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AN ASSESSMENT OF THE DOMINANT SOIL DEGRADATION PROCESSES IN THE ETHIOPIAN HIGHLANDS - THEIR IMPACTS AND HAZARDS

PREPARED BY THE JOINT ECA/FAO AGRICULTURE DIVISION FOR THE ETHIOPIAN HIGHLANDS RECLAMATION STUDY - UTF/ETH/037/ETH

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1. PREFACE

1.1 Terms of reference

The Consultant originally accepted a one-month consultancy to "undertake a macro-economic survey of the highlands of Ethiopia, and to propose solutions for land resource management and land use planning problems". Subsequently, substantive changes were made to the terms of reference and the consultancy was extended up to 29 February 1984.

The revised terms of reference were:

(a) To assess the nature, causes and relative importance of soil degradation processes in the Ethiopian Highlands;

(b) To provide data on projected changes in soil fertility due to continued soil degradation that would enable members of the Ethiopian Highlands Reclamation Study (UTF/ETH/037) to predict changes in land productivity and hence the economic costs of soil degradation;

(c) To assess the hazards of the dominant soil degradation processes in terms of their impacts on soil fertility.

1.2 Constraints encountered

The major constraint experienced by the consultant was the very considerable time devoted to cartographic work, i.e. in the preparation and checking of draft maps and the checking of corrections. Twelve maps were produced to show the distribution of soils, erosion rates, hazards and soil fertility characteristics within the Ethiopian Highlands. This consumed the major part of the consultant's time, notwithstanding the hard working assistance of the cartographers in the Land Use Planning and Regulatory Department of the Ministry of Agriculture, Addis Ababa. A further constraint was the paucity of basic soils data available and the time spent in acquiring and compiling the limited information that did exist.

1.3 Emphasis of the study

It soon became apparent that soil degradation in the Ethiopian Highlands may be posing a threat not only in terms of the physical loss of soils, but also in terms of deteriorating soil chemical fertility. This study has therefore emphasised both the physical and chemical deterioration of soils due to degradation.

2. THE NATURE, CAUSES AND RELATIVE IMPORTANCE OF SOIL DEGRADATION PROCESSES IN IN THE EHTIOPIAN HIGHLANDS

Degradation refers to a deterioration in the quality of the environment for man, vegetation, animals and aquatic life. Soil degradation may be manifested by a reduction in the actual or potential productivity of soil to produce food, fodder, fibre, building materials and fuel. It can also lead to a lowering of the quantity and quality of domestic, livestock and irrigation water supplies, a decrease in hydroelectricity power generation and to a deterioration of habitats for aquatic and other forms of wildlife.

There are a wide range of soil degradation processes, some of which are closely interrelated, which have been classified into six categories (FAO, 1979). These are water erosion, wind erosion, salinisation and alkalisation, chemical degradation, physical degradation and biological degradation. The causes of these processes are invariably a combination of natural phenomena and man's actions such as the destruction of vegetation cover, overgrazing and inappropriate agricultural practices that are not in harmony with the ecological environment. It is man's actions, often as a result of increasing population pressure, that extend and accelerate the processes of degradation. Water erosion includes sheet, rill, gulley erosion and mass movements; salinisation and alkalisation refer to the accumulation of excess salts and sodium, and chemical degradation to the leaching and removal of nutrients and the build up of toxicities other than those due to excess salts. Physical degradation includes those processes such as poor cultivation practices, which adversely affect soil physical properties such as infiltration rate, structural stability, root penetrability, and permeability. Some of these processes which result in the exposure of the soil surface to rainfall are closely related to sheet and rill erosion. Biological degradation refers to processes which accelerate humus mineralisation rates, and largely reflects the moisture/temperature regimes of the environment and land use practices.

2.1 Salinisation and alkalisation processes

These processes become important in areas where evapotranspiration exceeds precipitation for much of the year resulting in the upward migration of salts from ground waters into the upper parts of the soil profile. The Ethiopian highlands are characterised by perhumid to semi-arid moisture regimes using Thornthwaite's moisture surplus - deficit index (Thornthewaite, 1955) as illustrated by Gamechu (1974). The semi-arid areas, in which salinisation and alkalisation most commonly occur, are of very limited extent in the highlands as shown by the restricted occurrence of salt rich soils e.g. solonchak, in the Lake Abiyata area (Fig. 4). Salinisation and alkalisation processes are relatively unimportant in the Ethiopian highlands.

2.2 Chemical degradation processes

Chemical degradation is mainly due to leaching and poor farming practices which result in the loss of nutrients and a concomitant increase in exchangeable Al, and sometimes Mn. Leaching will tend to be highest in the high rainfall regions of the highlands, i.e. in regions D and E (Fig. 11). The detrimental effects of leaching will also tend to be most serious in soils with a low cation exchange capacity,

since these soils possess a low reserve of available nutrients to replace those lost by leaching. Thus, sandy soils such as the Cambic Arenosols (Qc) and soils dominated by low organic matter contents and kaolinitic clays such as the dystric nitosols and orthic acrisols will be most prone to deterioration as a result of leaching. These soils belong to the generalised soil chemical fertility class 3b (see Table 10 and Fig. 5). As leaching coninues the soils become more acid, with more of the cation adsorption sites becoming occupied by exchangeable Al. Ultimately, the percentages Al saturation of the effective cation exchange capacity (ECEC) may become sufficiently high to cause the soil solution Al concentrations to reach toxic levels for some crops. The average soil chemical fertility values for the dystric nitosols are given in Appendix 6, class 3b (no data were obtained for the orthic Acrisols). The average top soil and sub-soil pH values are 4.9 and 4.5 respectively, and the average per cent Al saturation values of the ECEC are 3.5 per cent and 7.2 per cent respectively. These average values are unlikely to result in a decline in crop yields. However, in one of the profiles analysed (K4), the percentage Al saturation of the ECEC was 13.1 and 17.7 per cent for the top soil and sub-soil respectively (see Appendices 4 and 5). These values are sufficiently high to reduce the yields of Al sensitive crops such as sorghum and cotton for which the critical Al saturation values, beyond which yields rapidly decline, are 10 to 20 per cent and 10 per cent respectively. Barley and some wheat varieties are also particularly sensitive to aluminium toxicity (Krampath, 1972; Foy and Brown, 1964). More data is required on the Al and Mn saturation levels of the soils in class 3b before the impacts of chemical degradation due to leaching can be satisfactorily assessed.

Table 1

Nutrient removals by maize, wheat and sorghum

Crop	Grain Yield (t/ha.)	Nutrients removed (kg/ha)				
		N	P	K	Ca	Mg
Maize	1.0	40	9	33	7.5	5.0
Wheat	0.6	15	3.2	17	2.3	3.0
Sorghum	1.0	26	1.3	6	8.6	5.6

Total nutrients removed by grain + straw.

Source: Sanchez, 1976.

Chemical degradation can also be caused by poor farming systems which "mine" the soil, i.e. where there is a steady removal of nutrients with no, or only minimal, nutrient replacements. It is assumed in the following discussion that fertilisers are not applied, crop residues are largely removed for fodder, and that most of the dung is burnt as fuel. These practices are prevalent throughout much of the highlands and result in minimal quantities of nutrients being returned to the soils. The situation becomes aggravated where fallow periods are non-existent or very short. The soils in the Ethiopian highlands have been grouped into four generalised soil

chemical fertility classes (section 5.2) on the basis of the nature of their humic horizons, their base saturation, and whether or not they become seasonally waterlogged. Characteristics of the four classes are given in Table 10 and their distribution is shown in Fig. 5. The soils are generally moderate to well supplied in the nutrient bases, low to moderate in nitrogen and very low to low in phosphorus.

Typical nutrient removals by cereal crops are given in Table 1. When these values are compared with the estimated nutrient contents of the four generalised soil chemical fertility classes (given in Table 21 for N and K, and in Appendix 6 for Ca and Mg) there would appear to be sufficient K in the soils to satisfy crop requirements for at least 40 years, or 20 years for class 3a soils, and sufficient Ca and Mg to meet the crop demands for at least 100 years. Thus no problems of "mining" Ca, Mg or K are likely to arise in the near future.

For nitrogen the position is more difficult to assess, because only a small fraction, possibly 2 per cent, of the soil's total nitrogen will be released by mineralisation each year. Moreover only part of the mineralised nitrogen will be taken up by crops, the remainder being lost by immobilisation, leaching and denitrification. Furthermore, for soil chemical fertility classes 1 and 3b the total N values have been estimated by applying assumed C/N ratios to the organic carbon values (Appendix 6). Nevertheless, class 3a soils, characterised by ochric A horizons, with their low total N values would appear to be most susceptible to N "mining". If 2 per cent of the total N is assumed to be mineralised each year from the top 0-15 cm. of soil, then about 40 kg/ha/yr would be released from class 3a soils. This value is not dissimilar to the estimated N removal figures given in Table 1 for cereal crops. Chemical degradation due to a "mining" of soil nitrogen is likely to be most serious on class 3a soils, and the situation will be exacerbated in areas with no or very short fallow periods, where legumes are not a usual component of the crop rotation, where "gaye" i.e. the burning of mounds of top soil, and burning of the grasslands are regular practices. In the latter two processes nitrogen losses will be increased through volatilisation.

The situation with regard to phosphorus is even more difficult to assess because the quantities of available phosphorus present in the soils are unknown. The Olsen values given in Appendix 6 are merely indices of the available phosphorus levels and cannot be compared with the crop P removal values. However, there can be very little replenishment of the already very low to low available phosphorus levels in the soils except in areas with long fallow periods. Thus a strong possibility exists that chemical degradation due to the harvesting of phosphates in grain and straw is occurring, especially in areas with non-existent or very short fallow periods.

To assess the relative importance of nutrient mining in situations of minimal nutrient replenishments with nutrient losses due to sheet and rill erosion, the crop nutrient removal values given in Table 1 need to be compared with the soil nutrient erosion losses given in Table 23. The latter values have been very roughly estimated from the estimated sheet and rill erosion rates, the soil nutrient contents of the top soils of the four generalised soil chemical fertility classes (Appendix 6) and from the nutrient enrichment ratios (see section 7.4). A comparison of the two sets of figures shows the nutrient crop removals to be generally equivalent to the low to medium soil nutrient erosion rate classes,

and appreciably lower than the high to very high soil nutrient erosion rate classes. Thus the "mining" of soil nutrients will assume greater importance in areas where the losses of soil nutrients due to sheet and rill erosion are low.

2.3 Physical degradation processes

Physical degradation that results in surface sealing and crusting is a result of the exposure of the soil surface to the impact of rain drops. The surface aggregates of soils low in organic matter and high in silt contents are usually most prone to structural disintegration and the formation of surface seals or crusts. It is the infilling of pores and the orientation of soil particcls parallel to the surface that results in seal or crust development,1/ and the rather impervious nature of these surfaces encourages runoff. The enhanced runoff in turn accelerates erosion and thus the physical degradation processes of sealing/crusting and sheet and rill erosion are inextricably linked. Surface sealing and crusting will be most pronounced in areas where the storms are highly erosive, e.g. rainfall regimes E and D (Fig. 11), and especially on soils of low organic matter and high silt contents, e.g. class, 3a soils (Fig. 5). Crusting indices have been calculated for four soil types (Appendices 1, 2, and 3) using the formula:

$$\text{Crusting Index} = \frac{\%\ \text{Silt Content}}{(\%\ \text{Clay} + 10.\ \%\ \text{OM})}$$

which is a simplification of the formula given in "A provisional methodology for soil degradation assessment", (page 18, FAO, 1979). The relationship between crusting indices and crusting susceptibility ratings are given in Table 2 and the estimated crusting susceptibility ratings for four soils, for which at least four profile data were available, are given in Table 3. The entric Cambisols and chromic Luvisols both exhibit medium crusting susceptibilities and are dominant soil units within the soil chemical fertility class 3a which is generally characterised by ochric (low organic matter) top soils. As the increased runoff causes further sheet and rill erosion, it will be the finer, more nutrient-rich, more humic soil fraction which is preferentially eroded. Consequently, the organic matter of the surface soil will decrease and the relative proportion of the coarse silt and sand may increase. Thus, the soils will progressively become increasingly susceptible to surface crusting. Farming practices which reduce the protective vegetative cover of the soil surface such as overgrazing, annual crops which give a low ground cover, and late planting will all be conducive to sealing and crusting. In addition to promoting runoff, surface crusts can inhibit or reduce sealing emergance during dry periods and may reduce the supply of oxygen to plant roots during wet periods.

The loss of runoff can seriously reduce crop yields especially in areas where water is an important factor limiting yields. This would be most likely to occur during some years in rainfall regimes E and D (Fig. 11). Stewart (pers. comm.) showed for an area of high moisture deficit probabilities in Kenya, that for evey extra mm. of water infiltrating into the soil, that is not lost as runoff, the grain

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1/ Seals are generally very thin and composed of compacted clay particles whereas crusts are generally ticker and with higher silt and sand contents.

Table 2

Relationships between crusting index and crusting susceptibility ratings

Crusting index	Crusting susceptibility rating
0-0.2	Very low
0.2-0.5	Low
0.5-1.0	Medium
1.0-2.0	High
2.0	Very high

Table 3

Crusting susceptibility ratings for top soil and sub-soil horizons of selected soil types (first approximation)

Soil Unit 1/	Top soil (0-15cm) 2/	Sub-soil (15-50cm) 2/
	Crusting susceptibility rating 3/	Crusting susceptibility rating 3/
Chromic Luvisols	Medium	Medium
Eutric Cambisols	Medium	High
Dystric Nitosols	Low	Low
Pellic and Chromic Vertisols	Low to Medium	Low

1/ Classified according to the legend of the Soil Map of the World (FAO, UNESCO, 1974).

2/ Average values

3/ Refer to Appendices 1-3 for derivation of crusting idices.

yield of maize was increased by 16 kg. Marked yield increases due to the prevention of runoff have also been demonstrated for maize and sorghum on the Alemaya soil series in the Hararghe highlands from tied-ridging experiments (Tamirie Hawando, 1983). Table 4 gives the mean percentage yield increases obtained with and without tied ridges for the two seasons 1981, 1982 from N and P fertiliser trials.

Table 4

Influence of tied ridging on sorghum and maize grain yields

Average yield increase due to tied ridges (%)			
Maize		Sorghum	
1981	1982	1981	1982
36.4	20.7	16.8	18.4

Values are the average yields of all the nitrogen treatments.

Maize which is much more sensitive to moisture stress than sorghum gave higher yield increases when runoff was prevented by the construction of tied ridges, especially in 1981. Unfortunately, it was not possible to relate the yield differences to runoff losses.

Physical degradation can also be brought about by the traffic of animals and humans causing surface compaction. Livestock can compact soils at a pressure of 1-2 kg/cm^2 or more; the static load of a sheep is approximately 0.5 kg/cm^2 and for cattle and horses about 1.75 kg/cm^2 (Wenner, 1982). Presumably the dynamic pressures would be higher. As a result of surface compaction, particularly along cattle tracks and footpaths, the increased runoff is likely to accelerate erosion resulting particularly in the formation of gullies.

The deterioration of soil structures due to untimely or excessive tillage is another example of physical degradation. The vertisols, sometimes called "afternoon soils" because of the very short time periods during which they can be successfully cultivated, are particularly prone to structural deterioration which further impairs their already unfavourable structural and drainage characteristics. The excessive number of cultivations required to produce a very fine tilth that will permit an adequate soil-seed contact for the very small teff seeds is a further example of structural or physical degradation. Up to six cultivations are often needed to prepare a suitable seed-bed and the fine tilth is then far more susceptible to crusting, runoff and erosion.

