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MECHANICAL SOIL CONSERVATION WITH CONTOUR RIDGES: CURE FOR, OR CAUSE OF, RILL EROSION?

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ABSTRACT

Based on the results of an erosion damage assessment in Southern Zimbabwe, where mechanical conservation work has been carried out since the 1940s, this paper describes the impact of mechanical conservation systems on processes leading to rill erosion. In a study of a catchment area, it was found that influxes of water from roads and waterways as well as contour ridges that were originally designed to control rill erosion had a major role in the formation of rills. Existing rills and depressions which cause water concentration, siltation of contour drains and overflowing of contour ridges were the main factors leading to excessive rill erosion. The study showed that particularly during a highly erosive year like 1992/93, the damage due to rill erosion can be excessive, causing an abrupt degradation.

It is concluded that the present conservation system is insufficient to control rill erosion effectively and is often the cause of this erosion. Effective control of rill erosion is a pre-condition for optimal implementation of land management systems such as conservation tillage. Therefore, an integrated approach to land husbandry must be developed jointly with farmers and promoted in order to improve crop production and sustainable management of natural resources. This should consider improved mechanical conservation as well as agronomic and biological soil and water conservation techniques.

KEY WORDS Zimbabwe; land degradation; soil and water conservation; land husbandry; contour ridges; soil erosion; rill erosion; sheet erosion; erosion damage mapping; conservation tillage; tied ridging

INTRODUCTION

Widespread soil erosion on arable land in smallholder farming areas in Zimbabwe was described as early as the 1930s. Degradation became so severe that despite having promoted mechanical soil conservation measures for more than two decades, the then colonial administration decided in 1951 to enforce the construction and maintenance of mechanical conservation measures by law (Whitlow, 1988). During the following decade contour ridges were constructed in most arable areas in the 'communal lands'. However, the construction and maintenance of ridges were not of a universally high standard (Whitlow, 1988). Stocking (1972) reported runoff concentration and consequent gullying caused by contour ridges. In general, however, there was agreement that contour ridges improved the mechanical protection of arable lands. Nowadays, contour ridges, storm drains and grassed waterways are still being promoted by the Zimbabwean Agricultural Extension Service as the mainstay of conservation. A common perception is that the contour layout protects the arable land from rill and gully erosion, whilst sheet erosion between the ridges is still rampant (Elwell, 1984). As a consequence, research into conservation tillage systems which prevent sheet erosion on arable land has been initiated, and one effective conservation tillage system, 'no-till tied ridging' (Elwell and Norton, 1988) is presently being developed and tested in adaptive on-farm trials in the communal areas by the collaborative AGRITEX/GTZ Conservation Tillage Project. However, experience in these trials has shown that despite existing contour ridges, rill erosion is still a major threat to sustainable cropping.

The objective of this study is to identify the origin and underlying processes of excessive rill erosion and to indicate the weaknesses of the present conservation layout. Of primary interest is the quantifica-

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tion of soil loss due to rill erosion, and the extent of the damage in terms of area. As the study period covered a year where serious degradation occurred, it is also of interest to relate the damage in that single year to the total damage caused by rill erosion during the last five decades, ever since contour ridges were established. The effectiveness of future soil conservation measures, notably of conservation tillage (Elwell, 1993), must be guaranteed.

THE STUDY AREA

The study was carried out in Zaka District (Masvingo Province) in southern Zimbabwe (Figure 1). The area is located in Natural Region IV (Vincent and Thomas, 1960), which is characterised by a semi-arid climate with an average annual rainfall of 737 mm (Hussein, 1987). However, rainfall is highly variable between and within seasons. Most of the rainfall occurs between November and March, thus allowing one cropping season with high risk of crop failure due to mid-season drought spells. Highly erosive rains generally fall at the onset of the rainy season, at a time when bare soil is most exposed.

The geology of the area is dominated by the 'older gneiss complex', which is prevalent in the central part of Zaka District and on which an undulating landform with scattered rock outcrops developed. The soils are shallow, coarse-grained sands, often with a gravely subsoil (DRSS, 1992; Anderson, *et al.*, 1993). The low inherent fertility of these degraded arable soils is caused by very low organic matter content (<0·3 per cent) and low cation exchange capacity. According to FAO (1988), they are classified as Haplic Arenosols with poor structural condition and high erodibility.

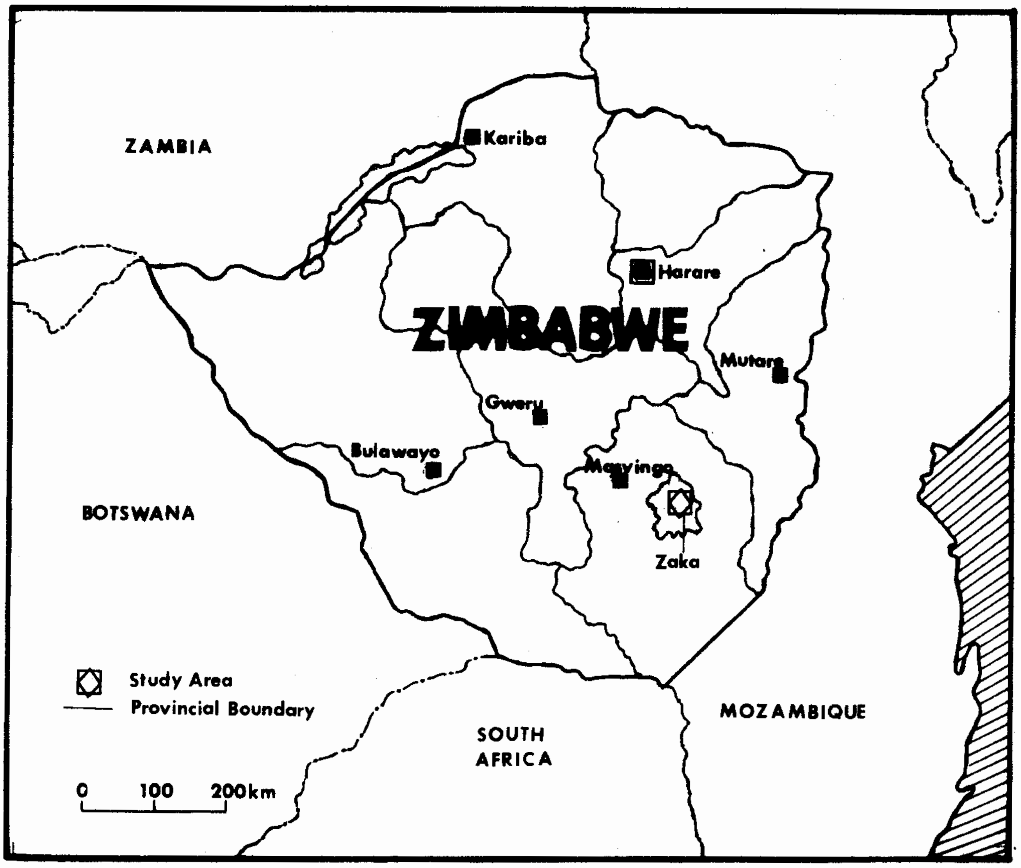

Figure 1. Location of the study area. This study is representative of the semi-arid areas which constitute 83 per cent of the land area of Zimbabwe. In sub-humid areas the underlying processes are similar, but the technical alternatives are different

The average arable land holding of farms under communal tenure in the area has been reduced through population pressures from approximately 5 ha in 1960 to approximately 2 ha at present. The population density in Zaka District is 62 persons km^{-2} (CSO, 1992), which is high considering the land's natural potential.

