that of nitrogen (grand mean of 44.4 kg/ha) and the least uptake was recorded for phosphorus, with a grand mean of 8.08 kg/ha. Potassium uptake was 33.7 kg/ha. While the uptake of nutrients is determined by the crop physiology, it is interesting to find out if the different treatments had any effect on the amount and ratio of the different elements, which were taken up. The uptake of nitrogen was higher than for the other nutrients, probably due to the high amount of N fertiliser that was applied. Conventional tillage recorded the highest mean N uptake of 50 kg/ha, while the uptake under mulch ripping and tied ridging was not significantly different as means of 40.6 and 42.6 kg/ha N were recorded respectively (Figure 6). N uptake under the different treatments was significantly different at P < 0.05. The different years influenced the N uptake resulting in significantly different values at P < 0.001. This was expected as nutrient uptake is a function of yield. Yield, which varied significantly among the different treatments, was found to be dependent on rainfall amount. More than six times less phosphorus was taken up as compared to N uptake, however, P uptake did not differ significantly among the three treatments. Grand means of ~ 8 kg/ha P uptake were recorded for all the treatments (Figure 6). Analysis of variance showed no significant difference among the treatments. During Year 3 significantly high P was taken up by the crop compared to Years 1 and 2, which did not differ significantly from each other. The overall P uptake as influenced by the year was significantly different at P < 0.001. This finding shows the dependence of nutrient uptake/yield on rainfall amount. K uptake varied only slightly among the different treatments and was generally higher under conservation tillage treatments compared to conventional tillage. This variation was, however, statistically not significant. The highest K uptake was recorded during Year 3, while Year 1 and Year 2 differed only slightly.