2.4 Biological degradation processes

Biological degradation processes resulting in a decline in soil humus contents through mineralisation are primarily governed by temperature and soil moisture conditions. The soil type, form of land use - particularly the extent to which the land surface is covered by crops throughout the year, and the fate of the crop residues and dung are also important factors. The risks of biological degradation will be greatest at low altitudes, where temperatures are higher and rainfall lower, and will probably correspond approximately to rainfall regimes A and B in Fig. 11. The rates of humus mineralisation will be highest in sandy soils, e.g. in the cambic Arenosols, low in the clay textured soils, and least in the rendzinas due to their high $CaCO_3$ content and in the Andosols due to their allophanic clays (Fig. 4). Low mineralisation rates will also be expected in the vertic Cambisols and the pellic and chromic Vertisols, particularly when they occur in the high rainfall areas - regions D and E, because of their impeded drainage characteristics reducing mineralisation rates. Birch (1970, 1971) showed that under saturated conditions no nitrification i.e. mineralisation occurred in vertisols for long periods of the growing season.

Land use is another factor influencing biological degradation. Loss of humus will be more pronounced in annual cropping areas where the soil surface is exposed for long periods, than under perennial crops which shade the soils and maintain soil moisture/temperature conditions less conducive to mineralisation. In much of the highlands, and particularly in the low to middle altitude/low to moderate rainfall areas, a steady decline in humus contents would be expected because of the use of crop residues for livestock and the use of most of the dung for fuel. However, the author knows of no evidence to substantiate this. Although Jahnke (1984) claims that in monetary terms, the value of the crop yield increase by applying dung to the land is at present approximately equal to the monetary value of dung as a fuel, this economic balance is unlikely to be maintained as the soils become more impoverished. Thus, the absolute yield increase from the application of dung to an impoverished soil will be lower than the yield increase from a less impoverished soil. Moreover, as yields decline, and farmers in the Kura Marian - Ankobar area claim yield reductions in teff from about 9q/ha. to 4.5q/ha. during the last 20 years, so the quantity of organic matter added to the soil in terms of roots and any stubble that remains, will decrease. Hence, the situation will be further exacerbated. Added to this is the decreasing fallow period which for example is now 1-2 years in the Arsi region compared to 4-5 years in the past (Gujral, 1979). In other areas fallow periods are not possible and consequently soils have less opportunity to replenish their humus contents. The progressive shortening of fallow periods is a response to the increase in population pressure. Yet another process of biological degradation is the practice of "gaye" in which the top soil is gathered into small mounds, mixed with small quantities (about 10 per cent) of grass, Erica and dung, and ignited. Although not all of the organic matter will be volatilised, there is undoubtedly a significant decrease in humus contents as a result of this practice. This practice is apparently quite widespread throughout the highlands. Burning of grasslands also promotes biological degradation through the volatilisation of organic matter. The consequences of biological degradation are a loss of nutrients, i.e. N and S in particular, and a decline in the soils' structural stabilities. Consequently, the soils become

more susceptible to physical degradation and to erosion. Most of the soils in the Ethiopian highlands contain moderate levels of organic matter, and are often characterised by deep humic horizons. Biological degradation is probably only important at present in rainfall regimes A and B and in class 3a soil (Fig. 5) which generally possess low organic matter contents. Nevertheless, with the current farming practices, a general trend of declining humus contents would be expected.

2.5 Wind erosion processes

Although wind erosion is believed to occur to a limited extent in the highlands, up to altitudes as high as 3000m (Hurni, pers comm.) and in the north (Kebede Tatu, EHRS Meeting, 1983), no studies have been written on this subject to the author's knowledge. The lack of trees and low vegetative cover during the dry season would seem to be conducive to wind erosion, although Brown (1973) states that wind eroion occurs predominantly in the southern Rift Valley. Lack of data precludes further consideration of this degradation process.

2.6 Gulley erosion processes

Gulley erosion is an extension of the process of rill erosion and is commonly defined as a process that results in channels that are two large or deep to be obliterated by normal cultivation practices. Gulley erosion is caused in areas where there is a concentration of runoff, and the rate of gulley erosion is consequently related to the gulley's catchment area. Activities that result in the removal of vegetative cover, e.g. deforestation, cultivation and overgrazing expose the soil surface to the direct action of raindrops and encourage the development of surface seals or crusts, which in turn promote runoff. The removal of vegetation combined with compaction of the surface soil due to overgrazing has been cited as one of the major causes of gulley erosion in the Mojo River basin (Pereira, 1968), in the Awash River Basin (FAO, 1965), and even beneath a dense canopy of Eucalyptus forest in the heart of Asella township in Arsi Region (Gujral, 1979). Compaction of the soil surface from the traffic of animals and humans is also responsible for low infiltration, the concentration of runoff and gulley development. This, and the absence of proper road drainage systems have also caused extensive gulley erosion in the Arsi region (Gujral, 1979) and on Mt. Choke at elevations above 2,500m (Thomas, 1983).

Soil type also exerts a major influence on the development of gullies. Impermeability or sealing of the soil surface are conducive to gulley formation. Thus, vertisols which become impermeable when wet due to the swelling nature of their clays, and their frequent occurrence in lower slope or valley bottom positions where the greatest accumulation of runoff occurs, may be susceptible to gulley erosion. In Hararghe, gulleys 5 m deep and 20m wide have developed in cambisols and vertisols in lower slope positions during the last 20 years (Hurni, pers. comm.). The presence of very erodible subsoils or parent materials also encourages rapid gulley erosion. A comparison of 1965 and 1974 aerial photographs of the Makalle Palteau in the Tigrai region revealed a gulley head encroachment, in highly erodible alluvial sediments, of 5 – 10 m/year (Virgo and Munro, 1978). Heavily dissected gullied land has also developed in Andosols formed in very erodible Quatermary volcanic ashes and tuffs in the Soddo area, and in erodible soils formed from sandstones in the Harar region (Pereira, 1968). The relative top soils and

sub-soil erodibilities influence both the gulley cross-sectional profile and the rate of lateral erosion. This relationship was observed in the Awash River Basin Survey (FAO, 1965). Although there are reports of gulley erosion being particularly prominent in some parts of the highlands, e.g. the Makalle and Enticho plateaux in Tigrai region (Virgo and Munro, 1978) and in the Harar region (Pereira, 1968, Hurni, ers. comm.), there has been no systematic study of the extent and intensity of gulley erosion in the Ethiopian highlands. Although the quantities of soil lost by gulley erosion may sometimes contribute significantly to river sediment loads, it would appear from preliminary results of Hurni (1983b) and from limited data on suspended sediment load values within the Awash catchment (FAO, 1965), that a high proportion of the soil removed from hillslopes is deposited in lower slope and alluvial plain sites without entering the drainage system. Furthermore, the area of agricultural land that is lost through gulley erosion is invariably insignificant (Hudson, 1971), and there is no evidence to suppose that this is not the case in the Ethiopian highlands.

2.7 Mass movement processes

Mass movement processes refer to both the imperceptible soil creep processes and the more rapid and dramatic processes of landslides, earthflows and mudflows. The latter processes are most likely to occur in very high rainfall areas, probably corresponding to rainfall regimes D and E in Fig. 11, and in soils with high inflitration rates and impermeable horizons at depth: Soils with high clay contents, particularly those containing very high moisture contents at saturation are particularly prone to mass movement. This is particularly prevalent where the soil's moisture content at saturation exceeds the soil's liquid limit as has been shown for smectite soils in Europe, and for Andosols in high rainfall areas of the Kenyan highlands (Tefera, 1981 reported by Barber, 1982). Steep topographies and changes in land use from deep rooted (natural) vegetation to shallow rooting crops also promote mass movements. Mass movement processes are discontinuous in nature, occurring only infrequently and usually after several days of exceptionally heavy rainfall. Poorly constructed cut-off drains that do not discharge, and the construction of level bench terraces often aggravate the situation because of their tendency to increase soil water retention which greatly increases the downslope shear component of the saturated soil mass. Mass movement processes have been reported as prevalent in the Hosaina Butajira areas of S. Shewa region in Andosols where the annual rainfall exceeds 1500 mm, in the E. highlands in Harar (Hurni, pers. comm.) and in the Chefedonsa area within the Awash basin (FAO, 1965). It is unlikely, however, that mass movements are important in the Ethiopian highlands, in terms of either areal extent or river sediment load contributions.

2.8 Sheet and rill erosion processes

Sheet erosion (now often termed interrill erosion) and rill erosion describe the more or less uniform diminution of soil depth over a period of time from a given slope segment. During any one rainstorm, however, the distribution of soil loss is likely to be spatially hetrogeneous. Rill erosion is the precurser to gulley erosion, and is generally distinguished from the latter by the washes being readily obliterated during normal cultivation practices. In the absence of cultivation, the rills will steadily enlarge until gullies are formed. The dominant interrelated factors responsible for sheet and rill erosion are rainfall erosivity,

soil erodibility, topography, ground cover, land management practices and other support practices which influence soil conservation.

A rainfall erosivity map has been produced for Ethiopia as a 1:1,000,000 scale by LUPRD (1983) using a modification of Fournier's index. The map shows the highest annual erosivity classes occur in the high rainfall areas and the lowest erosivity classes in the low rainfall zones. Notwithstanding this, rain storms with the highest erosivity generally occur in the lower altitude, drier areas where rain storm intensities are frequently more than 30mm/h and often more than 100mm/h (Brown, 1973), with intensities as high as 140mm/h being recorded from the lower Awash (Pereira, 1968). This is also supported by a one year detailed rainfall intensity analysis carried out by Virgo and Munro (1978) in Tigrai, where the altitude is 2000-2800 m and the average annual rainfall 500 to 800 mm/yr. The results showed that precipitation was concentrated within three months, and 75 per cent of the storms were characterised by intensities of more than 25 mm/h - usually taken as the threshold value for erosive rainfall. Moreover, a similar percentage of the storms of high intensity occurred at the onset of the rainy season when cultivated areas were bare, or possessed a very low crop cover, and the grazing land was in its worst condition. Under such conditions, the soil surface lacks a protective cover to dissipate the energy of the falling rain drops. Hence, soil losses are likely to be high. In the high altitude areas, rainfall is generally of a low intensity (Brown, 1973) with characteristic maximum 24 hour intensities of less than 50 mm/day, and 120 mm/day intensities occurring only once every 100 years (Pereira, 1968). A detailed study of daily rainfall data for the Awash River Basin (FAO, 1965), revealed that rains of 60 to 100 mm/day only affected the zone lying between 1800 and 2500 m a.s.l. Such rainfall was very localised and infrequent.

Soil erodibility values reflect the inherent resistance of soils to erosion and can be characterised by an index referred to as the K factor (Wischmeier and Smith 1978). Such values have not been measured in Ethiopia, although some runoff plot experiments are now in progress (Hurni, 1982 a, b, 1983b) from which K factors will eventually be obtained. Hunting Technical Services (1976) estimated the K factors for soils in the Tigrai area using Wischmeier's nomograph, but the accuracy of these values is not known. Examples of K factors calculated by this method are given in Table 5. Besides the questionable accuracy of the nomograph considerable variation in values must be expected for soil groups as broad as the FAO/UNESCO soil units.

Table 5

Estimated K factor values for selected soil units using Wischmeier's nomograph

Soil unit	Source	Estimated K factors
Haplic Phaeozems	Barber, 1984	0.08
Pellic and Chromic Vertisol	Huntings, 1976	0.17, 0.22
Eutric Cambisols	" "	0.17, 0.17, 0.27
Chromic Luvisols	" "	0.22
Dystric Nitosols	Barber, 1984	0.07
Rendzina	Huntings, 1976	0.19

The above values suggest that the Luvisols and the eutric Cambisols may be the most erodible soils and the dystric Nitosols and haplic Phaeozems the least erodible soils. This is more or less in agreement with the crusting indices given in Table 3. However, the stony phases of soil units, for example the haplic Phaeozems, and the Lithosols - which are invariably stony, will have much lower K factors than would be apparent from the values obtained from the nomograph. Wilkinson (1975) has suggested that erodibility may be reduced in direct proportion, to the percentage stone cover on the ground surface, but other work (quoted in section 3.3), and evidence in Wischmeier and Smith (1978) concerning mulch covers, suggests the relationship between soil loss and ground cover is probably non-linear.

Both slope gradient and slope length are positively correlated with soil loss. Consequently, the highest current erosion rates are found in steep mountainous areas such as the Simen Mountains (Fig. 1), and in areas with long slopes. However, even in gently sloping areas soil losses can be high if the catchment area, i.e. slope length is extensive and runoff susceptibility is high. In many parts of the highlands cultivated slope lengths are 100 meters and longer without any form of terracing, or vegetation strips to reduce the velocity of overland flow. Slope shape is another variable which is particularly important in affecting, not only the magnitude of soil losses from a hill slope (convex slopes result in greater soil losses than concave slopes), but more importantly in influencing the quantity of soil that is deposited on lower slope posiions and the quantity that enters the drainage system. (See section 4).

Land use is a major factor influencing the magnitude of soil losses from sheet and rill erosion. The main effects are through the canopy and surface cover dissipating the kinetic energy and destructive potential of the rain drops, and through the basal cover reducing the velocity and hence sediment transporting capacity of the overland flow. If the degree of ground cover varies during the year, it is the temporal relationship between rainfall erosivity and degree of ground cover that governs soil loss. It has been suggested that the late development of crop cover on the vertisols in Tigrai, and the high rainfall erosivities at the start of the rainy season, are the main causes of the high soil losses in this area. The delayed development of crop cover was attributed to the high moisture requirements of the vertisols before the soils could be plowed which consequently delayed planting. The notorious problems of the vertisols' short-tillage range may perhaps also be responsible for the late planting. Thomas (1983) suggested that high soil erosion in the teff growing areas was caused by the bare, finely cultivated fields being left for a number of weeks before planting to avoid the wettest period, which would presumably have an adverse effect on germination. Furthermore, the type of crop will affect the degree of erosion through the protective effect of its canopy and through the stand density influencing the velocity of runoff.

Perennial crops such as coffee and enset should cause less erosion than annual crops, and teff and wheat are claimed to result in less erosion than maize and potatoes (Brown, 1973), presumably because of the higher stand density of the former crops. The influence of natural vegetation cover, including grasslands, on soil loss is discussed in section 3.3.

Management practices such as tillage, drainage, and the fate of crop residues also have an impact on the magnitude of soil losses. The marked contrast in the coarse cloddy tilth produced by tilling vertisols and the very fine tilth produced by up to four cultivations for barley and six cultivations for teff has a marked effect on soil losses on even relatively gentle slopes. Very fine tilths posses a low surface-water retention capacity and will be more susceptible to sealing, runoff and hence erosion than a coarse tilth. The vertic Cambisols and the Vertisols used for annual crops are invariably drained by the construction of shallow furrows sometimes aligned at a fairly steep angle to the contour which encourages rill erosion. Although drainage is necessary on these soils, especially for teff, the furrow gradients should not exceed the critical value at which scouring occurs.