The present mechanical conservation system

Arable land is protected from soil erosion by contour ridges and storm drains which were constructed in the 1950s. To prevent gullying in the valley bottom, cultivation is officially prohibited along a strip of 30 m on either side of the natural waterway. The natural and artificial waterways are therefore utilised as communal grazing land. The arable land is utilised for rain-fed cropping (maize, groundnuts, millets), and the conventional tillage practice is annual ploughing with an ox-drawn mouldboard plough. After a severe drought in 1991/92, however, many draught animals died and many farmers are now tilling the land by hoe.

For a detailed study, a small catchment near Jerera growth point (20′25″S, 31′28″E, 743 m.a.s.l.) in Zaka District, approximately 100 km southeast of the provincial capital Masvingo, was chosen to carry out an erosion damage mapping. The catchment comprises 16·45 ha, of which 12·49 ha (76 per cent) are arable land and 3·96 ha (24 per cent) are covered with an open bushland vegetation and utilised as grazing land. Contour ridges and storm drains occupy 1·37 ha, which is 11 per cent of the arable area. The slopes in the catchment increase from the top near the watershed towards the natural waterway in the centre (from 1·5 per cent to 5 per cent). Sandy soils along the catena are generally homogenous except in the valley bottom, where heavier textured soils occur.

Before 1950, the land was utilised extensively under shifting cultivation. The contour layout in this catchment was constructed between approximately 1950 and 1953, but the present tenants of the land were resettled into the area in 1959. This implies that continuous cultivation with subsequent land degradation started around 1950. The present state of the contour layout is generally fair to poor. Slope lengths between contour ridges had originally been designed for a vertical interval of 1 metre. Except for some fields where farmers extended fields into grazing land, this still applies today. Only minor horizontal pegging errors were identified, but maintenance of the contour layout has been carried out at a minimum level for several years which is typical for most communal farms. In 1991, two new, rather narrow contour ridges were pegged and dug in order to reduce the slope length of two fields.

Four different tillage techniques were practised in the catchment area in 1992/93: ploughing with an ox-drawn mouldboard plough, ripping/opening furrows (carried out before the onset of the rains), no-till tied ridging, and hand planting with a hoe, which leaves most of the soil surface undisturbed.

METHODOLOGY

Rill erosion was monitored during two cropping seasons, from 1992 to 1994. To explain the processes of rill erosion, a detailed erosion-damage mapping of a small catchment was carried out in 1993. Rills which occurred in the catchment were measured and mapped in detail. Each rill was divided into portions with homogenous cross-sections. Then the depth, width and shape of the cross-sections were measured with two pegs on which a nylon thread was fixed (Figure 2). The volume of the rills, which is equivalent to the volume of soil lost, was calculated by multiplication of the area of the cross-section with the length of a homogenous section of the rill. The soil volume was converted into weight by multiplying by the average bulk density of 1·4 Mg m^{-3}. This procedure was adapted from Schmitt (1979) and Herweg (1988).

The point of origin of each rill was defined from visual assessment and aerial photographs. The effects of the different tillage techniques were evaluated. The existence of a compacted and erosion-resistant layer (plough pan) below the ploughed layer made it possible to distinguish between erosion of soil loosened by ploughing in this season and the total damage. The rills which had developed since the last ploughing operation at the onset of the previous season had developed a rectangular cross-section, as all

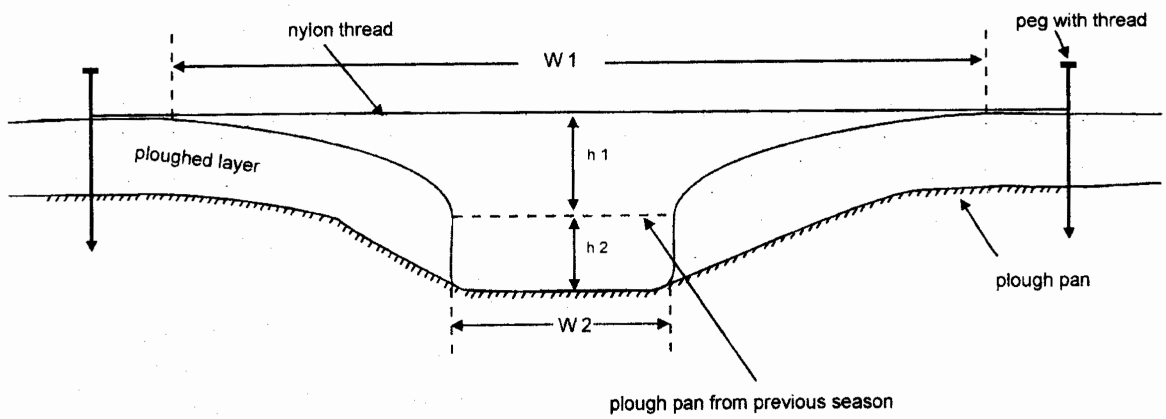

Figure 2. Methodology for measuring the cross-section and volume of rills. For the total rill volume, the area of the cross-section (based on width (w1) and depth (h1 + h2) was multiplied with the length of the homogenous part of the rill. For the soil loss attributed to 1992/93, only the rectangular cross-section w2 × h2 was measured

soil loosened down to the plough pan was washed away. Therefore, within a cross-section, layers originating from different years could be differentiated (Figure 2).

The surface area and depth of accumulations of eroded material were measured and the volume calculated. For each field, the slope was measured and the tillage method practised in 1992/93 was recorded. The areas damaged by rill erosion and siltation of sand through deposition of eroded material were added to give the total area damaged.

RESULTS

Erosion damage mapping

Erosion damage mapping in the catchment was carried out in June 1993, at the end of a highly erosive rainy season with a precipitation of approximately 600 mm (Figure 1) following a dramatic drought in 1992. At the onset of the rainy season in October 1992, owing to extremely intense grazing during the foregoing drought, no vegetation or litter cover was left in the area, either in the grazing land or in the fields. Even trees had been pruned to feed the leaves to livestock. The condition of the land after the drought provided a favourable environment for soil erosion.