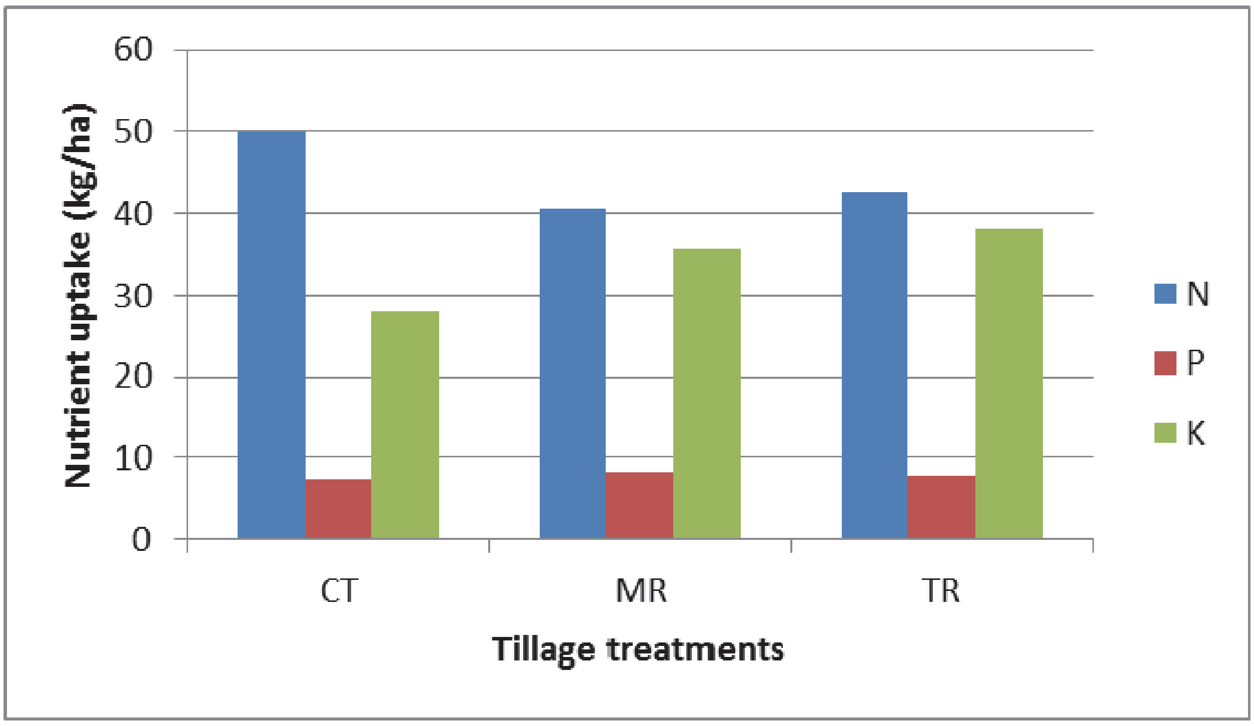

Fig. 6. Uptake of different nutrients by the maize crop on erosion plots, under three tillage systems at Makoholi Contill site (mean of three seasons)

Yield was found to be more dependent on seasonal rainfall than on tillage treatment. The treatment differences were minimal with mulch ripping recording an overall average of 2.9 t/ha; tied ridging and conventional tillage both at 2.6 t/ha. While conventional tillage recorded the highest yield during the wet year, the conservation tillage treatments had better yields during the drier seasons. This clearly highlights the moisture conservation potential of the conservation tillage treatments during drier years, while the higher yields under conventional tillage are only possible during wet years. There was a greater variation of yield under conventional tillage (0.9 - 4.6 t/ha) compared to the conservation treatments (2.2 - 3.9 t/ha) under mulch ripping and 1.1 to 3.7 t/ha under tied ridging. Mulch ripping was also found by Moyo and Hagmann (1994) to have the highest crop yield per mm of growth effective rainfall (water use efficiency). Tanaka (1995) reported that crop residue is not only the key to soil erosion control but also the key to ameliorating the eroded sites. It is expected that with high soil and runoff losses from conventional tillage further decline in productivity will be made apparent through reduction in the yield potential of this treatment. This is an indication that the two conservation tillage treatments can sustain yields better than the conventional tillage. The very high yields recorded under all the treatments during the wettest season confirm the direct positive relationship between yield and rainfall amount.

Nutrient uptake was dependent on yield, which also depended on rainfall amount. The element that was taken up most of all was N (44 kg/ha), followed by K (34 kg/ha), while only 8 kg/ha of P were taken up. Although the actual quantities of nutrients taken up by the crop varied from treatment to treatment, the differences were not statistically significant. Since nutrient uptake is directly dependent on yield, this was expected as yields did not differ significantly among the different treatments.

3.4 Comparison of nutrient losses due to erosion, leaching and plant uptake

Nutrient losses varied greatly depending on the tillage treatment, the element considered, the season in question and the type of loss that the element was subjected to (erosion, leaching or plant uptake). In general the highest losses were realised through plant uptake which is considered to be good since this is the only positive loss, when compared to the other two types of nutrient losses. There is, no doubt, a depletion in soil fertility, however, if only the harvested products are removed from the field and other crop residues are returned, in the absence of erosion and leaching, fertiliser requirements for the maintenance of soil fertility may be reduced. Erosion and leaching on the other hand are considered negative and should be minimised at all costs. Erosion losses were higher than those incurred with leaching for the conventional tillage, while the reverse was partly true for the conservation tillage systems.

A general overview of the nutrient losses showed that total nitrogen losses (through erosion, leaching and plant uptake) were least under mulch ripping with a range of 27 - 53 kg/ha/yr. followed by tied ridging (range of 25 - 64 kg/ha) and highest under conventional tillage (range of 44 - 87 kg/ha). The same trend was established for phosphorus loss although the amounts lost and the differences between the treatments were minimal (ranges of 7 - 10 kg/ha for CT; 6 - 8 kg/ha for MR and 6 - 10 kg/ha for TR). Potassium losses ranged from 29 - 92 kg/ha under CT; 30 - 43 kg/ha under MR and 22 - 57 kg/ha under TR. Table 8 shows the average losses of different elements found for the different treatments and years.