The fate of crop residues and its influence on erosion has been referred to in section 2.4. Considerable evidence exists from research work in various parts of Africa demonstrating the value of leaving crop residues on the surface and mulching for erosion control (Lal, 1976; Barber and Thomas, 1981). This practice combined with minimum tillage has successfully reduced erosion to very low levels, particularly in humid areas where the soils are not very susceptible to crusting (Lal. 1976). Thomas (1983) has suggested that the substitution of some of the teff by maize would reduce erosion, not only by providing a longer period of ground cover, but also by providing about three times as much stover, to be used for both fodder and surface mulch.

Well built terraces, and cut-off drains located above cultivated areas can greatly reduce soil losses. There are well built terraces with stone walls in some parts of the country, as for example in the Harrar region for irrigated chat and coffee (Pereira, 1968) and around Konso in Gemu-Gofa which have been in existence for centuries (Brown, 1973). However, for the majority of the country terraces are either non-existent or constructed so badly that they constitute a greater risk of erosion than if they had not been built at all. Ploughing at an angle to the contour also enhances soil losses especially on steeply sloping land. This topic is discussed in section 3.3.

2.9 The relative importance of soil degradation processes

Salinisation and alkalisation processes are virtually non-existent in the highlands, and wind erosion is probably not a serious threat although very little data on its extent or severity are available. Chemical degradation due to leaching is probably only important in some localised high rainfall areas where the soils are characterised by low effective cation exchange capacities. Under these conditions, aluminium may pose a threat to Al-sensitive crops such as cotton, sorghum and barley. Further studies on the extent of potential Al-toxicity problems need to be conducted. Chemical degradation through "mining" of soil nutrients is probably important with respect to phosphorus, and to a lesser extent for nitrogen,

and will be more serious in areas where fallowing periods are very short or non-existent. Biological degradation does not constitute a widespread problem because of the high altitudes and correspondingly low temperatures and high rainfall inhibiting humus mineralisation rates. However, in the drier, lower altitude zones corresponding to higher moisture deficit probability regimes, there is likely to be a steady decline in humus contents due to higher mineralisation rates. Physical degradation poses a more serious threat mainly as a consequence of surface crusting from raindrop impact, and localised compaction due to human and livestock traffic. These processes are intimately linked to water erosion processes of degradation, i.e. gulley erosion, sheet and rill erosion. The spectacular nature of gulley erosion all too often attracts disproportionate attention, particularly by the lay-man, whereas the often imperceptible, but insidious sheet and rill erosion processes are overlooked. Sheet and rill erosion processes are discontinuous in time and their effects on arable land are all too quicly obliterated by weeding, tillage, trampling, weed and crop growth, so that a few weeks after an erosive event the effects of the erosion may have been largely concealed or obliterated. Hence the effects of sheet and rill erosion and notalways apparent unless the observer happens to be in the area at the time of, or shortly after, an erosive event. This problem is particularly acute in high rainfall areas where weed growth is rapid, hence cultivation is frequent, and especially in soils with uniformly coloured profiles. This situation is true for many of the highland soils which possess deep, humic, uniformly coloured top soils. With respect to gulley erosion the quantities of soil lost may sometimes contribute significantly to river sediment loads, but the area of agricultural land affected is invariably insignificant compared to the area influenced by sheet and rill erosion consequently, sheet and rill erosion and the interrelated physical degradation processes are considered to be the dominant degradation processes in the Ethiopian highlands, in terms of both areal extent and their influence on land fertility and productivity. This conclusion cannot be proven unequivocally, but it is in accordance with views expressed by scientists familiar with the problems of soil degradation in the Ethiopian highlands, viz. Brown (1973) and Hurni (1984, pers. comm.).

3. ESTIMATION OF CURRENT SHEET AND RILL EROSION RATES

A knowledge of the current rates at which soils are being removed from hillslopes by sheet and rill erosion and data on present soil formation rates permits an estimation to be made of the net rate at which soil depth is decreasing under the existing land use pattern. On lower colluvial slopes sediment deposition may occur, in which case there will be a net increase in soil-depth (see section 4).

3.1 Soil formation rates

Rates of soil formation, i.e. the rates at which parent materials weather to form soils have been tentatively estimated for soils in Ethiopia by Hurni (1983a). Data on maximum soil formation rates were obtained in the field at a specific locality in Sidamo from the thin depth of soil that had developed over rocks which constituted an old road surface of known age. The rate at which the soil had developed was then empirically related to mean annual temperature, mean annual

rainfall, length of growing period, the FAO/UNESCO soil classification unit, soil depth, slope gradient, land cover and land use. Using this empirical relationship, Hurni tentatively estimated soil formation rates for the whole of Ethiopia and has produced a soil formation rates map as a scale of 1:1m. The maximum soil formation rates derived from field measurements in Sidamo varied from 25 to 30 t/ha/yr, and the derived soil formation rates for the whole of Ethiopia ranged from less than 2 t/ha/yr to more than 22 t/ha/yr. These rates are equivalent to < 0.16 mm/yr to greater than 1.76 mm/yr assuming a soil bulk density of 1.2 g/cm^3.

These rates are very high compared to most of the values quoted in the literature which are generally up to 1 t/ha/yr (0.08 mm/yr) from unconsolidated rocks and much lower rates from consolidated rocks (Smith and Yates, 1968, Smith and Stamey, 1965). Over much of the Ethiopian highlands the parent rocks are consolidated, i.e. basalts, trachytes and granites (Kazmin, 1974). In the Kenyan highlands, where conditions are not so dissimilar to some parts of the Ethiopian highlands, the soil formation rates from consolidated rocks in the humid areas have been estimated at 0.18 to 0.30 t/ha/yr, i.e. 0.014 to 0.024 mm/yr (Dunne et.al., 1978). These rates are two to three orders of magnitude lower than the rates estimated by Hurni.

The disparity in soil formation rates between those estimated for Ethiopia and those determined elsewhere may be partly attributed to the use of soil formation rates derived for exposed rock surfaces. The rate of weathering of an exposed rock would be expected to be far more rapid than the rate at which a comparable rock buried beneath a mantle of soil would weather. Rocks at the earth's surface will be directly exposed to the kinetic energy of rain drops, and will be subject to far more extreme changes in moisture content and temperature (which accelerate the weathering processes) than would a rock protected by a thick cover of soil. Thus, the rate at which soil depth increases due to the weathering of an exposed rock would be expected to diminish exponentially during the initial stages of weathering. The possibility of wind-blown soil materials having accumulated over the old road surface and thereby exaggerating soil weathering rates cannot be discounted.

The empirical relationshp developed by Hurni to infer rates of soil formation for the whole of Ethiopia, suffers from the exclusion of the parent material as an independent variable. The nature of the parent material such as the degree of consolidation, the grain size, the chemical composition of the parent rock and the degree of structural development within the rock will all exert a pronounced influence on its susceptibility to weathering. Nevertheless, for areas with similar parent materials, Hurni's relationship probably indicates the relative rates of soil formation due to differences in temperature, rainfall, land use, etc. The tentatively derived soil formation rates must, however, be viewed with extreme caution.

Because of the doubts concerning the aboslute values of soil formation rates derived for Ethiopia, and since rates of soil formation are generally insignificant in relation to the magnitude of accelerated soil erosion rates, the former will be ignored in the estimation of net soil losses. Henceforth, the term "sheet and

and rill erosion rates" will be used as an approximation of net soil losses. Sediment deposition rates on colluvial footslopes are probably fairly high in some areas and will be discussed in section 4.

3.2 Method used in estimating sheet and rill erosion rates

Current sheet and rill erosion rates have been estimated for the Ethiopian highlands and have been presented as a map at a scale of 1:1m (Boerwinkel and Paris, 1984). The methodology used was that given for the estimation of sheet and rill erosion at sclaes greater than 1:1m in the FAO provisional methodology for soil degradation assessment (FAO, 1979). This method was devised and used for mapping N. Africa and the Middle East at a scale of 1:5m. The very small scale at which the study was carried out, and the paucity of basic data for many areas, necessitated a simple method. Consequently, the proposed methodology is a rather crude simplification of the universal soil loss equation - familiarly referred to as the USLE, (Wischmeier and Smith, 1978).

The USLE predicts the long-term average annual soil losses from field areas, due to sheet and rill erosion processes only. It is an empirical relationshp derived from 10,000 plot years of data gathered mainly from the eastern parts of the USA, and relates the annual soil loss per unit areas to six factors, viz. rainfall erosivity, soil erodibility, slope length, slope steepness, land cover and management, and support practices*. Since this is an empirical relaticnship, there is no justification for assuming this relationship will hold in areas where the conditions are markedly different to those where the relationship was established (Hudson, 1980). In areas with markedly different conditions to those found in the eastern parts of the USA, high errors can be expected.

The modification of the USLE for estimating sheet and rill erosion rates as given in the provisional FAO methodology for scales greater than 1:1,000,000 is as follows:

Soil loss (t/ha/yr) = Climatic Factor x Soil Factor x Topographic Factor x Human Factor

The climatic factor (R) is a modification of Fournier's index i.e

$$R = f \sum_{1}^{12} (P_i^2/P)$$

where P_i is the average montly precipitation and P the annual precipitation. Precise functions for different climatic regimes were obtained from modifications of the functions given in Land Resources for Population of the Future (FAO/UNFPA 1979). The soil factor was derived from the soil's textural class, presence or absence of a stony phase, the FAO soil classification unit (FAO, 1974), and a topographic factor applied to the slope classes given in the FAO/UNESCO World

*Support practices refer to the type of ploughing, strip cropping and physical conservation measures.

Soil Map, but with adjusted ratings being given for fluvisols, gleysols nnd gleyic phases. The human factor was obtained from the broad type of land use and the percentage ground cover. Further details regarding the type of land use/land cover mapping units and their composition are given in the report by E. Boerwinkel and S. Paris (1984).

3.3 Sources and magnitude of erros in estimating sheet and rill erosion rates

The provisional FAO methodology used in this study has not yet been adequately tested, and is based on an empirical relationship for which the applicability without validation and modifications to areas outside the eastern part of the USA is questionable. This method cannot, therefore, be expected to give accurate e estimates of current sheet and rill erosion rates for Ethiopia. However, given the absence of any long-term soil loss data from field measurements, and in the absence of any proven alternative methods for predicting sheet and rill erosion rates, the FAO provisional methodlogy probably gives the best estimate that can be obtained. The absolute values, however, and even the relative differences in erosion rates at different locations, should not be regarded as reliable.

For the purpose of this consultancy the eight 1:1m erosion rate maps produced by Boerwinkel and Paris were reduced to a 1:2m scale (Fig. 1). Some generalisations were introduced during the reduction in scale, but without markedly detracting from the level of detail given on the 1:1m maps. Although generalisations are unavoidable at a 1:1m scale of working, it is important to appreciate the conditions under which such generalisations may sometime lead to serious over- or under-estimations. For example, the adoption of a 0.5 factor for stony soil phases in the estimation of the soil factor can seriously over-estimate soil losses from very stony land with a high percentage stone cover. Very stony soils occur widely on the NE Escarpment and in the Chercher highlands. A study by Hurni (1982 b) in the Kori Sheleko catchment, although for only one year, convincingly demonstrated for that year, a soil loss of 56 t/ha/yr from a non-stony soil on a 16 per cent slope, compared to a soil loss of only 2 t/ha/yr from the stony phase of a comparable soil on a much steeper slope of 37 per cent. Similar studies in Kenya have also shown that very stony soils give significantly greater reductions in soil loss than 50 per cent for both cropped land (Smith, 1982 pers. comm.) and grazing land (Barber and Thomas, 1981).

The topographic factor used in the provisional FAO methodology understandably ignores the influence of slope length since at a 1:5m scale the estimation of meaningful slope lengths is very difficult. Nevertheless, when the equivalent slope length is calculated for each topographic factor using the average slope value of each slope class interval and assuming that the USLE topography factor is reasonably valid, the slope length values are low (see Table 6, column 4). This is particularly so for the Ethiopian highlands where hill slopes are often 100m. in length, and very rarely have wall constructed effective terraces to cause sediment deposition. Colum 5 given the topographic factor for a 100m. slope lengh calculated according to the USLE, and column 6 gives the factor by which the topographic factor in the provisional FAO methodology would under-estimate soil losses from a 100m. slope length, assuming that the USLE topographic factor is reasonably applicable. Regardless of the accuracy of the calculated under-estimation factors given in column 6, it is clear that the omission of slope length can lead to serious under-estimations in soil erosion rates.

Table 6

Influence of slope lengths on the topographic factor

1	2	3	4	5	6
Slope class interval (%)	Average slope (%)	Topographic factor a/	Equivalent slope length (m)	Topographic factor for 100 m slope b/	under estimation factor c/
0 - 2	1	.15	50	0.17	1.1
2 - 8	5	.35	22	1.00	2.9
8 - 16	12	2.0	37	3.3	1.7
16 - 30	23	4.2	20	9.5	2.3
30 - 50	40	8.0	14	23	2.9

a/ As given in the provisional FAO methodology (FAO, 1979).

b/ The combined slope gradient-length factor as given by Wischmeier and Smith 1978.

c/ Under-estimation factor when the topographic factor given in the provisional FAO methodology is used for a 100 m slope length.

The human factor in the provisional FAO methodology is based on the broad land use type and on the percentage vegetation cover of the natural vegetation. It ignores the influence of management practices, which cannot be taken into account at such small working scales. It should be realised, however, that by excluding management practices, there is an implicit assumption that the land is not terraced and cultivation is up and down the slope at right angles to the contour (Wischmeier and Smith, 1978). Although farmers commonly plough across the contour they seldom plough at right angles to the contour, and consequently the soil erosion rate will be lower than if ploughing at right angles to the contour, especially on gentle slopes less than 12 per cent. A further under-estimation of soil losses may arise from the land cover factors given in the provisional FAO methodology for rangelands and grasslands (Table 7). Studies on

Table 7

Influence of percentage ground cover of pasture, grassland and rangeland on the human factor

	Percentage ground cover					
	0-10	1-20	20-40	40-60	60-80	80-100
'Human' factor	0.45	0.32	0.20	0.12	0.07	0.02

Source: FAO, 1979.

the influence of basal grass cover on soil losses from grasslands by Moore et.al (1979) and Dunne (1977) have shown a strongly exponential decrease in soil losses with increasing grass cover up to a critical value of 10 to 20 per cent beyond which increasing grass cover causes little additional soil loss. This trend is not evident in the values given in Table 7. Hence, the use of these values may lead to significant under-estimations in soil loss, especially at very low ground cover values of 0 - 10 per cent.

The use of satellite and aerial photography to demarcate forest and bushland mapping units cannot generally distinguish between those mapping units where there is a high percentage ground surface cover of litter and grasses and those mapping units where the ground cover is absent due to overgrazing. Thus, similar land cover factors would be given although the soil losses could be far higher in situations where the grass/litter cover is absent compared to situations where the ground cover is high. Examples of high erosion rates beneath dense eucalyptus forests and beneath scrub forest where the grass/litter cover is low or absent have been quoted by Gujral (1979).