Types and patterns of rill erosion damage within the catchment

The distribution of rills/depressions, accumulations of eroded material and visible sheet erosion (flushing) in each of the 20 fields are shown in Figure 3. A total of 134 rills of total length 2949 m were mapped on 12·49 ha of arable land, with a total soil loss of 1299 t. This is equivalent to an average of 104 t ha^{-1} and a rill density of 236 m ha^{-1}. The total area damaged was 1·28 ha, which is 10.2 per cent of the arable area in the catchment. Rills and depressions damaged 1·05 ha and subsequent siltation through deposition of eroded material damaged 0·23 ha. This damage included depressions which were formed during a long period of continuous erosion, and can thus be considered to be the result of approximately 40–45 years of cultivation.

The rills on arable land (Figure 3) were classified into three groups. The width of the rills varied greatly, but the depth correlated well with the volume and was therefore taken as the criterion for classification. Conventional definitions and classifications of 'rills' and 'gullies' were not suitable, as the sides of the rills are flattened through annual ploughing, which results in the formation of depressions up to 400 mm deep and several metres wide. In this case the repeated ploughing actually contributes to the development of wide depressions instead of closing the rills.

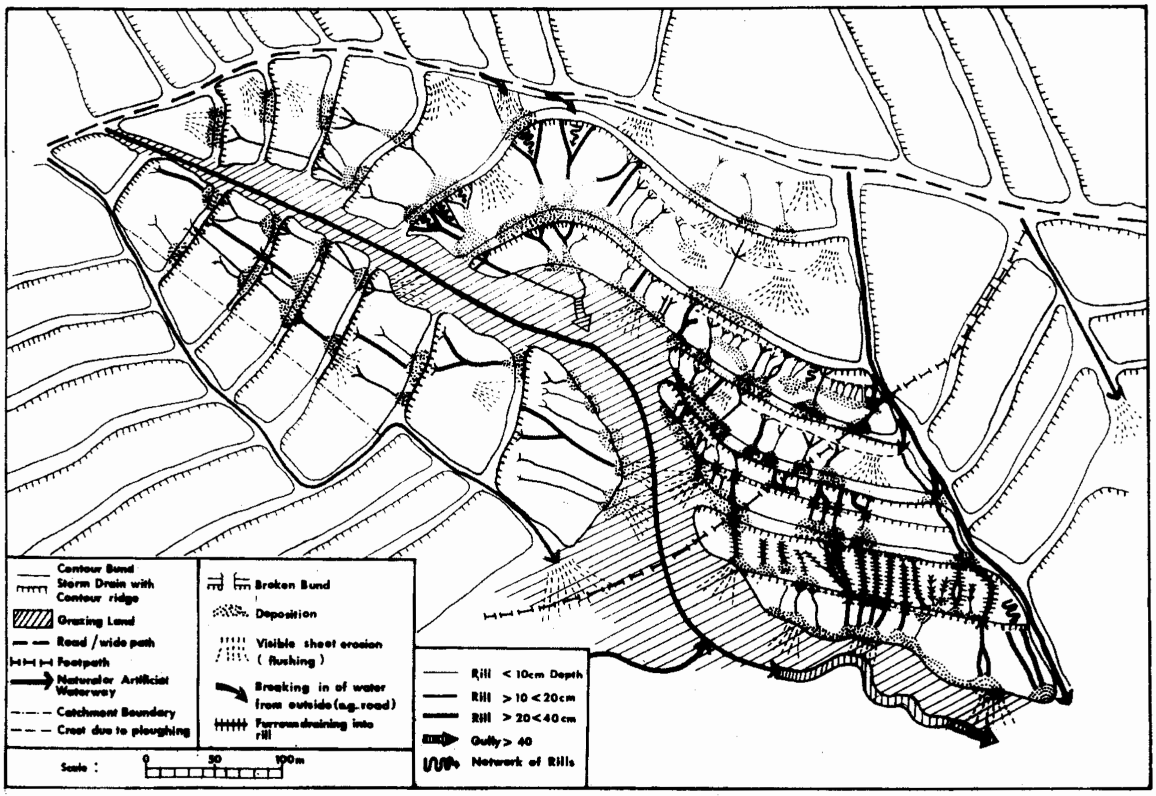

Figure 3. Erosion-damage map of the study catchment area near Jerera/Zaka. The catchment boundary at the top of the map is a road along a crest, on the right the boundary is an artificial waterway, and on the left the boundary is formed by a topographic ridge downslope which then enters another artificial waterway. The natural catchment boundaries were modified by the contour layout

The first group consists of small rills up to 100 mm depth, the second group consists of medium rills between 100 and 200 mm depth, and the third group is large rills between 200 and 400 mm depth. Large rills and most medium rills are readily visible as depressions in the field. Large rills made the highest contributions to total soil loss (60·8 per cent) and total area damaged (52 per cent), whereas the damage caused by small rills was minor, with a soil loss of 4·5 per cent and a damaged area of 11.2 per cent (Table I). Twenty-one large rills (15·7 per cent of all rills) caused 51 per cent of the total soil loss. Gullies deeper than 400 mm occurred only in grazing land and were not considered in this study.

Rills occurred all over the catchment except on two fields at the top end, where only sheet erosion was observed. Most of the rills, except those which broke contour ridges, ended in the field where they started, leaving eroded material as accumulations in the field or in the contour drain (Figure 3). Although rill densities appeared to increase with slope, this could not be confirmed because of other dominating influences.

Damage in 1992/93 compared with the total of 1950–1993

As described in the methodology section, the pattern of the cross-sections of the rills showed a distinction between soil loss which had occurred during the season when the mapping was carried out (1992/93), with highly erosive conditions) and the overall soil loss (1950–1993). Table I shows that 56·9 per cent of the total soil loss in rills and depressions which originated between 1950 and 1993 had been eroded in 1992/93. This figure appears high, but considering rainfall erosivity, zero vegetation cover at the onset of the rainy season, and existing depressions before the 1992/93 rainy season, it is realistic. However, the calculation does not consider the deepening of the whole surface due to continued sheet

Table I. Rill-erosion damage from different categories of rills in the catchment area during the period 1950–1993 and in 1992/93

Size of rill	Rills		1950–1993 Soil loss		1950–1993 Damaged area		1992/93 Soil loss		1992/93 Deposition	
	No.	%	t	%	m^2	%	t	%	t	%
Small	38	28·4	58·0	4·5	1442	11·2	51·5	88·8[a]	21·3	41·4[b]
Medium	52	38·8	451·2	34·7	4726	36·8	257·5	57·1[a]	66·5	25·8[b]
Large	44	32·8	789·8	60·8	6673	52·0	429·9	54·4[a]	88·5	20·6[b]
Total	134	100·0	1299·0	100·0	12841	100·0	738·9	av. 56·9[a]	176·3	av. 23·8[b]

[a] Per cent refers to cumulative soil loss in 1950–1993 in this category.
[b] Per cent refers to soil loss in 1992/93 in this category.

erosion for 40 years which, assuming a moderate sheet erosion of 10 t ha^{-1} $year^{-1}$, would be approximately 30 mm. In terms of soil loss per hectare, 59·2 t ha^{-1} were lost from arable land through rill erosion in 1992/93.