Treatment	N	P	K
CT	63.54	8.42	60.70
MR	38.21	7.41	36.48
TR	49.85	7.83	39.61
Signif. level	*	NS	NS
Year	N	P	K
1	52.0	7.40	64.20
2	31.6	6.77	27.00
3	68.0	9.49	-
Signif. level	**	*	***

- = missing data

Table 8. Average total nutrient losses under different tillage treatments during three seasons at Makoholi Contill site

Generally, more nutrients were lost under conventional tillage as compared to the conservation tillage system. Only N losses gave significant treatment differences at $P < 0.05$. However, when the mean of the conservation tillage systems was compared to conventional tillage, the systems were significantly different at $P < 0.01$. Although quantitatively more P was lost under conventional tillage than under the conservation tillage systems, the treatment differences proved not to be significant. Overall there were no significant treatment differences for K loss, however conventional tillage differed significantly from the mean of the two conservation tillage treatments. The different years affected the nutrient losses more than tillage, resulting in all the elements differing significantly between the years (Table 8).

After the total nutrient losses were calculated and assessed, each type of nutrient loss was evaluated relative to the total nutrient loss. Plant uptake contributed between 38 and 99% of total nutrient loss, erosion losses were between 0.1 and 51%, while leaching accounted for 0 to 16% of total nutrient loss. This is the reason why different treatments did not show significant differences overall because plant uptake was very high and masked the effects of the other forms of nutrient loss. However, this general finding shows clearly that after plant uptake, erosion is the main factor contributing to nutrient loss in agricultural arable lands.

The different nutrients as influenced by tillage were then evaluated and gave the following results:

Nitrogen: the losses were highest due to plant uptake (Figure7), however the percentage of N taken up under conventional tillage (56 - 84%) was lower than under mulch ripping (88 - 95%) and tied ridging (85 - 92%). This finding implies therefore, that the contribution of the losses by leaching and erosion were lower for the conservation tillage systems. Nitrogen losses as a result of erosion were thus highest under conventional tillage, contributing to more than a quarter of total N loss (range 16 - 29%). The conservation tillage systems on the other hand realised minimum losses of less than one percent and highest losses of 11% (MR) and 8% (TR). The leaching losses were in all cases lower than the erosion losses and the highest percentage leaching loss of 15% was recorded under conventional tillage, while mulch ripping had a maximum of 7% and tied ridging of 10% of total N loss.

Phosphorus: Plant uptake contributed to most of the P loss even under conventional tillage (Figure 7). A range of between 82 and 97% was found under conventional tillage, while the conservation tillage systems had higher percentages of between 97 - 99.8% (MR) and 96 - 99.8% (TR). Erosion losses were high under conventional tillage (between 3 and 18%), while these were maintained at below 5% under both MR and TR. The results also prove that P is not very susceptible to leaching as all the treatments recorded less than 1 % of total P loss.

Potassium: The crop uptake of potassium had a low percentage under conventional tillage, where it ranged from 38 - 77% of total K loss. This was as a result of very high losses of K due to erosion, ranging from 23 - 46%. K leaching was almost as high as N leaching under this treatment (0 - 16%). The percentage of K uptake under the conservation tillage treatments was relatively higher than under conventional tillage (85 - 96% MR; 79 - 95% TR). This means that the contribution of erosion and leaching was also less than under conventional tillage. K loss as a result of erosion under mulch ripping remained very low, < 1 - 2%, while it was higher under tied ridging, 1 - 14% of total K loss. The contribution of leaching to total K loss was higher when compared to that of N and P. Between 3 and 13% of total K loss was lost through leaching under mulch ripping and 4 - 6% under tied ridging.