Clearly, as a result of the questionable validity of applying the provisional FAO methodology to the Ethiopian highlands, the lack of basic resource data, the limited ground checking due to access and time constraints and the unavoidable generalisations due to the scale of working, high errors must be anticipated in the absolute values presented in Fig. 1. Average errors of ± 200 per cent would not be surprising and in some areas the errors may be much lower and in other areas the errors may be much higher. Nevertheless, and this constitutes the main value of Fig. 1, the method used is probably sufficiently sensitive to distinguish between areas where sheet and rill erosion rates are undoubtedly low and may give rise to little concern, and areas where the current sheet and rill erosion rates are high or very high and may constitute a serious problem. Reference to Fig. 1 shows that the areas characterised by extremely high sheet and rill erosion rates occur in S. Gonder and NE. Gojam regions, around Mt. Amba Farit, in the E. Highlands and in N. Wellega region.

4. THE DEPOSITION OF SEDIMENTS FROM WATER EROSION

The main transporting agent for eroded sediments is runoff, and deposition of the suspended sediments will occur when the velocity of the runoff and the eddy velocities have been reduced below the critical settling velocities of the particles in suspension. For sediments eroded by sheet and rill erosion, the deposition may occur behind the bands of ridge terraces, within the channels of channel terraces, along field boundaries, within grass strips and on gently sloping colluvial foot-slopes, or the suspended sediment may pass directly into the drainage system. For gulley erosion in humid environments the majority of the suspended sediment will probably enter a permanent drainage channel directly, whereas in the more semi-arid environments the transportation may be discontinuous; the sediment may be trans ported, deposited and re-entrained several times before entering a permanent river system.

A clear distinction must therefore be made between the loss of soil from hillslopes which may result in decreasing productivity, the deposition of sediments on lower slope colluvial sites where productivity may be increased or decreased, and the quantity of soil which enters the permanent river systems.

The quantity of eroded sediment which enters a permanent river system compared to the quantity of sediment removed from the hillslopes is referred to as the sediment delivery ratio. Many parts of the highlands are characterised by concave lower slopes which would be expected to encourage sediment deposition. The corollory is that low river sediment loads and hence a low sediment delivery ratios would not be unexpected. There is, as yet, insufficient evidence to confirm this, but preliminary results from work by Hurni (pers. comm.), and the low degradation rates calculated from suspended sediment loads in catchments upstream of the Awash station, i.e. 1.5 to 17.5 t/ha/yr for the period 1962-64 (FAO, 1965) support the speculation that sediment delivery ratios are low to very low. Moreover, values of suspended sediment loads in rivers will also include sediment derived from stream bank erosion. Virgo and Munro (1978) measured suspended sediment loads of 16.8 and 33 t/ha/yr during an 18 month period from two catchments in Tigrai region. These rates were not dissimilar to the rates estimated by Fournier's (1960) method, viz. 14.6 t/ha/yr, but were 20 to 40 times lower than estimates of soil losses from hillslopes derived from the USLE. However, in catchments where gulley erosion is dominant the suspended sediment loads may be high. Hurni (pers. comm.) has recorded sediment yields of 500 g/l from a catchment in Hararghe where gulley erosion is the dominant soil degradation process.

The suspended sediments which enter the river system may in turn be deposited, within river channels, on alluvial plains during peridos of flooding, and more importantly within reservoirs and lakes. The rapid siltation of reservoirs can have serious consequences in terms of water supplies and hydroelectric power production.

The impacts of soil loss from hillslopes and of soil deposition on colluvial slopes on the fertility of land is discussed in section 6.

5. THE TOLERANCE OF SOILS TO WITHSTAND FURTHER SHEET AND RILL EROSION

The tolerance of soil to withstand erosion determines how much damage will be done by a specific rate of erosion, and therefore facilitates an evaluation of the impact of current erosion rates on the fertility and hence productivity of the soil. The tolerance of a soil to further erosion is an inherent characteristic of the soil profile and can be considered in terms of both its physical fertility tolerance and its chemical fertility tolerance. Soil tolerance levels are a function not only of the present physical and chemical fertility status of soils, but also of the physical and chemical fertility profile gradients, i.e. the rates of change in soil physical and chemical fertility with depth.

5.1 Soil physical tolerance

A soil's physical tolerance can be expressed by the present effective soil depth which governs the ability of a soil to provide adequate anchorage, and to store sufficient quantities of available water to meet the crop/vegetation's water requirements between successive rainstorms without suffering from water stress. Thus for similar soils and for a specified erosion rate, a deep soil will possess a greater physical tolerance to erosion than a shallow soil, i.e. a much longer time interval would elapse before the deeper soil becomes unproductive than would be the case for the shallow soil. Other soil physical properties which will influence soil physical tolerance are the infiltration rate, susceptibility to sealing or crusting, permeability, root penetrability and drainage characteristics. The profile gradients of these physical characteristics will also influence the soils' physical tolerance to withstand further erosion.

Due partly to the paucity of basic data on soil physical properties and partly because of time constraints the physical tolerance of the Ethiopian highland soils to further sheet and rill erosion has been expressed solely in terms of their effective depth. The influence of Bt horizons of clay illuviation in the luvisols, nitosols and acrisols, and the influence of the intractable vertisol structures on soil physical tolerance levels have been ignored. Six soil physical tolerance levels based on effective soil depth classes, have been defined as shown in Table 8. The distribution of the soil physical tolerance classes to further sheet and rill erosion is shwon in Fig. 2. This map has been produced at a scale of 1:2,000,000 from the existing 1:1,000,000 soil depth map of Ethiopia (Henrickson et al., 1983). The reduction in scale necessitated some generalisations but without appreciably detracting from the level of detail shown on the 1:1,000,000 maps. The effective soil depth map from which the soil physical tolerance map was produced, was compiled from data gathered in the Wabi Shebelle survey (Orstrom, 1973) for the eastern part of the highlands, from field traverses along the main roads by LUPRD soils staff during 1980 to 1983, and by extrapolation from satellite imagery interpretation. Data on effective soil depths were obtained from some of the facets in about 280 of the 382 landscape units in Ethiopia. Limited amounts of soil depth information were also obtained from the Tigrai Rural Development Study, (Hunting Technical Services, (1976), from the Awash River Basin survey (FAO, 1965) and from the Soil Map of the World (FAO/UNESCO, 1977) for the nitosol areas. For three regions viz. Wello, Tigrai and Eritrea there was virtually no data. Consequently the reliability of the effective soil depth map is very low in some regions but of greater reliability in areas where surveys have been conducted and in the vicinity of main roads Fig. 3 gives an indication of the reliability of the soil depth map. The problem is further accentuated by the different dates at which the soil depth data were gathered, given the existing very high sheet and rill erosion rates in some parts of the country. Thus a soil mapped as 25 to 50 cm. deep in 1973, which occurs in an area of class VII sheet and rill erosion rate (i.e. 16.5 to 25 mm/yr), may now, at least 11 years later, belong to the 10-25 cm depth class.

Table 8

The relationship between effective soil depth classes and soil physical tolerance to further sheet and rill erosion

Effedtive soil depth class (cm)	Soil physical tolerance class
150	Very high
100 - 150	High
50 - 100	Moderate to low
25 - 50	Very low
10 - 25	Extremely low
10	None

Although it would have been possible to remove the influence of these two variables, i.e. the year of data collection and recent sheet and rill erosion rates, on the present soil depth values, the time available did not permit this.

Despite the rather low reliability of the soil depth map and consequently of the soil physical tolerance map, the latter must be considered as the best estimate currently available given the paucity and uneven distribution of soil depth information. The absolute values and even the relative differences in soil depth must be regarded with great caution. However the physical tolerance soil map is probably sufficiently discriminating to be capable of delineating areas with extremely low and low tolerance levels from those areas with high and very high tolerance levels.

5.2 Soil chemical tolerance

A soil's chemical tolerance to sheet and rill erosion can be considered in terms of the soil's nutrient status. Less damages would be caused by a given erosion rate on a soil of high nutrient status compared to a soil already low in nutrients. The gradient of a soil's available nutrient contents down the profile will also influence the chemical tolerance of a soil to further erosion. Thus a soil in which the available nutrients are relatively uniformly distributed down the soil profile will be more tolerant of further erosion than a soil in which the top few centimeters contain 75 to 80 per cent of the profile's nutrients. The quantity - depth distribution of available nutrients is of course likely to vary with the nutrient being considered, and it is therefore difficult to assign a single index for a soil's chemical tolerance in terms of

its available nutrient content-depth gradients. Another factor influencing soils' chemical tolerance is the presence/absence of toxic elements such as Al, Mn and Na, or high salt contents and the depth at which they occur within the profile.

5.2.1 Assessment of the soil chemical fertility levels

Serious problems arose in attempting to characterise the chemical fertility of soils in the Ethiopian Highlands. For many areas and many soil types there were no reliable analytical data available. Where data were available it was often incomplete, inconsistent, or was not related to specific soil classification units. Moreover, different, sometimes inappropriate, and sometimes unspecified, analytical methods were used to measure the same soil characteristic.

A refined approach was therefore not possible, and it became necessary to resort to a broad grouping of the soil units classified according to the Soil Map of the World legend (FAO/UNESCO, 1974), that is presented in Fig. 4. This map is taken from the provisional soil map of Ethiopia (Henrickson et al., 1984). Four generalised soil chemical fertility classes were defined according to the nature of the A_1 horizon, base saturation and the existence of vertic properties. The distinguishing characteristics and dominant soil units within each of the soil chemical fertility classes are summarised in Table 9 and their geographical distribution shown in Fig. 5.

For each soil fertility class between five and 14 typical profiles of some of the dominant soil units were selected to give the best estimate that could be obtained for the typical soil chemical characteristics of each class. Considerable use was made of the data given in the Tigrai Rural Development Study report (Huntings Technical Services, 1976) for classes 2 and 3a. For fertility classes 1 and 3b most of the data was provided by LUPRD. An attempt was made to use the considerable volume of data obtained by Murphy (1968) by correlating his sampling traverses with the soil classification units delineated on the provisional soil map. However the values found by Murphy did not always coincide very well with the top soil characteristics expected for the soil units shown on the 1:2,000,000 soils map. This is probably a reflection of the problem of using such small scale maps, and was aggravated by Murphy's data not being related to soil classification units. Moreover some of Murphy's chemical values were quoted only in a qualitative way and the references cited giving information on the methods used, were not readily accessible. Thus Murphy's data was not ultimately used. Data for individual soil profiles in each of the four chemical fertility classes are given in Appendix 4 for the top soils and in Appendix 5 for the sub-soils. The average soil chemical values of the profiles selected to characterise each soil chemical fertility class are given in Appendix 6. These values must be treated with caution they give only a very approximate indication of the nutrient status of the soils in each chemical fertility because of the broad nature of the classes, the limited number of profiles used, their limited geographical occurence, and some doubts concerning the accuracy of the analyses. Moreover, a considerable variation in absolute values must be expected within each fertility class.

Table 9

Classification of soil units into generalised soil chemical fertility classes

Class	Dominant soil units 1/	Minor soil units 1/	Generalised distinguishing characteristics of the soil classes
1	Haplic Phaeozems	Humic Cambisols 2/ Rendzinas Mollic Andosols Vitric Andosols Lithic Phaeozems Calcic Chernozems	Characterised by mollic top soil i.e. a top soil which is generally more than 25cm deep with a high organic matter content and 50 per cent or more base saturation
2	Chromic vertisols Vertic Cambisols Pellic Vertisols	Vertic Luvisols	Possess vertic properties i.e. containing a high content of swelling clays which crack in the dry season, and swell in the rainy season causing impeded drainage
3a	Eutric Cambisols Chromic Luvisols Orthic Luvisols Eutric Nitosols	Eutric Regosols Calcaric Regosols Calcic Cambisols Chromic Cambisols	Lacking a mollic A horizon but with a sub-soil base saturation of 50 per cent or more. (Generally possessing an ochric A horizon which is often of low organic matter content).
3b	Dystric Nitosols Orthic Acrisols	Cambic Arenosols Dystric Cambisols	Lacking a mollic A horzon and with a sub-soil base saturation of less than 50 per cent (often possessing an ochric A horizon)

1/ Classified according to the legend of the soil map of the World (FAO/UNESCO, 1974). The distinctions between different phases have not been considered.

2/ Humic Cambisols posses umbric A horizons, but since they are of only limited extent they have been included in Class 1, which is characterised by mollic A horizons.

Table 10

Soil chemical ratings for organic matter, nitrogen, phosphorus, potassium and alumium toxicity for each generalised soil chemical fertility class

Generalised soil chemical fertility class	Dominant soil units present	Horizon	Soil chemical rating				
			OM[a]	N[b]	P[c]	K[d]	Al toxicity[e]
1	Haplic phaeozems	Top soil[f]	m	m[h]	vl	h	n.a.
		Sub-soil[g]	m	l[h]	vl	h-m	n.a.
2	Vertisols	Top soil	m	l	vl	h	n.a.
	Vertic Cambisols	Sub-soil	m	l	vl	m	n.a.
3a	Orthic, Chromic Luvisols	Top soil	l	l	vl	m	n.a.
	Eutric Cambisols Eutric Nitosols	Sub-soil	l	l	vl	m	n.a
3b	Dystric Nitosols	Top soil	m	l[h]	l	h	vl
	Orthic Acrisols	Sub soil	m	l[h]	l	m	l

Key

vh = very high; h = high; m = medium; l = low; vl = very low.

a organic matter
b Total nitrogen
c Available phosphorus (Olsen extraction)
d Exchangeable potassium
e Aluminium toxicity in terms of the Al percentage saturation of the effective cation exchange capacity and expressed for Al - intolerant crops such as sorghum and cotton. The Al was determined by extraction with N. Kcl.

f General 0-15cm
g Generally 15-45 cm.
h Estimated values based on assumed C/N ratios.

A qualitative rating of the soil chemical fertility classes in terms of their organic matter, total nitrogen, available phosphorus, exchangeable potassium and aluminium toxicity levels is given in Table 10. The relationship between the absolute chemical values shown in Appedix 6 and the qualitative ratings shown in Table 10 are given in Appendix 7. Appendix 7 also refers to the analytical methods employed.

An examination of the organic matter values in Table 10 shows that three of the four chemical fertility classes are of medium status with only class 3a, characterised by ochric horzons, containing low organic matter levels. Correspondingly the total nitrogen values - not a reliable index of nitrogen availability, are low apart from the humus rich top soils of class 1 which contain moderate (estimated) nitrogen levels. Class 2 soils possess low nitrogen levels, but when they waterlogged as a result of their vetric properties humus mineralisation rates will be inhibted. Birch (1970, 1971) showed that under saturated conditions denitrification occurred in the vertisols for long periods during the growing season, further reducing the soils' nitrogen availability. The available phosphorus values are very low for all but class 3b soils where P levels are low. All classes are medium to high in potassium.

It is of interest to compare these very generalised estimates of N, P and K availability levels with the responses to N, P and K obtained from the FAO/EPID fertiliser demonstrations (FAO, 1970) conducted during the 1969-1970 season (Table 11). This set of results is for one of three seasons during which a total of 1,578 fertiliser trials were conducted in farmers fields in 12 regions. For the 1969-1970 season, which was typical of the two previous seasons, significant responses were obtained from N and P treatments with the average responses for different crops varying between 31 and 86 per cent for N, between 43 and 55 per cent for P, and between 78 and 145 per cent for N and P combined. These results support the generally low nitrogen and very low available phosphorus levels given in Table 10 for the four soil chemical fertility classes. However, despite the high average responses by crops to N, P, and particularly to N and P combined, not all of the sites gave significant responses. At the sites where there were five or more trials, 52 per cent of the sites gave significant responses to N, 56 per cent to P and 100 per cent to N + P and to N + P + K combined. This suggests that where N and P were applied singly the other major nutrient, i.e. P and N respectively, was low as to be limiting.