The major erosion damage occurred in three storms: on 26 October, during a high-intensity storm with 25 mm rainfall, on 13 December, during a storm with 37 mm rainfall, and on 23/24 December, when 157 mm of rain fell in 2 days. After each storm a drastic deepening of the rills was observed. Spot measurements after the first storm indicated a soil loss of up to 40 t ha^{-1} through rill erosion in some fields. Other heavy storms in January and February did not cause serious erosion as vegetation cover had developed in the fields and on the contour layout.

The percentage of soil loss in 1992/93 varied with the size of the rills. Whereas this single season caused approximately 55 per cent of the soil loss from medium and large rills, 88·8 per cent of small rills were induced in 1992/93. This can be explained by the fact that small rills up to 100 mm depth mainly originate from a localised, concentrated flow of water in the field and are levelled annually during ploughing operations. With time, however, they develop into soft depressions which can then cause major damage during an erosive rainy season.

Deposition of eroded material

The deposition of eroded material was measured, and was related to the soil loss of the 1992/93 season. Soil was mainly eroded in the central and upper part of the slope in the fields, and was deposited at the bottom along the contour drain or silted up the contour drain (Figure 3). In 1992/93, 23·8 per cent of the eroded soil was identifiable as deposition in the field and in the contour drains (Table I). Some sand accumulated in a thin layer which could not be quantified, but most left the fields and the catchment because of broken or overflowing contour ridges and spilled into the gully at the valley bottom (Figure 4).

Small rills had higher deposition rates (41·4 per cent) than medium and larger rills (20–25 per cent) (Table I). As they are more localised and often remain limited to one field, they contribute to a more limited translocation of material. Generally the occurrence of depositions relates closely to the morphology of the fields.

Areas where the accumulation of eroded material (mainly infertile sand, with organic matter <0·15 per cent) reached a measurable thickness were classified as damaged areas, and resulted in stunted plant growth. Fine material and organic matter were mostly transported out of the fields in suspension in surface runoff, except in cases where water retention in pools led to an accumulation of highly fertile soil.

Origins and processes of rill formation

The prime causes of rill erosion damage, which were identified during damage mapping, fell into three major categories: (a) influx of water from outside; (b) non-effective contour ridges/drains; (c) concentrated runoff flow within the field.

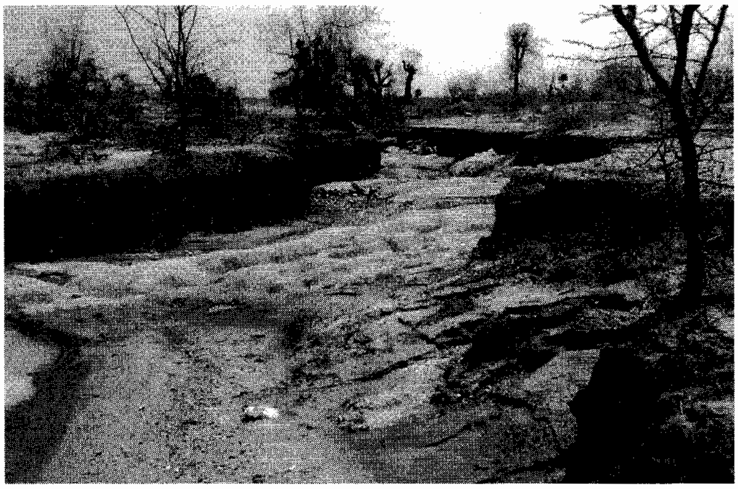

Figure 4. The gully at the valley bottom (bottom right in Figure 3) with excavated rocks and sand depositions

Table II. Soil loss and damaged area caused by the three primary causes of rill erosion

Primary causes	Rills		Soil loss		Damaged area	
	No.	%	t	%	m^2	%
Non-effective contour layout	72	53·7	909·6	70·0	8349	65·0
Influx from roads/waterways	26	19·4	328·9	25·3	3492	27·2
In-field concentration of runoff	36	26·9	60·5	4·7	1000	7·8
Total	134	100·0	1299·0	100·0	12841	100·0

(a) Water influx from outside occurred mainly along badly maintained artificial waterways and along roads/footpaths. These concentrated the water, which then broke into the fields and formed a sequence of rills and depositions down-slope. Three such rill systems are seen in Figure 3. One rill system with two large branches was caused by a road/wide path along the watershed (top of Figure 3). The second one (indicated by the top arrow in the series of three, to the right in Figure 3) was caused by water flowing from a waterway onto a footpath and then into the field. The third major rill system is below the second one where water broke in from the waterway into the field (the two lower arrows). A dynamic cascade was created, whereby the influx of water and eroded soil filled up the next contour drain, formed a triangular deposition fan, and finally overflowed and broke into the next lower field, where the process was repeated. Even if the contour drain had been in good condition and regularly maintained, a single storm could silt it up again and create the described dynamic. This category consisted of 26 rills (19·4 per cent) which caused 25 per cent of the total soil loss and 27 per cent of the total area damaged (Table II). Due to the often continuous influx over many years, 76·9 per cent of these rills are medium or large. Apart from roads and footpaths, silted waterways are one of the major reasons for the break-in of water.

(b) The category of non-effective contour layouts comprises broken or overflowing contour ridges owing to incorrect layout on the slope, poor maintenance of the ridges, and contour drains which tend to silt up regularly. With 72 rills (53·7 per cent) falling into this category, causing 70 per cent of the total soil loss and 65 per cent of the damaged area, it is apparent that non-effective contour layouts are the major immediate cause of rill erosion. The severity of the damage is also reflected in the fact that 88·9 per cent of the rills in this category are medium or large rills which cannot be levelled easily by annual ox-plough

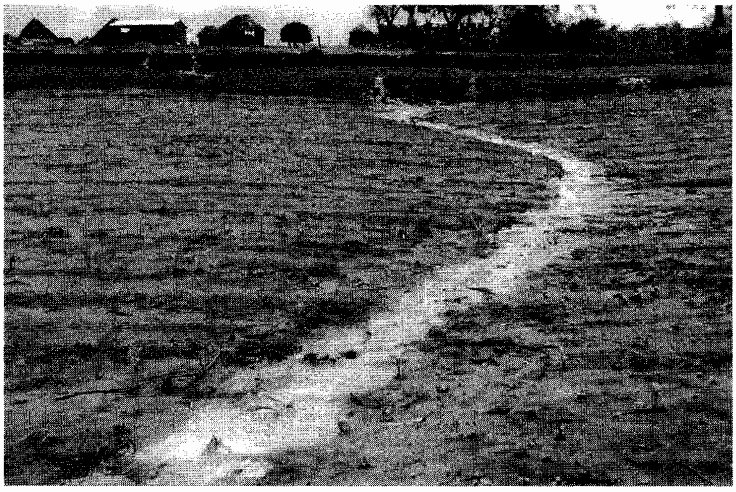

Figure 5. A cascade of overflowing contour ridges with subsequent rill formation during a rainstorm. The large depression developed over many years through annual ploughing across the rill