Total nutrient losses were significantly lower under conservation tillage treatments than under conventional tillage. Although nutrient uptake did not differ significantly among the different treatments, erosion and leaching losses accounted for the differences. After plant uptake, erosion presents higher nutrient losses than leaching. While N and K are mobile in the soil and vulnerable to leaching (Stoorvogel and Smaling, 1990), the N and K losses attributed to this type of nutrient loss were lower than the amounts lost with erosion and plant uptake, except for leached K under mulch ripping, where the losses were higher than erosion losses. This may be due to the high amount of K in solution, leached from the decomposing stover (Havis and Alberts, 1993). There could be an over supply of K in the soil and the high uptake may be because K is available, "luxury uptake" rather than due to demand. P loss with leaching was lowest and this was expected as P is immobile in the soil and many researchers have highlighted the affinity of P to fixation in the soil. This study has shown that P is not prone to leaching, but is susceptible to erosion, while N and K are mobile in the soil and are very susceptible to leaching and erosion. Although plant uptake contributes the highest percentage of total nutrient loss, the low percentages of 38, 49 and 56% under conventional tillage are a cause for concern as this means that leaching and erosion sometimes contribute up to > 50% of total nutrient loss.

3.5 Soil nutrient balance

The main purpose of this section is to try and balance the nutrients lost from the field with added inputs. The total nutrients from the field have been quantified in the previous section (erosion, leaching and plant uptake) and the inputs have only been limited to applied fertilisers. The results of this nutrient balance for the different treatments and elements, calculated using Equation 3, have been summed up in Table 9.

Tillage	IN1 kg/ha	OUT1 kg/ha	OUT2 kg/ha	OUT3 kg/ha	Balance kg/ha
Nitrogen					
CT	51.5	44.63	15.81	3.10	- 12.04
MR	51.5	34.70	2.25	1.26	+ 13.29
TR	51.5	44.38	2.70	2.77	+ 1.65
Phosphorus					
CT	12.0	7.65	0.75	0.01	+ 3.59
MR	12.0	7.30	0.09	0.01	+ 4.60
TR	12.0	7.65	0.17	0.02	+ 4.16
Potassium					
CT	12.0	34.05	24.50	9.31	- 55.86
MR	12.0	35.18	0.60	4.58	- 28.36
TR	12.0	40.67	4.30	2.99	- 35.96

Where: IN1 = mineral fertilisers; OUT1 = plant uptake; OUT2 = soil erosion; OUT3 = leaching

Table 9. Nutrient balance assessment of the three tillage systems, average over three years at Makoholi Contill site

Under conventional tillage, there is evidence of soil mining (negative balance) for all elements except P. The conservation tillage systems only recorded negative nutrient budgets for K losses, due to very high losses as a result of crop uptake, which were generally very high to be compensated by the amount applied. Under conservation tillage soil mining was mainly as a result of crop harvests, while under conventional tillage substantial amount of nutrients were also lost as a result of soil erosion and leaching. Thus under this treatment, maintenance of soil fertility means to first of all replace nutrients lost with leaching and erosion before replacement of the amount taken up by the crop. The sum of N losses under conventional tillage is in excess of the amount of N applied annually (an equivalent of 125% of applied N) and some of the losses are directly from the soils' nutrient reserves (Table 10). Under mulch ripping an equivalent of 76% of applied N was also removed annually. The depletion rate was lower and was contained well below the annual N application rate. Soil fertility is thus better maintained under mulch ripping. An equivalent of 99% of applied N was lost under tied ridging, indicating that the rate of N applied under tied ridging is literally just adequate to offset the nutrient losses, however, great care has to be exercised to ensure that the losses do not exceed the fertiliser applied. P losses under all the treatments were maintained well below the equivalent amount of P applied, an average of 70% under CT; 62% under MR and 75% under TR (Table 10). This implies that part of the applied fertiliser was retained in the soil, showing the extreme fixation of P under these conditions. Such low levels of P fertilisation may not show any yield response due to the high rate of fixation. The crop also took up relatively low amounts of P when compared to the other elements. Potassium on the other hand showed that much, more K was lost when compared the amount applied (CT 505%; MR 304% and TR 330%), see the negative balance on Table 9.