Possible toxicity to aluminium was investigated because of the very low pH values as low as 4.35 found in some of the dystric nitosols (see Appendices 4 and 5). Soil chemical fertility classes 1, 2 and 3a are all characterised by high pH values above 5.5 and so will not possess exchangeable aluminium. The best index of Al toxicity is the percentage saturation by Al of the effective cation exchange capacity (Krampath, 1970). Although the average top soil and sub-soil Al/ECEC values were very low (3.5 per cent) and low (7.2 per cent) respectively, for class 3b soils (see Appendix 6), for individual soils e.g. profile K4, the corresponding values were medium (13.3 per cent) and high

(17.7 per cent) respectively (Appendices 4 and 5). The qualitative ratings of the Al/ECEC values given in Appendix 7 are for Al - intolerant crops such as sorghum, barley and cotton. The specific ratings were based on an Al/ECEC yield response relationships found for sorghum (Abruna et al, 1964); quoted by Sanchez, 1976). Similar ratings may apply to barley and cotton, also very Al - intolerant, but the consultant had no access to the relevant literature. Thus, although the limited data available suggests that class 3b soils have only very low to low Al toxicity levels, there is a distinct possibility that there may be areas where the Al levels are sufficiently high to markedly reduce the yields of Al - intolerant crops. Aluminium tolerant crops such as coffee, maize, cassava and soyabeans would not be expected to be adversely affected by the Al saturation values found so far. For some crops e.g. wheat there is a great varietal difference in their Al - tolerance levels. Further analyses of the dystric nitosols and the orthic acrisols should be carried out, and the available manganese levels - which can cause toxicity problems in some very acid soils, also need to be investigated.

5.2.2 Determination of soil chemical tolerance

Soil chemical tolerance to withstand further erosion is governed by the chemical status of the soils and by the chemical fertility gradients down the profile. The relationship between soil chemical ratings and the difference in the ratings between the top soil and sub-soil horizons, i.e. the rating gradients, and soil chemical tolerance levels are shown in Table 12. Using these relationshps and the soil chemical ratings for organic matter, nitrogen, phosphorus, potassium and aluminium toxicity given in Table 10 the soil chemical tolerance levels have been established for the four soil chemical fertility classes (Table 13). The geographical distribution of the chemical tolerance levels of the four soil fertility classes is shown in Fig. 5.

Clearly, the establishment of soil chemical tolerance levels will vary dependeing upon the depth over which the soil chemical gradients are considered. In this exercise top soil and sub-soil horzons of 0-15 cm and 15-45 cm respectively have been considered. An examination of Table 13 shows that the four classes generally exhibit a very low tolerance to nitrogen losses (though for two classes the total N values were estimated), an extremely low tolerance to phosporus losses and a high tolerance to potassium losses. Class 3a is noticeably different with respect to its organic matter tolerance level which may have important implications to the supply of micronutrients and its susceptibility to physical degradation (refer section 2.3). Class 3b differes from the other three groups in exhibiting a medium tolerance to Al toxicity, i.e. it will become moderately susceptible to Al toxicity problem for crops such as sorghum, barley and cotton which are highly sensitive to even low concentrations of aluminium in the soil solution. The tolerance of the soils to losses of Ca and Mg have not been considered, but Appendix 6 shows that they are generally present in medium to high concentrations and should not present a problem. In conclusion it must

Table 11

Percentage difference in yields between N, P and K treatments for selected crops

	N v C	P v C	NP v C	NPK v C	P v N	NP v N	NPK v N	NP v P	NPK v P	NPK v NP
Teff	41.9(.001)	55.1(.001)	99.3(.001)	112.8(.001)	9.3(.05)	40.5(.001)	50.0(.001)	28.5(001)	37.2(.001)	6.8(n.s.)
Wheat	32.5(.001)	43.2(.001)	78.7(.001)	88.7(.001)	8.0(n.s.)	34.9(0001)	42.4(.001)	24.8(.001)	31.8(.001)	5.6(n.s.)
Barley	30.9(.02)	48.7(.001)	86.5(.001)	83.6(.001)	13.6(n.s.)	42.5(.001)	40.2(.001)	25.4(.01)	23.5(.01)	1.6(n.s.)
G. Sorghum	86.9(.001)	51.5(.001)	129.2(.001)	140.2(.001)	18.8(01)*	22.8(.01)	28.7(.001)	51.3(.001)	58.5(.001)	4.8(n.s.)
Maize	54.0(.05)	46.1(n.s.)	102.7(.001)	140.8(.001)	5.4(n.s.)	31.6(n.s.)	56.4(.03)	38.7(n.s.)	64.8( )	18.8(n.s.)
Noog	71.9(n.s.)	96.5(n.s.)	145.2(.05)	152.9(.05)	14.3(n.s.)	42.7(n.s.)	47.2(n.s.)	24.8(n.s.)	28.7(n.s.)	3.0 n.s.)

Source: FAO, 1970

* N v P

N applied as urea
P applied as triple superphosphate
K applied as potassium sulphate
C Control

Levels of significance are given in brackets.

Table 12

Relationships between soil chemical ratings of top and sub-soils and soil chemical Tolerance levels for organic matter, total nitrogen, available phosphorus exchangeable potassium and aluminium toxicity

Soil chemical ratings		Soil chemical tolerance level	
Top soil[a]	Sub soil[b]	OM, Total N, Avail P, Exch. K	Al Toxicity[c]
Very high High High	Very high High High-Medium	Very high	Extremely high
High	Medium	High	Extremely high
Medium	Medium	Medium	Extremely high
Medium	Low	Low	Extremely high
Very low	Low	n.a.	Medium
Medium	High	n.a.	Low
Medium Low Low	Very low Low Very low	Very low	Extremely high
Very low	Very low	Extremely low	Extremely high

a = Generally 0-15 cm

b = Generally 15-45 cm

c = Refers to Al - intolerant crops only such as sorghum and cotton.

Table 13

Soil chemical tolerance levels for each of the generalised soil chemical fertility classes

Generalised soil chemical fertility class	Soil chemical tolerance level				
	Organic matter	Total N	Avail, P	Exch., K	Al Toxicity
1	Medium	Low	Extremely low	Very high	Extremely high
2	Medium	Very low	Extremely low	High	Extremely high
3a	Very low	Very low	Extremely low	Medium	Extremely high
3b	Medium	Very low	Very low	High	Medium

be emphasized that this whole study on the chemical tolerance of the soils to further sheet and rill erosion is tentative and suffers from a shortage of data.

6. THE HAZARDS OF CURRENT SHEET AND RILL EROSION RATES ON SOIL CHEMICAL AND PHYSICAL FERTILITY

The hazrds 1/ of the current sheet and rill erosion rates express the degree of damage or deterioration that will occur in the physical and chemical fertility of the soils and hence in land productivity. The degree of deterioration will be a function of the current sheet and rill erosion rates (discussed in section 3), and the physical and chemical tolerance of the soils to withstand further erosion. The latter is governed by the present fertility status of the soils and by their fertility - depth gradients (discussed in section 5). To illustrate the concept a soil with a high chemical fertility status, i.e. possessing a high chemical tolerance, would be able to withstand higher erosion rates than a soil of low fertility status, i.e. low tolerance. Hence the hazard due to the higher erosion rates acting on the more fertile soil could be lower than the hazard due to a lower erosion rate acting on a soil of low nutrient status. Similarly there may be a greater hazard due to a relatively low erosion rate acting on a soil that is already close to its critical depth, beyond which further reductions in depth would cause a rapid decline in productivity, than the hazard due to a high erosion rate acting on a very deep soil.

The soil physical and chemical hazard indices or ratings can therefore be used to delineate those areas where the effects of current sheet and rill erosion rates acting on the soils will result in soils with a very low physical and/or chemical fertility status. This information can be used as one of the parameters in assessing priority areas for intervention (see section 9.5). The physical hazard index will assist in making decisions as to where soil conservation measures are most needed, and the chemical hazard rating will aid decision-making concerning the areas where soil fertility improvements require most attention.

6.1 Soil physical erosion hazards

Soil physical erosion hazards can be determined in relation to various soil physical properities e.g. anchorage depth, available water capacity, root penetrability, permeability, susceptibility to crusting, runoff susceptibility, ease of cultivation and suitability for seed-bed preparation. 2/ Time constraints and a dearth of basic data precluded such a detailed study being undertaken. Consequently, a general soil physical erosion hazard index was used

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1/ The term hazard is used here in a different sense to that used by some workers. It does not refer to the maximum or potential erosion rate that would occur if the land were cultivated up-and-down the slope and in a bare fallow co dondition.

2/ The hazards of soils to further sheet and rill erosion cannot sensustricte be divorced from the present, or anticipated forms of land use.

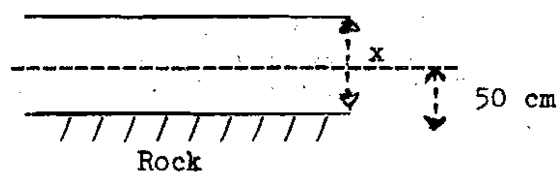
which expresses the hazard due to reductions in soil depth reflecting the resultant status of the soil's available water capacity and the soil's depth for crop/vegetation anchorage.

6.1.1 Soil physical erosion hazard index

The soil physical erosion hazard index (EHI) is a comparison of current sheet and rill erosion rates against a specified tolerable sheet and rill erosion rate.

$$\text{i.e. EHI} = \frac{\text{current sheet and rill erosion rate}}{\text{tolerable sheet and rill erosion rate (TR)}}$$

The usual soil loss tolerance rates for sheet and rill erosion as used in the USLE (Arnoldus, 1979) were not used in this study since they are primarily related to the rates of formation of the A_1 horizon. Moreover, tolerance values are now being debated and re-evaluated (McCormack and Larson, 1980) since they depend very much on the time frame or planning horizon being considered. Consequently an arbitrary tolerable sheet and rill erosion rate (TR) was selected as the rate at which the present soil depth in excess of 50 cm would be during a 100 years period:



$$\text{Thus TR} = \frac{(x - 50)}{100}\ \text{mm/yr}$$

A minimum soil depth of 50 cm was selected as being the minimum depth required by many crops to give reasonably high yields, though the precise value will be governed by crop or vegetation type, rainfall amount, and distribution, and the soil's available water capacity. A 100 years resource life for the soil is entirely arbitrary. Consequently the absolute erosion hazard index values are not of particular significance. It is the relative values which are of importance; the higher the EHI the greater the hazard to the physical fertility of that soil. The relationship between erosion hazard indices and the physical erosion hazard class are given in Table 14 and the distribution of the classes is shown in Fig. 12. Soils with an effective depth of ≤ 50 cm are classified as unable to tolerate further sheet and rill erosion.

Table 14

Relationship between soil physical erosion hazard indices and soil physical erosion hazard class

Physical erosion hazard index	Physical erosion hazard class
≤0.1	Low
0.11 - 0.5	Moderate
0.51 - 1.5	High
1.51 - 5.0	Very high
>5.1	Extremely high

Figure 12 also sub-divides the erosion hazard class that cannot tolerate further erosion, denoted by the symbol F, into three soil depth classes representing 0-10, 10-25 and 25-50 cm effective depths since these depth classes will affect the suitability levels for different land use types. However the EHI would need to be recalculated if a different critical depth other than 50cm were selected.

An examination of Fig. 12 shows that the areas currently with an extremely high physical erosion hazard and which urgently require soil conservation measures are in Eritrea, E. Gonder and throughout much of Wello region; also in E and W. Sidamo, parts of Gamo-Gofa and Keffa regions and in the E. Highlands.

In some areas, particularly lower slope colluvial footslopes there is like likely to be an increase in soil depth due to the deposition of eroded sediments, (see section 4). Such areas are too limited in extent to be shown at a 1:2,000,000 sclae on Fig. 12, and would probably not be considered as constituting a physical hazard. It is in these areas that vertisols associated with pastures occur most frequently. It has been suggested that in these reasonably poorly drained areas, compaction of the deposited sediments by livestock would result in a deterioration of physical fertility. The author has no evidence to support or contradict this hypothesis, but would be of the opinion that the generally poor physical structures of these colluvial soils, often vertisols, would probably not suffer significantly from the addition of compacted sediments. The pronounced wetting and drying conditions experienced by these soils would tend to assist in structural aggregation and would probably compensate to some extent for the loss of structure due to sediment compaction by livestock.

6.2 Soil chemical erosion hazards

Soil chemical erosion hazards will be determined by the chemical tolerance of soils to withstand further erosion, by the current sheet and rill erosion rates, by the rate of top soil formation and by the time period under consideration. Since soil chemical fertility frequently decrease with depth, the longer the time period being considered, the greater will be the chemical erosion hazard. For this study an arbitrary period of 25 years has been selected.

The rate at which the humic top soil developes within a profile is also important since it is this horizon which generally contains a major proportion of the soil's nutrients, and the formation of this horizon will compensate, to some extent, for the loss of top soil by erosion. No values of A_1 formation rates are available for the Ethiopian highlands, but values given in the literature range from 0.8 to 3.0 mm/yr (Buol, Hole and McCracken, 1973). An average value of 1.5 mm/yr has been assumed in this study, which may over-estimate rates of formation in the high altitude areas and under-estimate the rates for the lower, hotter altitutdes.

To simplify procedures, the current sheet and rill erosion rates have been grouped into two broad classes, viz. low erosion rates equivalent to classes I to V and high erosion rates equivalent to classes VI to VIII. The soil chemical erosion hazards have then been estimated for the four generalised soil chemical fertility classes subject to the lower erosion rates I to V, and for the individual soil units subject to the higher erosion rates VI to VIII. For the higher erosion rates it is necessary to consider the soil nutrient gradients over a greater depth.

In the determination of soil chemical erosion hazards for current sheet and rill erosion rates I to V there will be a net soil loss of 0 to 12.5 cm over a 25 year period, assuming an A_1 formation rate of 1.5 mm/yr. For these erosion rates it would therefore seem appropriate to consider the chemical ratings and gradients within the top two horizons i.e. within the 0-15 cm and 15-45 cm horizons. Hence the soil chemical tolerance levels given in Table 13 for each of the generalised soil chemical fertility classes can be used, and the soil chemical hazards will be inversely related to the soil chemical tolerance levels as shown in Table 15. The chemical erosion hazard classes for each of the four generalised soil chemical fertility classes are given separately for organic matter, total nitrogen, available phosphorus, exchangeable potassium and aluminium toxicity in Table 16.

In the evaluation of soil chemical erosion hazards for soils occurring within the current sheet and rill erosion rates VI to VIII, only four soil units viz. eutric Cambisols, chromic Luvisols, dystric Nitosols and haplic Phaeozems were involved. At these extremely high erosion rates there would be a net soil loss of from 12.5 cm to more than 58 cm over a 25 year period, assuming on A_1 formation rate of 1.5 mm/yr.