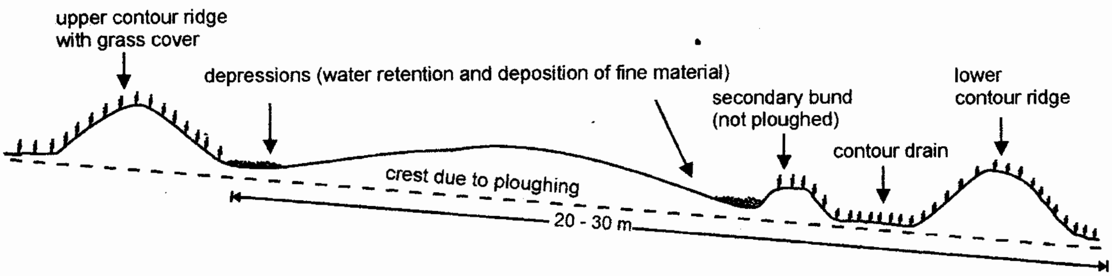

Figure 6. Morphology of the fields after continuous ploughing towards the centre of the field (gathering)

tillage, and which will develop into larger depressions which then further encourages their expansion (Figure 5).

(c) The origin of the third category (runoff concentration in the fields) is solely surface runoff, sheet erosion and related tillage, as water from surface runoff is concentrated in depressions. These are often caused by continuously ploughing across the slope, throwing the soil towards the centre of the field. With time, this ploughing practice (gathering) changes the morphology of the field. A 'plough crest' is formed in the centre of the field, leaving a depression on either side. This also results in the formation of a bund before the actual contour drain at the downslope field margin (Figure 6), as farmers do not plough in the drain but leave some space between the drain and the cropped area. The two depressions, the one above the plough crest in particular, and the one above the contour drain, act like water-retention basins where fertile, fine material is deposited. Except during heavy storms, this morphology results in water retention and can be considered to be positive. However, serious damage can occur during heavy storms with substantial surface runoff, when the water in the basin spills out and cuts rills into the crest. Runoff concentration in the field was the prime origin of 36 rills (26·9 per cent), but caused only 4·7 per cent of the total soil loss and 7·8 per cent of the damaged area. The majority of those rills (66·7 per cent) were small rills which were mainly induced during the 1992/93 rainy season. Compared with the other two categories, the effect of water concentration in the field on rill erosion damage appears to be minor (Figure 7).

The above three categories classify the prime causes of rills in as far as the methodology allows for

Figure 7. A second bund above the contour ridge creates a retention basin and prevents water and fine material from flowing straight into the contour drain

separation of different effects. Often, however, several factors can interact and reinforce each other. This applies, for example, to the overflowing of contour ridges, when a plough crest downslope further concentrates the overflowing water and thus causes a large rill when it spills over. As primary and secondary causes of rill formation, plough crests/field morphology influenced 35·8 per cent of the rills. Including the influx from roads and waterways, which are part of the mechanical conservation measures set up in the 1950s, 73·1 per cent of the rills are primarily influenced by these structures, causing 95·3 per cent of the soil loss. Broken or overflowing contour ridges played a role in 87 rills (64·9 per cent). Of these, breaking of contour ridges occurred in only 16 cases (18·3 per cent) and was mainly limited to the newly dug ridges which were not yet fully stabilised (Figure 3). This highlights the stability of old contour ridges.

Influence of different tillage practices

Another factor which directly influenced rill erosion in 1992/93 was tillage. Four different tillage techniques were practised in the catchment in that season: (1) ripping into bare ground to open a planting furrow; (2) mouldboard ploughing to a depth of 100–120 mm by oxen or donkeys; (3) hand-hoeing (no primary tillage, planting by hoe); (4) tied-ridging with ridges spaced about 800–900 mm apart, 140–200 mm in height and cross-tied in the furrows at intervals of 2–3 m, which is similar to 'no-till tied-riding' (Elwell and Norton, 1988). For an assessment of the influence of different tillage practices, which varies from year to year, only the soil loss attributed to 1992/93 is considered (Table III). It is evident that tillage effects are interacting with other effects such as plough crest or overtopping contour ridges. However, while excluding from the analysis of tillage practices all rills with very strong outside influences, such as broken bunds or influx from roads and waterways, and considering that the tillage treatments were distributed in the whole catchment and on different slopes, the figures do provide a good indication of tillage effects.

By far the highest soil loss and damage in terms of area were recorded from the ripping technique (1) where furrows were opened; bottom right in Figure 3. If the riplines, which look like furrows, were opened before planting they acted as a drainage system. Water from numerous furrows was drained and flowed towards the numerous depressions which then, owing to the concentrated flow, developed into severe rills during the season. This process deepened the furrows and extended the damage towards both sides of the rill. As the field above was under tied-ridging which stopped surface runoff, hardly any over-

Table III. Effect of different tillage techniques on rill erosion (erosion due to break-in of water excluded)

Tillage system	Area (ha)	No. of rills	Soil loss 92/93 ($t\ ha^{-1}$)	Damaged area[a] ($m^2\ ha^{-1}$)	Rill density ($m\ ha^{-1}$)
Ripping	0·79	13	113·9	1402	386·7
Ploughing	4·74	29	37·1	643	155·3
Hand hoe	5·73	56	35·2	486	176·1
Tied-ridging	0·51	1	1·8	20	19·6

[a] Only rill damage considered.

flow into the ripping field occurred, except into the rills which were excluded from the analysis. Therefore, a soil loss of 114 $t\ ha^{-1}$ as a ripping effect appears very realistic.

Rill erosion on ploughing (2) and hand-hoeing (3) tillage practices appear to be similar. Soil loss of approximately 35–37 $t\ ha^{-1}$ in the 1992/93 rainy season as a result of these tillage practices appears realistic. The number of rills under hand-hoeing is higher, but their length and width are less than under ploughing. Therefore, the rill density ($m\ ha^{-1}$) is only slightly higher under hand-hoeing. Visual observations during the season revealed high sheet erosion in the form of flushing from the hand-hoe practice in particular. On ploughed land, rills were formed by the removal of all loose soil down to the plough pan. Visual observation of one ploughed site at the beginning of the season showed that all loosened soil had been removed by sheet erosion. Therefore, the total soil loss, including sheet erosion, would be far higher.

Tied-ridging effectively protected the land from rill and sheet erosion, with less than 2 $t\ ha^{-1}$ soil loss in rolls. However, if all the rills in tied-ridging are considered, including those caused by breakthrough of contour ridges and influx from outside, 5·9 t had been eroded in the entire tied-ridging field area. The total accumulated material was 12·3 t, which implies that a net accumulation occurred. Visual observations also confirmed that well-tied ridges were able to stop rills caused by break-in of water. The water and eroded material spilled into the furrows, which provided a retention volume (Figure 8).