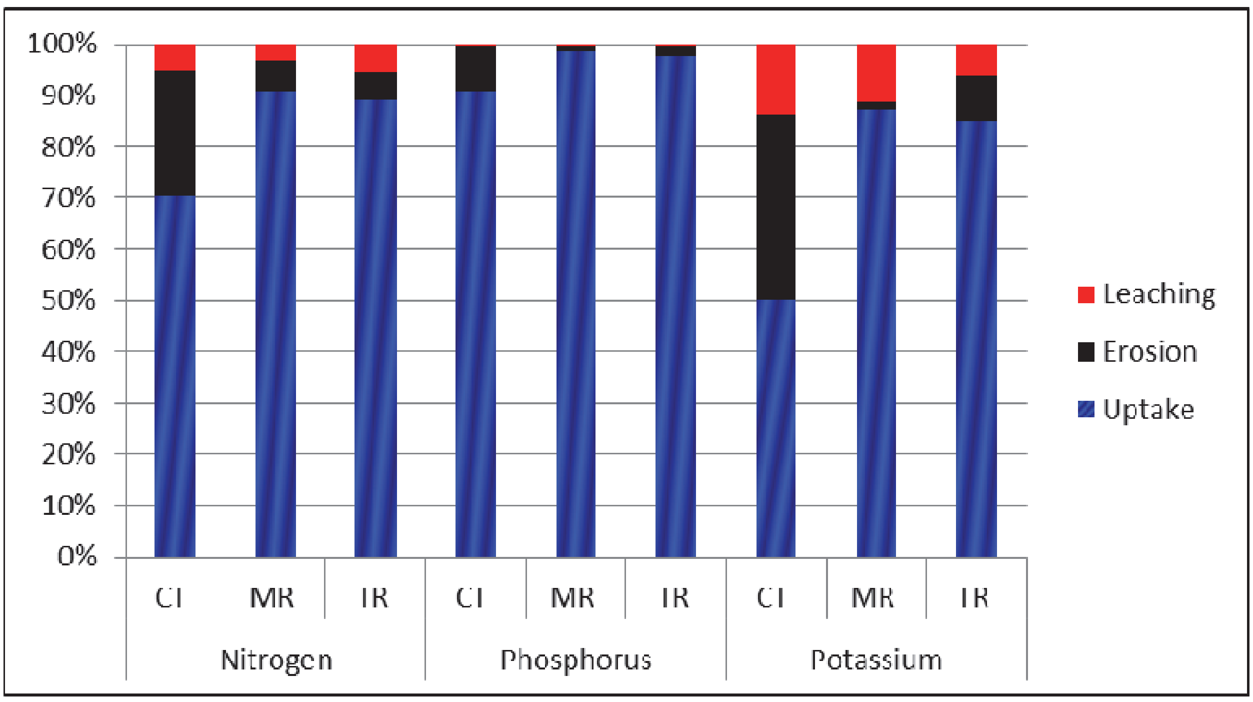

Fig. 7. Comparison of nutrient losses (N, P, K) through leaching, plant uptake and erosion under different tillage systems over three seasons at Makoholi Contill site

Nutrient budgets should be employed and fertiliser application should aim at replacing lost nutrients as well as meeting the crop requirements, for the following season. Conservation tillage is highly recommended as it reduces the danger of soil mining drastically, but the problem of soil mining may not be wholly solved through the introduction of soil and water conservation systems if inputs and outputs are not well balanced. While most of the nutrients may be conserved, even up to accumulation, other nutrients, especially those not applied as fertilisers may need replacement once in a while. Nitrogen is the only element that is significantly affected by the atmosphere, increasing its amount in the soil through biological fixation and natural deposition (Hach, 1979). Due to these factors, changes resulting from the N losses may not be easily quantifiable within a few seasons.