Table 15

Relationship between soil chemical tolerance levels and soil chemical erosion hazard classes

	Soil chemical tolerance levels					
	Very high	High	Medium	Low	Very low	Extremely
Soil chemical erosion hazard class	Very low	low	medium	high	very high	extremely high

Table 16

Soil chemical erosion hazards for each of the generalised soil chemical fertility classes in sheet and rill erosion rate classess I to V

General soil chemical fertility class	Soil chemical erosion hazard				
	Organic matter	Total N	Available P	Exchangeable K	Aluminium* toxicity
1	Medium	High	Extremely high	Very low	Extremely low
2	Medium	Very high	Extremely high	Low	Extremely low
3a	Very high	Very high	Extremely high	Medium	Extremely low
3b	Medium	Very high	Very high	Low	Medium

* For Al - intolerant crops only

Table 17

Relationships between soil chemical ratings for soils in sheet and rill erosions rate classes VI to VIII and their soil chemical tolerance levels

Soil unit	Horizon	Soil chemical status rating					Soil chemical tolerence level				
		OM[a]	N[b]	P[2]	K[d]	Al Toxicity[e]	OM[a]	N[b]	P[c]	K[d]	Al Toxicity
Eutric Cambisol	1[f]	l	vl	vl	m	na					
	2[g]	l	vl	vl	l	na	vl	el	el	l	eh
	3[h]	vl	vl	vl	l	na					
Chromic Luvisol	1	l	l	l	l	na					
	2	l	vl	vl	vl	na	vl	vl	vl	vl	eh
	3	l	vl	vl	vl	na					
Dystric Nitosol	1	m	m	l	h	vl					
	2	m	l	l	m	l	l	vl	vl	vh	m
	3	l	vl	l	h	vl					
Haplic Phaeozem	1	m	m	vl	h	na					
	2	m	l	vl	h	na	l	vl	el	h	eh
	3	l	vl	vl	m	na					

a. Organic matter
b. Total Nitrogen
c. Available Phosphorus
d. Exchangeable Potassium
e. Al Toxicity, expressed as Al/ECEC, for Al-intolerant crops only
f. Generally 0–15cm
g. Generally 15–45cm
h. Generally 45cm

el extremely low
vl vey low
l low
m medium
h high
vh very high
eh extremely high

The chemical erosion hazards were therefore determined according to the chemical ratings and chemical gradients over the top three horizons i.e. from the 0-15 cm horizon to the horizon deeper than 45 cm. Chemical values and ratings of selected profiles for these four soil units are given in appendix 8, and the average ratings of their organic matter, nitrogen, phosphorus, potassium and aluminium toxicity levels for each of the three horizons, and the corresponding soil chemical tolerance levels for each of the four soils are given in Table 17. The soil chemical tolerance levels were derived from the chimical rating/rating gradient - tolerance level relationships given in Table 12. The chemical erosion hazard classes were then obtained from the soil chemical tolerance levels using the relationships given in Table 15 and are presented in Table 18.

Table 18

Soil chemical erosion hazard classes for soils occurring in sheet and rill erosion rate classes VI to VIII

Soil unit	Map symbol in Fig. 6	Soil chemical erosion hazard				
		Organic matter	Total N	Available P	Exchange-able K	Aluminium toxicity
Eutric Cambisols	4	Very high	Extremely high	Extremely high	High	Extremely low
Chromic Luvisols	4	Very high	Very high	Very high	Very high	Extremely low
Dystric Nitosols	5	High	Very high	Very high	Very low	Medium
Haplic Phaeozems	6	High	Very high	Extremely high	Low	Extremely low

The chemical erosion hazards of the four generalised soil chemical fertility classes subject to the lower sheet and rill erosion rates (i.e. classes I to V), and the erosion hazards of the four soil units exposed to very high sheet and rill erosion rates (i.e. classes VI to VIII) are presented in Fig. 6. The soil chemical erosion hazards of the eutric Cambisols and Chromic Luvisols are designated by the symbol 4, the dystric Nitosols by the symbol 5, and the haplic Phaeozems by the symbol 6 in Fig. 6. The areas with the highest chemical erosion hazard in terms of organic matter and nitrogen losses (classes 3a and 4 in Fig 6),

occur in the northern parts of the highlands in Tigrai and Eritrea, and on the western edge of the highlands in Gojam and Gonder regions. Areas subject to high and very high chemical erosion hazards in terms of potassium losses (class 4 in Fig 6) occur mainly in W. Shewa, N. Gojam and S. Gonder regions. Very high to extremely high chemical erosion hazards with respect to phosphorus losses occur throughout the highlands. Areas with a medium chemical erosion hazard in relation to aluminium toxicity problems (class 5 in Fig. 6) are probably restricted to local areas within Wellega, Ilubabor and Keffa regions in the high rainfall zones.

In colluvial footslope positions where sediment accumulation occurs there is likely to be an enhanced fertility, i.e. a negative chemical erosion hazard. The processes of sheet and rill erosion preferentially remove the finer particles from the soil surface of the hillslopes, and it is these fine particles, particularly clays and organic colloids which contain a relatively higher proportion of nutrients than exist in the original soil. As a result the eroded sediments are usually enriched with nutrients, and the enrichment ratio, defined as:

$$\text{Enrichment ratio} = \frac{\text{nutrient concentration in the eroded sediments}}{\text{nutrient concentration in the original soil}}$$

is often approximately equal to two. Hence the colluvial footslopes and alluvial plains become enriched in nutrients at the expense of the hillslopes. This is likely to benefit low-lying pastures, but their areal extent is generally too limited to be delineated on a 1:2,000,000 scale map. This aspect receives more attention in section 7.4.

7. PROJECTIONS OF THE FUTURE IMPACTS OF SHEET AND RILL EROSION ON SOIL FERTILITY

The objective of this part of the study is to predict changes in soil fertility that would occur if the current sheet and rill erosion rates were allowed to continue unabated. It is intended this data would subsequently be used by the agronomist/forester/pasture-livestock experts of the Ethiopian Highlands Reclamation Study Team in an attempt to relate changes in soil fertility parameters to changes in land productivity so that an estimate can be made of the economic costs of soil degradation.

A time span of 25 years has been adopted and the impacts of sheet and rill erosion have been studied in relation to projected changes in effective soil depths (which influence the anchorage of plants), available water capacities, and soil nutrient losses.

7.1 The assumption of constant sheet and rill erosion rates

It has been assumed that the current sheet and rill erosion rates remain approximately constant over the next 25 years. This implies that the existing farming practices do not appreciably change, and that soil erodibilities do not significantly alter. However, if the top soil is removed and the sub-soil becomes exposed, the sheet and rill erosion rates will change if there is a significant difference between top-soil and sub-soil erodibilities. For the sheet

and rill erosion rate classes I to V, it has been estimated that a maximum net loss of 12.5 cm of top-soil will occur over 25 years (section 6.2). Since the top humic horizons in the highlands are frequently deeper than 12.5 cm. (Y.H. Wintjne Bruggeman, pers., comm.) the assumption of more or less constant sheet and rill erosion rates for classes I to V is probably not unreasonable. This assumption becomes less valid for the extremely high sheet and rill erosion rate classes VI to VIII where a net loss of from 12.5 cm to more than 58 cm in 25 years has been estimated (section 6.2). Table 19 illustrates the differences in top-soil and sub-soil erodibilities, and the crusting indices for three of the dominant soil units found in these very high erosion rate classes. These values, which can only be taken as a rough guide, indicate that differences in erodibility may well arise when the sub-soils of the eutric Cambisols and the dystric Nitosols are exposed. Nevertheless, there was insufficient time available to take such differences into account, and hence the severity of the effects of erosion in classes VI to VIII may have been underestimated.

Table 19

Estimated to-soil and sub-soil K factors and crusting indices for soils commonly occurring in sheet and rill erosion rate classes VI to VIII

Soil unit	Estimated K factor [a]		Estimated crusting index[b]	
	Top-soil	Sub-soil	Top-soil	Sub-soil
Eutric Cambisol[c]	0.20	0.24	0.57	1.08
Chromic Luvisol[c]	0.22	0.22	0.69	0.60
Dystric Nitosol	0.07	0.19	0.30	0.41

[a]From the Nomograph in Wischmeier and Smith (1978)

[b]From the equation: crusting index = $\frac{\% \text{ silt}}{\% \text{ Clay} + 10 \text{ Organic matter } (\%)}$

A modification of equation 8 in FAO (1979)

[c]See appendices 1, 2, 3, 4 and for the data sources.

7.2 Predicted changes in effective soil depths

The effective soil depth is the depth of soil profile that can be readily penetrated by roots, and for each crop or vegetation type there is a critical soil depth required for support and anchorage. The higher the rate of sheet and rill erosion the more rapidly the effective soil depth will be reduced and the more rapidly the land will become too shallow for agriculture. The impact of current sheet and rill erosion rates on effective soil depth has been investigated by combining the estimated sheet and rill erosion rates map (Fig. 1) with the existing soil depth map (Fig. 2) and calculating the expected soil depth in 25 years time assuming a bulk density of $1.2 g/cm^3$ for all soils

(see Appendix 9). The distribution of soil depth classes in the year 2007 or earlier is shown in Fig. 8. Areas where the soil depth classes have changed are delineated by thick solid lines and assigned a quotient symbol where the first (numerator) symbol denotes the present effective depth, and the second (denominator) symbol represents the effective depth in the year 2007 or earlier. In areas where there have been no changes in depth class only one symbol is given. As explained in section 5.1 the date at which the original soil depth data were gathered varied, and was earlier than 1982 in some areas. Consequently the effective soil depth classes represented in Fig. 8 may be attained earlier than 2007 in some areas.

Previous sections, viz. 5.1 and 3.3 have emphasized the large errors that can be expected in the soil depth values and in the current sheet and rill erosion rates (probably ± 200 per cent, and possibly higher). When these two sets of values are combined to generate the expected soil depths at around the year 2007, the resultant errors may become considerably higher for some areas, and may be partially compensated in other areas. Furthermore, at a scale of 1:2m there must inevitably be tremendous variability within both the sheet and rill erosion rate mapping units and within the soil depth mapping units. This variability will become further accentuated in the generated "soil depth in the year 2007" mapping units. It is not possible to give any reliable estimate of the expected errors, but over-estimates or under-estimates of the order of 3- or 4- fold may well occur. Moreover, in the hatched areas in Fig. 8, the changes in soil depth are particularly unreliable because of lack of data concerning the current sheet and rill erosion rates. Extreme caution must therefore be adopted in the use of this generated data. Nevertheless the soil depth in the year 2007 (Fig. 8) is probably capable of distinguishing between those areas where the effective depth changes are expected to be extremely high and those areas where the changes are likely to be minimal. Areas where significant changes in the effective soil depth are expected over the next 25 years occur in N. and S. Gonder, around Mt. Ras Dejen, in E. Gojam, W. Shewa, N. Wellega regions and in the E. Highlands. Preliminary measurements of the expected changes in effective soil depth classes given in Fig. 8 reveals that approximately 30,000 km^2 of land would be reduced to exposed rocks, over 40,000 km^2 would be reduced to soils of less than 10cm depth and about 17,000 km^2 would be reduced to soils of 10-25 cm depth in 25 years. Thus approximately 70,000 km^2 would be rendered unsuitable for arable agriculture and 17,000 km^2 would become only marginally suitable if the current sheet and rill erosion rates are allowed to continue unabated.

7.3 Predicted changes in available water capacities

The available water capacity (AWC) of a soil represents the quantity of water that can be stored within a soil between field capacity and permanent wilting point and which is available for plant uptake. Very limited available water capacity data is available in the literature for soils from the Ethiopian highlands. Selected data is given in Appendix 10, but the values are complicated by field capacity sometimes having been determined at 0.3 bars and sometimes e.g. by Huntings Technical Services (1976), at 0.1 bars. This leads to very pronounced differences in the AWC values. Since the moisture tensions at which soils attain field capacity, and not all soils do reach field capacity, vary between 0.1 to 0.3 bars, it was decided to use field capacity values

estimated at 0.2 bars wherever possible in the estimation of AWC values. A linear relationship was assumed between moisture content and moisture tension between 0.1 and 0.3 bars. From the data in Appendix 10 combined with the use of AWC values reported in the literature for specific soil types, a very tentative assignment of available water capacity values was made for the top-soils (0-15cm) and sub-soils (below 15cm depth) of specific soil units (see Table 20).

Table 20

Tentative available water capacity (AWC) values* assigned to different soil units

Soil units	Available water capacity (%; v/v)	
	Top-soil (0-15 cm)	Sub-soil (below 15 cm)
Mollic and Vitric Andosols	30	30
Rendzinas and Calcic Chernozems	25	25
Haplic and Luvic Phaeozems and humic Cambisols	20	20
Cambic Arenesols	10	5
All other soil units	20	15

*Based on F.C. = 0.2 bars and P.W.Pt. = 15 bars.

For each soil unit, the available water capacity values were calculated using the top soil and sub-soil available water capacity values given in Table 20, and the effective soil depths from Fig. 2. The calculated AWC values were then rated into eight classes according to the scheme shown in Table 21. To facilitate the mapping of the AWC values, a relationship between soil units, effective soil depths and AWC ratings was developed, shown in Table 22. A map showing the distribution of available water capacity classes is presented in Fig. 9. 1/ It must be emphasized, however, that errors are likely to be high. The soil depth data is not particularly reliable (see Fig. 3) and the AWC values asssigned to the soil units are based on a very limited amount of data and must therefore be regarded as very tentative. Moreover, the AWC values of the very stony phases, found most commonly within the haplic Phaeozems and the eutric Cambisols, will be over-estimated. Nevertheless, despite these serious short-comings, Fig. 9 should be capable of discriminating between areas with very high to high AWC values and areas with low to very low AWC values.

1/ Because of the broad ranges in AWC values found for individual soil type - soil depth mapping units, it became necessary to delineate 15 AWC classes in Fig. 9. This large number of AWC classes can be simplified according to the boundary values that are of interest, by reducing the number of AWC classes into fewer broader classes.

Table 21

Ratings for available water capacity (AWC) values

	A.W.C. Classes (mm)							
	0–25	25–50	50–75	75–100	100–150	150–200	200–300	300
Rating	7	6	5A	5B	4	3	2	1

Table 22

Relationships between soil units, soil depths and available water capacity ratings

		Available water capacity ratings				
Soil depth symbol	Soil depth (cm) \ Soil unit	Mollic Andosols (Tm) Vitric Andosols (Tv)	Rendzinas (E) Calcic Chernozems (Ck)	Haplic Phaeozems (Hh) Humic Cambisols (Bh)	Cambic Arenosols (Qc)	Other soil units
a	>150	1	1	1	4–5B	2
b	100–150	1	1–2	2	5A	2–3
c	50–100	2–3	2–4	3–4	6	4–5B
d	25–50	4–5B	4–5A	5A–5B	6	5A
e	10–25	5A–6	5A–6	6	7	6
f	0–10	7	7	7	7	7

To permit an assessment of the impacts of current sheet and rill erosion rates on available water capacity values over a period of 25 years, it is necessary to compare the present AWC values in Fig. 10 with the projected AWC values for the year 2007. (The apparent discrepancy between the period of 25 years and the date 2007 is due to the date at which the soil depths were measured, see section 5.1). The estimated available water capacity values for the year 2007 were obtained by combining the provisional soil map (Fig. 4) with the estimated effective soil depth map for the year 2007 (Fig. 8) and using the soil unit - soil depth - available water capacity ratings presented in Table 22. The distribution of the estimated AWC values in the year 2007 or earlier is shown in Fig. 10. For cartographic reasons it was not possible to represent the present AWC and AWC expected in 25 years time on the same map. The considerable inherent errors likely to be present in Fig. 10 must be emphasized, especially in the hatched areas of Fig. 10 for which no calculated sheet and rill erosion rate data were available. The data presented in Fig. 10 can be regarded as the best estimates possible for projected available water capacities in the year 2007, but they must be viewed with considerable caution. The areas where the most significant reductions in available water capacity are expected during the next 25 years occur in N. and S. Gonder regions, around Mt. Ras Dejen, in E. Gojam, W. Shewa, N. Wellega and in the E. Highlands.