Decline of productivity

The major direct impact of rill erosion on productivity is a reduction in the area of productive land through rill damage and sand depositions. This reduction was 10·2 per cent of the arable land in the catchment area. Assuming an estimated decrease in yield of 60 per cent on the damaged area, the total

Figure 8. Tied-ridging retains water in the furrow basins during a rainstorm and reduces runoff and soil loss

productivity of the catchment would have decreased by 6·1 per cent through rill erosion. Indirect impacts such as increased runoff and sheet erosion due to depressions, etc., are difficult to quantify.

DISCUSSION

The results of the erosion damage mapping showed that despite mechanical conservation using contour ridges, rampant rill erosion is degrading considerable areas (over 10 per cent) of arable land through soil loss and deposition of infertile sand. The measured rates of soil loss in rills (59 t ha^{-1} in 1992/93) are higher than those estimated by Elwell (1983) for sheet erosion in communal areas (50 t ha^{-1} $year^{-1}$). Most of the soil was lost in large and some medium-size rills, mainly during a few highly erosive storms at the onset of the rainy season.

Impact of one extremely erosive season

The extent of the damage in one highly erosive year such as 1992/93, compared with the cumulative damage projected back to about 1950, suggests that over several decades very few years when conditions cause severe erosion result in most of the overall damage (see Table I). According to these observations, the years following severe droughts, during which communal grazing eliminates litter and vegetative cover, provide the most favourable conditions for soil erosion and land degradation in general. This was the case in 1992/93, when no soil cover was left and the bare soil was exposed to erosive rains at the onset of the season. Since 1950 there have been two other significant drought years, 1966 and 1983. According to farmers in the area, however, erosion damage in these years was not as bad as in 1992/93 because more vegetative cover remained. Therefore, it is apparent that overall land degradation, such as occurred in Zaka, is not a gradual process, but that degradation levels sometimes change abruptly for the worse. Only in the period between such devastating years are erosion and degradation very gradual, and hardly measurable or noticeable. The frequency of such devastating years depends on climatic conditions and on human and livestock population pressure. As devastating droughts also cause a drastic drop in livestock populations, one would assume that the land would have time to regenerate. In Zaka, however, the reduced animal population, with its lower demand for grazing land, caused a change of use from grazing land into arable land, which made the system even more vulnerable during the next drought years. If the frequency of devastating years increases in future, their impact could be disastrous.

Effect of the technical design and implementation of the conservation layout

Conservation measures should be designed and maintained to provide adequate safety levels in the most critical years, a criterion which was not fulfilled in the catchment near Jerera, where the overflow of contour ridges actually turned out to be the immediate origin of most rills. The analysis showed that part of their ineffectiveness was due to poor horizontal pegging when they were implemented, poor maintenance and siltation of the drains at sites where rills ended, causing overflowing or breaking of the ridge. Overflowing was a general feature, but only a few, mainly newly dug, contour ridges broke. This shows the stability of old ridges, which is provided by the root systems of grasses and bushes even when there is no aboveground biomass. Once one contour ridge broke or overflowed, it caused the progressive failure of others lower down the slope, in particular when an influx of water from outside occurred, a feature also observed by Hudson (1992). The influx of water from roads and waterways, which caused considerable damage, is clearly due to lack of maintenance of the contour layout. It turned out that individually owned contour ridges within the fields are often better maintained than waterways, which are a common responsibility.

The analysis also showed that in many cases sheet erosion is so high that even with perfect maintenance, contour ridges would not be able to protect the land from rill erosion. This indicates that they might be inappropriate in certain conditions, and gives an indication of their origin. They were designed for large-scale mechanised farms in high rainfall areas, and not for small-scale subsistence farmers (Hudson, 1992) in semi-arid areas. Because implementation of this system was enforced by law, communal farmers could not reject the imposed water-draining design which in their view was inappropriate (Hagmann and Murwira, 1995). They adapted it as much as possible within the legal framework to create water-retention volumes. Farmers willingly adjusted the system to partly suit their needs as a water-harvesting system, providing them with an increase in productivity at the bottom of the field where the moisture availability was higher and the fertility was improved through the deposition of fine material. This modification was not able to stop overflowing of the contour ridges under all circumstances because the horizontal pegging errors, etc., were not rectified, but without the creation of retention volumes by farmers, more water would have flowed out in peak periods and might have caused even more damage. This widespread modification (89 per cent according to Hagmann and Murwira, 1995) is the evidence of farmers' rationale.

A survey of the contour layout by Hagmann and Murwira (1995) showed that the results of the damage mapping for communal farms in Zaka District and in a similar natural region in the southern part of Masvingo Province are representative of the overall situation. Out of 115 fields, the conservation layout provided effective rill-erosion control in only 23 per cent of the area. This confirmed that ineffective contour layouts which induce rill erosion are a widespread phenomenon, and that protection by contour ridges does not always guarantee reduced soil erosion, a fact also reported by Whitlow (1988).

Effects of different tillage techniques

Tillage had a substantial influence on rill erosion. Ripping to open furrows, often recommended as a water-harvesting method, caused excessive rill erosion when applied in fields with depressions. Regarding sheet erosion measured on-station, ripping into bare ground can reduce runoff and soil loss when compared with annual ploughing (Chuma and Hagmann, 1995). However, these experiments were carried out only on-station in levelled fields without any depressions or rills. Owing to its vulnerability to rill-erosion, ripping can only be recommended if furrows are opened only after the first rains for planting and are covered immediately thereafter, or when furrows are being tied with cross-dams. However, minimal sheet erosion rates were achieved in on-station experiments in even fields where ripping was applied in combination with a stover mulch cover, called 'mulch ripping' (Vogel, 1994). According to some recommendations, no-till tied-ridging (Elwell and Norton, 1988) should only be applied in even fields. In this study, however, despite uneven terrain and break-in of water from outside, this system was able to slow down rill erosion. This can only work with cross-ties. Without ties the same danger of rill erosion exists as in ripping. Measurements confirmed that ploughing as well as hand-hoeing into bare ground, which is also called 'zero-tillage', are not sustainable in terms of rill erosion.

Impacts on productivity

Looking at the reduction in productivity of the whole catchment due to rill erosion, the impact appears less spectacular than the visual damage. However, it must be taken seriously because the damaged area will increase considerably during an erosive rainy season, as happened in 1992/93. Furthermore, one cannot look at rill erosion as a single factor. Rill erosion is a result of surface runoff and sheet erosion, but at the same time it increases surface runoff through the deepening of rills/depressions. Increases in runoff and sheet erosion have a much higher impact on productivity than the loss of productive area through rills because they deprive the entire field area of fine material and organic matter. Measurements have shown higher levels of organic matter in the subsoil (150–300 mm; 0·51 per cent) than in the topsoil (0–150 mm; 0·35 per cent), which is a clear indication of this degradation process in these soils. The same process was identified in similar soils by Chuma (1993), who also found a rapid decrease in organic matter in the topsoil due to erosion after only 5 years of cultivation. Therefore, the overall impact of rill erosion on productivity must be considered as being far higher than that calculated on the basis of the damaged area alone.