Treatment	Elements	Year 1	Year 2	Year 3	Average
		Total loss %	Total loss %	Total loss %	%
CT	N	119.80	86.32	171.37	125.8
MR	N	68.63	52.91	105.45	75.7
TR	N	120.34	48.59	127.23	98.7
CT	P	66.67	57.17	86.58	70.1
MR	P	53.58	62.50	69.08	61.7
TR	P	64.75	79.50	81.58	75.3
CT	K	768.67	243.00		505.8
MR	K	358.75	249.17		304.0
TR	K	477.50	182.58		330.0

Table 10. Relationship between total nutrient loss and applied fertiliser over three seasons at Makoholi Contill site

Nutrient losses with plant uptake, erosion and leaching result in the depletion of nutrient status of the soil, i.e. "soil mining". Balancing the nutrients applied in a system with the outputs from the same system gave negative nutrient budgets, confirming the above hypothesis. What is important however, is that under conservation tillage, mainly the nutrients lost through plant uptake need to be replaced, while under conventional tillage, a significant amount of nutrients lost with erosion and leaching also need to be replaced. The maintenance of soil fertility under this system is more costly than under conservation tillage. Although the conservation tillage systems have proven without doubt that they conserve soil, water and nutrients, the nutrient budgets have also shown that it is of utmost importance to balance the inputs and the outputs. To maintain soil fertility and ensure sustained productivity of the soils, fertiliser rates have to address both the crop needs of the following season and replace the nutrients lost during the previous season.

4. Conclusions

The losses of nutrients with sheet erosion are primarily dependent on the content of each element in the soil, the amount of soil loss (determined by the type of tillage system) and the type of sediment fraction. Plant nutrient losses are higher when the nutrient status in the soil and/ or soil loss from a field is high. There is a very high association between nutrients and fine soil particles. This makes the suspended material the most detrimental sediment fraction with very high concentrations of nutrients. Drainage is dependent on rainfall and on tillage system. The bare fallows tend to have more drainage than cropped treatments, while the conservation tillage systems have more drainage than conventional tillage. Nutrient losses with leachate are highest under bare fallows compared to cropped treatments. Despite the higher drainage, the conservation tillage systems however, have lower nutrient losses compared to conventional tillage, due mainly to improved soil structure. N and K are mobile in the soil and are prone to leaching, while P is immobile and thus not susceptible to leaching. N and K are mobile in the soil and are prone to leaching, while P is immobile and thus not susceptible to leaching. Nutrient uptake by the crop is dependent on yield and nutrients are taken up in the following order: N > K > P. More nutrients are lost with plant uptake, followed by erosion and then leaching. For the conventional tillage system erosion and leaching contribute to a substantial amount of total loss, while under the conservation tillage systems most of the nutrients are taken up by the crop and a negligible amount is attributable to erosion and leaching losses. The nutrient balance of inputs versus outputs is negative for N and K under conventional tillage, while under conservation tillage systems, negative nutrient budgets are confined to K, which is subject to higher losses due to its high concentration in the soil. The optimal applications are adequate to offset all nutrient losses under conservation tillage treatments, while under conventional tillage these are inadequate and indicate soil mining. The conservation tillage treatments significantly reduce nutrient losses from agricultural lands due to their ability to reduce soil erosion and leaching.

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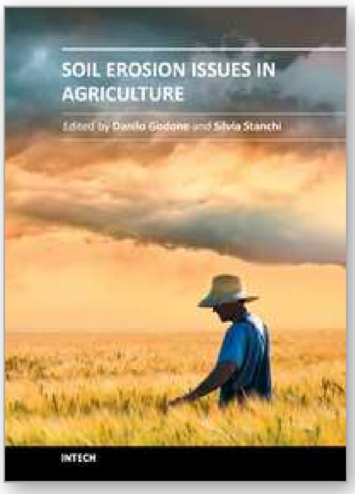

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The book deals with several aspects of soil erosion, focusing on its connection with the agricultural world. Chaptersâ€™ topics are various, ranging from irrigation practices to soil nutrient, land use changes or tillage methodologies. The book is subdivided into fourteen chapters, sorted in four sections, grouping different facets of the topic: introductive case studies, erosion management in vineyards, soil erosion issue in dry environments, and erosion control practices. Certainly, due to the extent of the subject, the book is not a comprehensive collection of soil erosion studies, but it aims to supply a sound set of scientific works, concerning the topic. It analyzes different facets of the issue, with various methodologies, and offers a wide series of case studies, solutions, practices, or suggestions to properly face soil erosion and, moreover, may provide new ideas and starting points for future researches.