7.4 Predicted soil nutirient losses

The annual soil nutrient losses were estimated by calculating the quantity of organic matter, total nitrogen, exchangeable potassium and Olsen-extractable phosphorus that would be present in the depth of soil removed in one year from each sheet and rill erosion rate class acting on each of the four generalised soil chemical fertility classes. The representative organic matter, total nitrogen, exchangeable potassium and Olsen-extractable phosphorus values given in Appendix 6 for each of the generalised soil chemical fertility classes were used in the calculations. The depth of soil lost by sheet and rill erosion in one year was taken to be the average value for each sheet and rill erosion rate class, and was converted into a weight basis using a bulk density of 1.2 g/cm^3 for all soils. To account for the fact that eroded sediments generally contain a higher proportion of nutrients and organic matter than the original soil, enrichment ratios of 2.0 for organic matter, exchangeable potassium and total nitrogen and an enrichment ratio of 2.4 for Olsen-extractable phosphorus were introduced. These values were taken from Hudson and Jackson (1959).

$$\text{Enrichment ratio} = \frac{\text{nutrient concentration in the eroded sediments}}{\text{Nutrient concentration in the original soil}}$$

The The calculated annual nutrient losses for each sheet and rill erosion rate class and for each soil chemical fertility class are given in Appendix 11. These values are very tentative since they are based on very scanty chemical fertility data and on sheet and rill erosion rate classes subject to high errors. To avoid the impression of false precision the nutrient losses have been grouped into five broad classes as shown in Table 23 and in the legend to Fig 7 where they are related to erosion rate-chemical fertility class mapping units. Figure 7 can be readily simplified by using the broad nutrient loss classes for each of the nutrients in turn.

The absolute values of annual nutrient losses range up to more than 21 t/ha/yr. of organic matter, up to and exceeding 1.2 t/ha/yr. of total nitrogen, up to and in excess of 180 kg/ha/yr. of exchangeable potassium and up to and greater than 5.1 kg/ha/yr., of Olsen-extractable phosphorus (Appendix 11). The quantities of nutrients lost by erosion over a 25 year period however, cannot be obtained simply by multiplying the values given in Table 23 or the legend to Fig. 7 by 25. This is because the nutrient enrichment ratios generally decrease with time; the greater the soil loss, the lower will be the enrichment ratio. Moreover, the rate of change of the enrichment ratio with increasing soil loss will vary depending on the nutrient being considered. The total nutrient losses over a 25 years period may therefore exceed the annual values given in Table 23 by a factor of between 15 and 25.

It needs to be emphasized that the Olsen-extractable phosphorus values do not indicate how much available phosphorus has been lost from the soils. The Olsen-extractable values are merely indices of phosphate availability and cannot be related to the amounts of available phosphorus lost through erosion. The same situation arises for any other chemical extraction method used to characterise phosphate availability. Consequently, these values in Appendix 11 can only be used to illustrate the relative differences in available phosphate losses between different erosion rate classes or between different generalised soil chemical fertility classes. These values cannot be used in an economic analysis of the replenishment costs of phosphorus losses by sheet and rill erosion, and have therefore been excluded from Table 23.

The exchangeable potassium values can be considered as a more reliable indication of the quantity of readily available potassium that has been lost from the soils. The annual exchangeable potassium losses due to sheet and rill erosion given in Table 23 have been converted into very tentative nutrient losses over 25 years by multiplying the annual losses by a 25 year enrichment ratio factor of 20. This value of 20 is to account for the decreasing enrichment ratio with increasing depth of soil removed. Table 23 also gives the estimated exchangeable potassium contents in the top 45 cm of soil calculated from the values given in Appendix 11. A comparison of the 25 years exchangeable potassium losses with the contents in the top 45 cm of soil for each soil fertility class shows that for soil fertility classes 1, 2 and 3b the exchangeable potassium contents will not be depleted from the very low to medium untrient erosion rate classes but will be depleted from the high and very high nutrient erosion rate classes. For class 3a soils, the very low and low nutrient erosion rate classes will not deplete the soil's exchangeable potassium during a 25 year period but medium and higher nutrient erosion rate classes will deplete the soils of exchangeable potassium from the top 45 cm. A crude estimate of the projected potassium losses from the Ethiopian highlands over a 25 year period can be obtained from Fig. 7 by measuring the areas occupied by each of the five nutrient erosion rate classes for K, and multiplying the areas by the mean K loss in kg/ha/25yr for each of the K erosion rate classes. A lack of time prevented the consultant from making these calculations. In attempting to estimate the replenishment costs of K losses it would be assumed that all of the potassium which is lost is 'useful' potassium rather than surplus potassium. This is probably not altogether true since responses to K fertilisers on Ethiopian soils are rare. Nevertheless, over a 25 year period the bulk of the potassium lost by sheet and rill erosion could probably be considered as 'useful' potassium.

Table 23

Relationship between nutrient losses by sheet and rill erosion and soil nutrient levels

	Generalised soil fertility class																							
	Class 1						Class 2						Class 3A						Class 3B					
	OM t/ha		N t/ha		K kg/ha		OM t/ha		N t/ha		K kg/ha		OM t/ha		N t/ha		K kg/ha		OM t/ha		N t/ha		K kg/ha	
	t/s[a]	s/s[b]	t/s	s/s	t/s	s/s	t/s	s/s	t/s	s/s	t/s	s/s	t/s	s/s	t/s	s/s	t/s	s/s	t/s	s/s	t/s	s/s	t/s	s/s
mated soil ient ents	70	94	4	2.7	560	840	46	74	2.9	2.5	490	700	30	40	2.1	1.8	210	420	80	87	3.6	2.5	700	700
l est'd soil ient	164		6.7		1400		120		5.4		1190		70		3.9		630		167		6.1		1400	
ient erosion classes	Estimated annual (and 25 years) soil nutrient losses due to sheet and rill erosion*																							
	OM[c]		N[c*]		K[d]		OM[c]		N[c]		K[d]		OM[c]		N[c]		K[d]		OM[c]		N[c]		K[d]	
low	0–1 (0–20)		0–0.1 (0–2)		0–5 (0–100)		0–1 (0–20)		0–0.1 (0–2)		0–5 (0–100)		0–1 (0–20)		0–0.1 (0–2)		0–5 (0–100)		0–1 (0–20)		0–0.1 (0–2)		0–5 (0–100)	
	1–5 (20–100)		0.1–0.2 (2–4)		5–20 (100–400)		1–5 (20–100)		0.1–0.2 (2–4)		5–20 (100–400)		1–5 (20–100)		0.1–0.2 (2–4)		5–20 (100–400)		1–5 (20–100)		0.1–0.2 (2–4)		5–20 (100–400	
um	5–10 (100–200)		0.2–0.5 (4–10)		20–50 (400–1000)		5–10 (100–200)		0.2–0.5 (4–10)		20–50 (400–1000)		5–10 (100–200)		0.2–0.5 (4–10)		20–50 (400–1000)		5–10 (100–200)		0.2–0.5 (4–10)		20–50 (400–1000)	
	10–15 (200–300)		0.5–1.0 (10–20)		50–100 (1000–2000)		10–15 (200–300)		0.5–1.0 (10–20)		50–100 (1000–2000)		10–15 (200–300)		0.5–1.0 (10–20)		50–100 (1000–2000)		10–15 (200–300)		0.5–1.0 (10–20)		50–100 (1000–2000)	
high	>15 (>300)		>1.0 (>20)		>100 (>2000)		>15 (>300)		>1.0 (>20)		>100 (>2000)		>15 (>300)		>1.0 (>20)		>100 (>2000)		>15 (>300)		>1.0 (>20)		>100 (>2000)	

0–15 cm depth

15–45 cm depth

In t/ha/yr

In kg/ha/yr

M – Organic Matter in t/ha

– Total Nitrogen in t/ha (Not available nitrogen)

– Exchangeable Potassium in kg/ha

Very tentative nutrient losses over a 25 year period have been estimated by the introduction of a factor of 20, and are given in (   ), beneath the annual nutrient loss values.

t/s – top-soil

s/s – sub-soil

[illegible]

The values given for annual total nitrogen losses in Appendix 11 range up to more than 1.2 t/ha, or in excess of 24 t/ha/25yr. if a 25 year enrichment ratio factor of 20 is introduced. Comparing the 25 year total nitrogen losses given in Table 23 with the total nitrogen contents in the top 45 cm of profile for the four generalised soil chemical fertility classes indicates that the very low and low nutrient erosion rate classes will not deplete the soils of total nitrogen. Higher nutrient erosion rate classes may however largely deplete the 0-45 cm soil horizons of total nitrogen depending on the extent to which nitrogen is added to the soil through plant roots, residues, symbiotic and non-symbiotic nitrogen fixation. Since the total N losses at the high and very high nutrient erosion rate classes are considerably higher than the estimated total nitrogen contents of the 0-45 cm soil horizons, it would be expected that total nitrogen would decrease appreciably over a 25 year period at these high nutrient erosion rates. This will be most pronounced where legumes are not a normal component of the crop rotation, and where fallow periods are very short or non-existent.

The total nitrogen losses from the Ethiopian highlands over 25 years can be obtained by planimetering the areas occupied by each of the five total N erosion rate classes in Fig. 7 and multiplying the area by the predicted mean 25 year total N losses for each total N erosion rate class. When attempting to quantify the replenishment costs for the loss of nitrogen through erosion the costs should be based not on the total nitrogen lost but on the quantity of available or useful nitrogen lost. It needs to be emphasized that the total nitrogen losses do not indicate the quantities of available or useful nitrogen lost by erosion. In any one year only a small porition of the total nitrogen may be mineralised, and only part of the mineralised nitrogen will be utilised by crops, the remainder being lost by leaching and denitrification. Probably only about 2 per cent of the total nitrogen may be mineralised from arable land in any one year (e.g. Willis and Evans; 1977) and less than 1 per cent possibly 0.5 per cent may be mineralised from grasslands (e.g. Greenland and Nye, 1959). These figu es must be treated with caution since they are not based on data derived from the Ethiopian highlands. To estimate very crudely the quantities of available or 'useful' nitrogen lost by erosion each year from the Ethiopian highlands the areas occupied by each N erosion rate class in Fig. 7 and the proportion of arable and grazing land in each N erosion rate class would need to be determined. The available nitrogen losses over a 25 year period could be estimated from perhaps 1.6 per cent and 0.4 per cent of the 25 year total nitrogen losses calculated for the arable and grazing lands respectively in each of the N erosion rate classes. These values of 1.6 per cent and 0.4 per cent are less than the annual mineralisation rates of 2 per cent and 0.5 per cent for arable lands and grasslands respectively to account for the progressive exponential decline in the quantities of nitrogen mineralised each year. This is clearly a very tentative and time consuming exercise, but replenishment costs should be based on the losses of "useful" nutrients to avoid over-estimations of the replenishment costs.

The annual soil organic matter losses are up to and in excess of 21 t/ha/yr. (see Appendix 11). Over a 25 year period the estimated quantities of organic matter lost by erosion are well in excess of the top 0-45 cm soil organic matter contents at the high and very high organic matter erosion rate classes. These

high organic matter losses have important implications to the losses of nitrogen in particular (see above), but also for the losses of associated nutrients such as sulphur, phosphorus and micro-nutrients that are present in soil organic matter, and which would be slowly released through mineralisation processes. Moreover, the steady decline in organic matter contents will increase the crusting susceptibility and erodibility of the so soils (section 2.3).

In the estimation of the replenishment costs for the sulphur and phos-phosphorus present in the soil organic matter it can be assumed that the C:S:P ratio in organic matter is 100:1:2, and if C forms 58 per cent of the organic matter, there would be 5,8 kg s/ha and 11.6 kg P/ha lost by erosion for every 1 t/ha of organic matter lost by erosion. However, the quantity of useful or available sulphur and phosphorus that would be lost in tonne of organic matter, i.e. the amount that would have been mineralised annually, might be only 2 per cent and 0.5 per cent of these values for arable and grassland soils respectively, i.e. 116 g of S and 232 g of P from arable soils, and 29 g of S and 58 g of P from grassland soils. The quantities of phosphorus and sulphur mineralised over a 25 year period might be 1.6 per cent and 0.4 per cent of the 25 year organic P and S losses from arable and grazing lands respectively, because of the exponential decline in mineralisation with time. These values are however very tentative. The total organic P and S lost through the erosion of organic matter from the Ethiopian highlands can be estimated by measuring the area of each organic matter erosion rate class in the highlands (Fig. 7) and multiplying the areas by the corresponding mean 25 year organic matter losses. The total organic P and S losses will be approximated by 1.16 and 0.5 per cent of the organic matter losses. To obtain the quantities of available P and S that would have been released by mineralisation during a 25 year period an estimate of the proportion of arable land and grazing land in each organic matter erosion rate class needs to be established. The total organic P and S lost by erosion from the arable and grazing lands should then be multiplied by 1.6 per cent and 0.4 per cent respectively to arrive at the quantities of useful organic P and S lost during a 25 year period.

This prediction of soil nutrient losses is a very dubious and precarious exercise based on a very limited amount of "hard" data, and involving many estimates, This is particularly so for the prediction of "useful" N, P and S losses, i.e. the quantities of organic N, P and S lost by erosion which would have been mineralised during a 25 year period. Although it is possible to calculate a figure for the replenishment costs of available nutrients lost by erosion, the validity of the figure obtained will be very much open to question.

8. CONCLUSIONS

8.1 Nature, causes and relative importance of soil degradation processes

(a) Sheet and rill erosion appear to be the most widespread and the most damaging degradation processes occurring in the Ethiopian highlands though this cannot be unequivocally proven. The main causes are poor farming practices characterised by a general lack of conservation practices, the cultivation of excessively steep slopes, deforestation and overgrazing, Areas with excessive rates of soil loss, i.e. in excess of 6.5 mm/yr occur in S. Gonder, NE Gojam, N. Wellega, around Mt. Amba Farit and in the E. Highlands;

(b) Physical degradation resulting in a physical deterioration of surface soils through a lack of protective ground cover is also probably widespread and closely inter-related with sheet and rill erosion. Physical degradation due to the traffic of humans and livestock is probably of local importance in some areas and the resultant surface compaction and increased runoff can lead to gulley and footpath erosion;

(c) Chemical degradation due to leaching and the development of Al toxicity problems are probably of only very local and limited extent - though the actual extent is unknown. Such areas would occur in class 3b soils (Fig. 5) associated with very high rainfall in the Wellega, Ilubabor and Keffa regions (rainfall regime A in Fig. 11);

(d) Chemical degradation due to the "mining" of soil nutrients as a result of poor farming practices are likely to be particularly widespread and serious with respect to phosphorus. Where fallow periods are short or non-existent, legumes are absent from the farming system, and in class 3a soils with very low nitrogen levels, the steady decline in nitrogen levels will also give cause for concern. This process is the result of continuous nutrient harvesting without, or with only a minimal, return of nutrients, This situation becomes most serious where fertilisers are not used, crop residues are utilised for fodder, the dung as fuel, and also where "gaye", i.e. burning the top-soil is practised, and where grasslands are burned during the dry season;

(e) Biological degradation is only expected to be important in low rainfall areas (D and E, Fig. 11) and in class 3a soils (Fig. 5) where organic matter levels are low;

(f) Salinisation and alkalisation processes causing the accumulation of salts and sodium are restricted to the area around Lake Abiyata in the Rift Valley;

(g) Mass movements resulting in landslides, mudflows and earthflows are probably also of very localised occurrence and would be expected to be most prevalent in the high rainfall areas, i.e. in rainfall regime A in Fig. 11;

(h) Gulley erosion is probably of widespread occurrence but the area of agricultural land affected is very limited. The main causes are overgrazing and compaction leading to physical degradation, and poor road drainage

8.2 The hazards of degradation

(a) The main hazards of the inter-related sheet and rill erosion and physical degradation are:

(i) a deterioration in the physical fertility status of soils i.e. in effective depth and available water capacity,

(ii) a deterioration in the chemical fertility status of soils through losses of organic matter and nutrients.