Options for improving conservation

Following analysis of the processes identified in the erosion-damage mapping, rehabilitation measures must start with elimination of water influx from roads, waterways and footpaths as a basis for the effective application of any other conservation measures. A second step should be the construction of check-dams or vegetative barriers in large rills to retain eroded soil and gradually level up some of the depressions. Unless these rills are reclaimed, they will continue to expand and other conservation methods will not be effective. Rill erosion is part of a process which starts with surface runoff and sheet erosion (the root causes of rill erosion). Therefore, techniques to reduce erosion must opt for maximisation of rainwater infiltration into the soil at the place where it occurs. In well-drained sandy soils under semi-arid conditions, maximal infiltration can be achieved if large enough retention volumes are created or when adequate soil cover increases infiltration, which is an argument for mulching.

There are two basic options to increase water retention: (1) contour parallel or slightly graded structures (mechanical and biological) such as fanja-juus, retention bunds, stone bunds and terraces, grass strips, hedgerows, etc., which are designed for that purpose (see, for example, Hurni, 1986; Critchley, 1991; Critchley, *et al.*, 1994); (2) conservation tillage through the creation of basins, as in tied-ridging or planting pits (Critchley, *et al.*, 1994), and by encouraging water retention and increased infiltration by using crop residues in mulching and strip-cropping systems (Elwell, 1993) in which agronomic measures are integrated. A combination of contour structures and conservation tillage would be ideal and offer the highest chances for efficient soil and water conservation.

Farmers' modifications to the contour layout, i.e. the creation of water-retention basins through ploughing, resemble the fanja-juu system (Wenner, 1988), except that there is no effective drainage of the water overflowing the contour ridge and the fertile land occupied by the contour drain is not utilised for cropping and is a net loss for the farmers. Had farmers been involved in the design of soil and water conservation measures, they might have come up with a system similar to the fanja-juu which supported their need to keep the water in the fields instead of draining it out through contour drains. This should be rectified in the future.

The second option to increase water infiltration, conservation tillage system such as 'no-till tied-riding' and 'mulch-ripping', has been tested in Zimbabwe. In on-station experiments where the fields were level and management was good, these two tillage techniques reduced surface runoff and soil loss to very low levels (Vogel, 1994; Chuma and Hagmann, 1995). The soil cover in mulch-ripping resulted in another positive effect in the form of higher levels of organic matter in the soil (Chuma, 1993), a factor which is also important for water infiltration. In on-farm trials both techniques also performed well in terms of soil and water conservation, but experience showed that they can only be efficient if the mechanical conservation system is functional. As long as break-ins of water occur, their success is limited. The application of a mulch is limited to areas with few cattle, as communal grazing regulations allow anybody to let their cattle graze residues left on the field.

Other conservation tillage and soil and water conservation methods were also tested (see, for example, Willocks and Twomlow, 1993; Vogel, 1994; Chuma and Hagmann, 1995) and showed considerable potential to contribute to effective soil and water conservation. It is most important that all these techniques are tested and developed in consultation with the farmers, who will then adapt them to their own site, situation and specific conditions. The importance of farmers' indigenous knowledge and practices, which should be taken as a basis for the joint development of soil and water conservation systems, is often stressed (see, for example, Critchley, *et al.*, 1994; Hagmann and Murwira, 1995).

CONCLUSION AND RECOMMENDATIONS

This study has shown that the performance of the present contour layout, consisting of contour ridges, drains and waterways, is inadequate to control rill erosion effectively, although that is the purpose for which it was built. In many cases contour ridges were a major factor contributing to accelerated rill erosion through the concentration of water. Several factors contributed to their failure. Firstly, the technology was imposed on the users (smallholder farmers) as a ready-made and non-modifiable package. Despite the fact that farmers considered the design to be inappropriate for semi-arid areas, their knowledge and opinion was not taken into account in the design of the contour ridges. They were not even allowed to modify the design. Had farmers been involved in the development of the technology, they might have opted for a system which retained the water in the fields instead of draining it away. Secondly, promotion of an isolated measure such as the contour system could not possibly succeed in controlling rill erosion effectively without controlling surface runoff and sheet erosion as well. This would have required a combination of various soil and water conservation techniques. Thirdly, the approach of enforcing the technology caused poor implementation and maintenance, particularly as soon as the pressure was released. Farmers obviously never identified with contour ridges and saw them mainly as a colonial measure for oppression (Hagmann and Murwira, 1995). According to older farmers, even before enforcement by law they were told to dig standardised contour ridges, but an awareness and understanding of soil erosion processes, which is necessary for good management, was not shown.

These facts are of great importance, as effective control of rill erosion is a pre-requisite for optimal implementation of improved land management systems such as conservation tillage. It was also revealed that the contour system has produced areas where fertile soil has accumulated and which have higher productivity potential, but which are not optimally utilised. Therefore, instead of promoting isolated conservation or production techniques, an integrated approach to land husbandry must be developed and promoted which allows intensive use of these fertile areas to improve crop production and sustainable management of natural resources. The basis for such a land-husbandry approach must be a thorough understanding of the causes and impacts of land degradation, and of a range of technical options to help the land users to combat it. This knowledge has to be built up in a process of learning by doing, e.g. farmers experimenting on their fields assisted by extension, as shown by Hagmann and Murwira (1995). This stresses the necessity for research and extension to develop and test other conservation options together with the implementers, the farmers. These approaches should focus on cheap, simple and flexible agronomic, biological and mechanical options.

One of the lessons learnt from this study is that contour ridges, which were implemented in good faith as a cure for rill erosion, have become a cause of such erosion. This example showed that practising a conservation method which was promoted as a generalised extension message does not automatically mean effective erosion control (even if standards are kept up). Therefore, it is necessary to set indicators for the success of soil and water conservation per se by farmers, researchers and extension workers. Extension work would not then be evaluated in terms of the number of farmers who adopted a certain technique, but, for example, in terms of the number of fields which are well conserved, by whatever techniques.

In practical terms in the Zimbabwean context, the following methods are suggested as options for testing and development in participation with farmers.

- To improve the existing mechanical conservation system, rill and gully reclamation with stone bunds, the use of vetiver grass strips, and the gradual conversion of contour ridges into the *fanja-juu* system (see Hagmann, 1994) appears promising.
- For land husbandry, the following steps are proposed, and should be further developed or adapted to specific local conditions in collaboration with farmers.

1. Concentration of all extra effort for improvement and conservation on one field at a time.
2. Elimination of destructive inflow of water from roads and waterways.
3. Reclamation of rills/depressions by putting in check-dams, stone bunds and vetiver grass strips in order to retain eroded material in the field, which will gradually level the rills.
4. Maintenance of contour ridges in places where they overflow, building up the ridge and/or stabilising it with vetiver grass where necessary.
5. Depending on available resources, conversion of contour ridges into *fanja-juus*; planting of fruit and fodder trees on the ridges and in the drains in order to make maximum use of the land.
6. Application of fertilising material such as manure, compost, termitaria, leaf litter and other organic material to the field in large quantities if possible; deep tillage to break existing plough pans and to incorporate fertilising materials; application of conservation tillage (if possible mulching, otherwise tied-ridging) in order to conserve the applied nutrients.
7. After the *fanja-juu* is operational and the field conserved, the former contour drain, which will be

very fertile, can be planted to crops, resulting in an increase of arable land and yields (which will be much higher on the strip where the drain was). This will be a direct pay-off for the conservation effort in the first year.

8. Repetition of this procedure in all other fields. Crop rotation should be practised as far as possible; green manure, intercropping with legumes and other agronomic measures beneficial to an optimal crop management should be practised.

This approach would overcome the dilemma of conventional soil conservation efforts, as they only benefit the farmer in the long term. The combination of soil conservation with soil improvement and good crop management methods generates a benefit in the first year and motivates farmers to continue. With the knowledge gained, farmers would be able to choose the best management practice for a certain piece of land with its specific soil and site conditions, as they know their land best.

The Zimbabwean example shows that technologies such as contour ridges, which originate in the paradigm of the superiority of 'modern', Western technology-based models, cannot simply be transferred to and imposed on other cultures. This paradigm has to give way to the fact that only the land users themselves can develop and implement sustainable resource management systems. Innovations are required, but should be based on a synthesis of old, traditional practices and new ideas.

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REFERENCES

Anderson, I.P., Brinn, P.J., Moyo, M. and Nyamanza, B. 1993. *Physical resource inventory of the communal lands in Zimbabwe – an overview*, NRI Bulletin No. 60, Natural Resources Institute, Chatham.

Chuma, E. 1993. Effects of tillage on erosion-related soil properties of a sandy soil in semi-arid Zimbabwe, pp. 319–330 *in* M. Kronen (ed.) *Proceedings of the Fourth Annual Scientific Conference, 5–7 October 1992*, SADC Land and Water Management Research Programme, SACCAR, Gaborone, Botswana.

Chuma, E. and Hagmann, J. 1995. Summary of results and experiences of on-station and on-farm testing and development of conservation tillage systems in semi-arid Masvingo, pp. 41–60 *in* S. Twomlow, J. Ellis-Jones, J. Hagmann and H. Loos (eds.) *Soil and Water Conservation for Smallholder Farmers in Semi-arid Zimbabwe*, Proceedings of a technical workshop, 3–7 April 1995, Masvingo, Belmont Press, Masvingo, Zimbabwe.

Critchley, W.R.S. 1991. *Looking after our Land. Soil and Water Conservation in Dryland Africa*, Oxfam, Oxford.

Critchley, W.R.S., Reij, C. and Willcocks, T.J. 1994. 'Indigenous soil and water conservation: A review of the state of knowledge and prospects for building on traditions', *Land Degradation & Rehabilitation*, **5**, 293–314.

CSO, 1992. *Census 1992*, Central Statistical Office, Harare.

DRSS, 1992. *Communal Land Physical Resource Inventory: Ndanga, Bikita, Matsai*, Department of Research and Specialist Services, Report No. 583, Harare.

Elwell, H.A. 1983. 'The degrading soil and water resources of the Communal Areas', *Zimbabwe Science News*, **17** (9/10), 145–147.

Elwell, H.A. 1984. Sheet erosion from arable lands in Zimbabwe: Prediction and control, pp. 429–437 *in Challenges in African Hydrology and Water Resources*, Proceedings of the Harare Symposium, July 1984, IAHS Publication No. 144.

Elwell, H.A. 1993. Development and adoption of conservation tillage practices in Zimbabwe, pp. 129–165 *in Soil Tillage in Africa: Needs and Challenges*, FAO Soil Bulletin No. 69, Rome.

Elwell, H.A. and Norton, A.J. 1988. *No-till Tied Ridging: A Recommended Sustained Crop Production System*, Department of Agricultural, Technical and Extension Services Handbook, Harare.

FAO, 1988. *Soil Map of the World. Revised Legend*, Food and Agricultural Organisation (FAO), Rome.

Hagmann, J. 1994. The fanja-juu system: An option for soil and water conservation in semi-arid Zimbabwe, Discussion Paper, Conservation Tillage Project, Institute of Agricultural Engineering, Department of Agricultural, Technical and Extension Services, Harare.

Hagmann, J. and Murwira, K. 1995. *Indigenous Soil and Water Conservation in Southern Zlmbabwe: A Study on Techniques, Historical Changes and Recent Developments under Participatory Research and Extension*, Project Research Report No. 13, Conservation Tillage Project, Institute of Agricultural Engineering, Department of Agricultural, Technical and Extension Services, Harare.

Herweg, K. 1988. 'Bodenerosion und Bodenkonservierung in der Toscana, Italien', *Physiogeographica, Basler Beiträge zur Physiogeographie*, Vol. 9, 169 pp.

Hudson, N. 1992. *Land Husbandry*, Batsford, London.

Hurni, H. 1986. *Soil Conservation in Ethiopia. Guidelines for Development Agents*, Community Forests and Soil Conservation Department, Ministry of Agriculture, Addis Ababa, Ethiopia.

Hussein, J. 1987. Agroclimatological analysis of growing seasons in natural regions III, IV and V of Zimbabwe, pp. 25–189 *in Cropping in the Semiarid Areas of ZImbabwe*, Proceedings of a workshop held in Harare, 24–28 August 1987, Department of Agricultural, Technical and Extension Services/GTZ/DRSS, Harare.

Schmitt, R.G. 1979. Probleme der Erfassung und Quantifizierung von Ausmass und Prozessen der aktuellen Bodenerosion (Abspülung) auf Ackerflächen. Methoden und ihre Anwendung in der Rheinschlinge zwischenl Rheinfelden und Wallbach (Schweiz), *Physiogeographica, Basler Beiträge zur Physiogeographie*, Vol. 1, 240 pp.

Stocking, M. 1972. 'Aspects of the role of man in erosion in Rhodesia', *Zambezia*, **2**(2), 1–10.

Vincent, V. and Thomas, R.G. 1960. *An Agricultural Survey of Southern Rhodesia. Part 1. Agro-ecological Survey*, Government Printer, Salisbury (now Harare).

Vogel, H. 1994. *Conservation Tillage in Zimbabwe: Evaluation of Several Techniques for the Development of Sustainable Crop Production Systems in Smallholder Farming*, African Studies Series A 11, Berne, 150 pp.

Wenner, C.G. 1988. The Kenyan model of soil conservation, pp. 197–206 *in* W.C. Moldenhauer and N.W. Hudson (eds.) *Conservation Farming on Steep Lands*, Soil and Water Conservation Society, Ankeny, IA.

Whitlow, R. 1988. *Land Degradation in Zimbabwe. A Geographical Study*, Department of Natural Resources, Harare.

Willcocks, T.J. and Twomlow, S.J. 1993. 'A review of tillage methods and soil and water conservation in southern Africa', *Soil and Tillage Research*, **27**, 73–94.