(b) A soil physical erosion hazard index has indicated (Fig. 12) that the areas suffering from the greatest deterioration in soil physical fertility are Tigrai, N. Gonder and Wello regions, parts of Gemo-Gofa and Keffa regions, and parts of the E. Highlands;

(c) Assuming, current erosion rates continue then over a 25 year period preliminary estimates show that about 30,000 km^2 of soils will be reduced to rock, 41,000 km^2 will be reduced to less than 10 cm depth and 17,000 km^2 of soils will be reduced to 10-25 cm depth. Thus, over 70,000 km^2 of the highlands would become unsuitable for arable agriculture and another 17,000 km^2 would be rendered only marginally suitable. The areas most affected are Wello region, the Simen Mts, N. Gonder and E. Shewa regions. Parts of Gojam, Wellega and the Eastern Highlands would also be subject to significant reductions in effective soil depth;

(d) A soil chemical erosion hazard classification has shown (Fig. 6) that hazards due to deteriorating phosphorus fertility are generally very high to extremely high throughout the highlands. The hazards of declining organic matter and nitrogen levels are very high in the Tigrai, Eritrea, Gonder and Gojam regions and in the Eastern Highlands. The hazards of diminishing potassium fertility are generally very low to low throughout the highlands except in restricted areas in Gonder, Gojam and N.W. Shewa regions and in parts of the Eastern Highlands where the hazards are medium. Aluminium toxicity hazards are generally very low apart from localised areas in S. Gojam, Wellega, Ilubabor, Gemu-Gofa and Sidamo regions where the hazards are medium for Al-sensitive crops such as sorghum and cotton;

(e) The areas expected to experience significant reductions in soil depth would be the smae areas where available water capacity reductions would be e expected. The present and expected available water capacities in the year 2007 have been mapped in Figs. 9 and 10;

(f) Very tentative predictions of the quantities of nutrients that would be lost by erosion over a 25 year period gave values up to and exceeding 300t/ha of soil organic matter, 20 t/ha of total nitrogen and 2000kg/ha of exchangeable potassium. Projected losses of inorganic phosphorus could not be estimated, and although calcium and magnesium losses were not predicted, it was likely that only surplus Ca and Mg would be lost. The total nutrient losses from the highlands predicted over a 25 year period were not calculated because of

insufficient time, though this data can be readily obtained from the areas occupied by the five nutrient erosion rate classes given in Fig. 7 for each nutrient. It was tentatively suggested that about 2 per cent of the total nitrogen, organic phosphorus and sulphur in the soil organic matter would be released each year by mineralisation from arable lands and 0.4 per cent would be released each year from the grasslands. The replenishment costs should be based on the quantities of nutrients lost by erosion that would be mineralised in a 25 year period.

8.3 Implication and use of the data obtained

(a) The physical tolerance of soils to further sheet and rill erosion indicates the areas which are now not suited to arable agriculture e.g. where soils are less than 25 cm or 10 cm in depth. Such areas can be considered in need of reafforestation and could be used to supply fuel, building materials and fodder for livestock;

(b) The chemical tolerance of soils to further sheet and rill erosion gives a very approximate indication of the chemical fertility status of the soils in different areas, and can also be used in combination with the soils map, to make more specific fertiliser recommendations as to the types of fertilisers to be used in different regions e.g. where acid-forming fertilisers should not be used (e.g. on class 3b soils), where phosphate fixation problems will affect the phosphorus fertiliser responses and method of application (e.g. on the andosols and to a lesser extent on the acrisols and nitosols), where liming may be necessary (e.g. class 3b soils), and where urea will be less efficient due to volatilisation losses (e.g. on class 2 and 3a soils);

(c) The physical erosion hazard index map indicates which areas are in most danger of declining productivity due to deteriorating physical fertility i.e. in effective soil depth and available water capacity. The influence of decreasing available water capacity on soil productivity will also be governed by the probability of moisture deficits occuring which are shown in Fig. 11. Thus decreasing available water capacity values will cause crops and vegetation to be more susceptible to water deficits particularly in rainfall regimes D and E (Fig. 11) with high to moderate moisture deficit probabilities. Areas with very high physical erosion hazard ratings are in urgent need of soil conservation measures, but see 9.5 concerning the identification of priority areas for government intervention;

(d) The chemical erosion hazard map delineates those areas that are in greatest danger of declining productivity due to deteriorating soil chemical fertility. Areas of high chemical erosion hazard are most in need of improved farming systems, but see 9.5 for the identification of priority areas;

(f) The estimated annual sheet and rill erosion rates map reveals which areas are currently suffering the highest rates of soil loss, and consequently in which areas there may be locally high suspended sediment loads causing

siltation problems downstream. The fact that high sheet and rill erosion rates exist does not necessarily imply that suspended sediment rates will be high since much of the soil lost from the hillslopes may not enter the drainage system.

8.4 The need for improved farming systems

The presence of severe soil degradation is symptomatic of poor, or inappropriate, farming systems. the existing farming systems should therefore be modified and improved (but not radically altered unless this is socially acceptable) and should be the main vehicle by which soil degradation is halted and agricultural productivity is increased. The improved farming systems need to meet the following requirements:

(a) They are suited to the local agro-ecological environment;

(b) The changes are socially acceptable and agreed by the peasants associations;

(c) They result in higher productivity;

(d) They do not necessitate high cost inputs or the use of large quantities of foreign exchange;

(e) They can be introduced at an appropriate technological level;

(f) They provide the farmer with a well balanced nutrientional diet;

(g) They will be capable of arresting soil degradation through effective soil conservation and will maintain, if not restore, the physical and chemical fertility of the soils.

The type and design of the recommended physical and cultural soil conservation practices should be part and parcel of the improved farming systems and should also be selected according to the nature of the soil type, particularly soil drainage, erodibility, effective depth, slope of the land and the rainfall regime. Thus specific recommendations based on local conditions are required, similar to the provisional proposals made by Thomas and Barber (1982) for support practices in Kenya, rather than using standard procedures for the whole of the country or region.

The farming system must maintain, if not improve, the chemical fertility status of the soils. Thus the use of leguminous crops, including tree crops and cover crops, will help to up-grade the soil nitrogen levels. Agro-forestry would seem to have considerable potential if nitrogen fixing tree crops can be introduced. Species such as Robinia pseudo-acacia (Black Locust) and Morus alba are suited to high altitude/low temperature regions, are fast growing, fix nitrogen, will coppice and can be used as fodder (Kernick - pers. comm.). Fruit trees will also have the advantage of diversifying diets.

Restoring the posphate fertility of the soils is likely to be the major obstacle to raising productivity. Tree crops are capable of nutrient enrichment of surface soil horizons through the Goldschmidt process of harvesting nutrients from deeper sub-soil horizons (beyond the reach of the roots of annual crops) and returning them to the soil surface through litter accumulation. In this way the presence of tree crops in the farming system, or fallow periods, if of adequate duration, may ameliorate the low phosphate levels to a limited extent. It is most likely however that phosphate fertilisers will need to be applied in many parts of the country if yields are to be maintained or increased.

8.5 The identification of priority areas for government intervention

The soil physical erosion hazard index map and the soil chemical erosion hazard map indicate those areas experiencing varying degrees of declining productivity due to a lowering of soil physical and soil chemical fertility. These are just two parameters that need to be considered when making decisions on priority areas for government assistance and intervention. Other parameters that need to be considered are population density and distribution, and the economic advantages of intervention in areas subject to different degrees of hazard. The costs of reclamation, conservation and development must be weighed against the benefits to be accrued from the land. Thus on purely economic grounds it may be better to select areas experiencing moderate degradation hazards if the potential productivity of these areas, once degradation has been arrested and soil fertility has been ameliorated, is expected to be greater than that of areas subject to high hazards. This becomes particularly important when, as is the case for Ethiopia, funds, manpower and experience, are very limited.

8.6 Further studies required

The generally acknowledged serious state of deterioration of the Ethiopian highlands due to soil degradation, the recognised urgency of the situation and the limited financial resources and trained manpower in the country militates against further studies devoted to data collection, such as the quantification or mapping of soil degradation processes, or long term studies requiring high inputs such as validating the USLE. To validate the USLE would require at least 10, if not 20, years of data collection and would be an extremely expensive study, so much so that no country in Africa has yet been able to fully test the applicability of the USLE for their country.

In the author's opinion first priority should be given to studies that investigate, for specific agro-ecological and socio-economic zones, the capability of improved farming systems to arrest soil degradation, maintain or enhance soil fertility, give higher yields and be socially and economically acceptable. Such studies should investigate and monitor the effects of integrated crop/pasture/livestock/forestry enterprises with appropriate conservation,

tillage and management practices on soil losses, soil fertility, yields and nutritional status of the local farmers. These investigations need to be conducted in catchments similar to existing studies being conducted by Dr. H. Hurni. They should also involve the active participation of, and decision-making by, the local peasants associations.

At a second level of priority further studies are required to assess the fertility status of soils in the highlands and crop-fertiliser responses. Field trials need to be established for important crops on selected soil types representative of large areas in different defined agro-ecological zones. The relationships between soil analyses and crop responses to different fertiliser levels need to be established if soil analytical data are to be properly interpreted and specific to soil type, crop and agro-ecological zone. Crop responses to phosphate fertilisers are considered to be particularly important since phosphate is likely to be the most limiting nutrient. Nitrogen should be capable of being maintained at a satisfactory level through the judicious use of legumes, crop rotations and fallow periods. Existing evidence indicates that, in general, calcium, magnesium (Appendix 6), potassium and sulphur (FAO, 1970) 1/ are unlikely to be limiting factors for most of the highland soils. Field trials should also be established to investigate the incidence of aluminium toxicity problems in the dystric nitosols and orthic acrisols and the need for, and responses to be obtained from liming. These activities should be considered just as important as the need to strengthen the country's soil analysis capability.

1/ Evidence for potassium and sulphur not being limiting factors was given by the non-significant yield increases between NP and NPK treatments; the K being applied as K_2SO_4.

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Derivation of Crusting Indices for Top-Soils of Chromic Luvisols, Eutric Cambisols and Dystric Nitosols

Soil	Profile number (Depth, cm)	% Silt	% Clay	%OM	%Clay + 10.OM%	% Silt (% Clay + 10.OM%)	Crusting and runoff index
Chromic Luvisols (Lc)	PB/1 (0-14)	28.72	26.98	2.75	54.48	0.52	
Source: Hunting Tech. Services, 1976	MS/14 (0-15)	32.50	14.99	1.03	25.29	1.28	
	QE/8 (0-25)	24.94	17.99	1.37	31.69	0.78	
LUPRD	(S.R.)	13.82	40.02	2.48	64.82	0.21	
Average						0.69	0.69
Eutric Cambisols (Be)	CSA4/6 (0-15)	7.58	8.09	0.51	13.19	0.57	
Source: Hunting Tech. Services, 1976	PG/1 (0.10)	11.60	4.62	1.03	14.92	0.77	
	MS/1 (0-6)	15.62	17.91	1.72	35.11	0.44	
	PE/13 (0-15)	9.37	5.20	0.51	10.30	0.90	
	CSA4/5 (0-15)	16.51	20.80	3.44	55.20	0.29	
	CSAR/8 (0-20)	14.28	20.80	3.78	58.60	0.24	
	QE/4 (0-20)	12.50	5.78	0.68	12.58	0.99	
	JS/1 (0-15)	7.58	8.09	0.30	11.09	0.68	
	QE/5	4.91	8.67	0.68	15.47	0.31	
Average						0.57	0.57
Dystric Nitosols (Nd)	K1	19.79	18.36	4.99	63.26	0.31	
Source: LUPRD	K2	20.83	21.09	4.35	64.59	0.32	
	K3	19.79	19.72	3.62	55.92	0.35	
	K4	18.74	21.09	4.66	67.69	0.27	
	K5	20.83	19.72	5.14	71.12	0.29	
Average						0.30	0.30

Derivation of Crusting Indices for Sub-Soils of Chromic Luvisols, Eutric Cambisols and Dystric Nitrosols

Soil	Profile number	% Silt	% Clay	% OM	% Clay + 10.OM%	% Silt / (% Clay + 10.OM%)	Crusting and runoff index
Chromic Luvisols							
(Lc)	PB/1	29.61	26.45	1.03	36.75	0.80	
	MS/14	24.81	20.30	1.37	34.00	0.72	
	QE/8	32.82	21.53				
	LUPRD (S.R.)	12.76	31.71	1.38	45.51	0.28	
Average						0.60	0.60
Eutric Cambisols							
(Be)	CSA4/6	10.63	7.88	0.2	9.88	1.07	
	PG/1	7.24	6.89	0.5	11.89	0.60	
	MS/1	16.91	8.33	0.8	16.33	1.03	
	PE/13	11.11	5.47	0.4	9.47	1.17	
	CSA4/5	18.84	9.28	2.0	29.28	0.64	
	CAA4/8						
	QE/14	16.91	8.33	0.2	10.33	1.63	
	JS/1	10.63	5.23	0.11	6.33	1.67	
	QE/5	7.73	3.80	0.5	8.80	0.87	
Average						1.08	1.08
Dystric Nitosols							
(Nd)	K1	23.20	17.40	3.45	51.90	0.44	
	K2	19.50	19.40	1.38	33.20	0.58	
	K3	14.58	27.38	1.73	44.68	0.32	
	K4	18.27	21.39	2.42	45.59	0.40	
	K5	24.43	14.41	3.07	45.11	0.31	
Average						0.41	0.41

Derivation of Crusting Indices for Top-Soils and Sub-Soils of Pellic and Chromic Vertisols

Source	Profile number	Depth (cm)	% Silt	% Clay	%OM	% Clay+ 10.0M%	% Silt / (% Clay+10.0M%)
		Top-Soil					
Hunting Tech.Services 1976, Tigrai							
	MS/5	0-15	48	40	2.23	62.30	0.77
	CSA1/1	0-10	44	39	2.58	64.80	0.68
	QE/2	0-8	23	35	3.39	68.90	0.33
	CV/1	0-10	24	58	3.44	92.40	0.26
	MS/3	0-10	28	49	1.03	59.3	0.47
		0-10	33.40	44.2	2.53	69.5	0.50
		Sub-Soil					
	MS/5	15-40	42	46	2.23	68.30	0.62
	CSA1/1	10-30	30	48	2.06	68.6	0.44
	QE/2	8-75	20	48	1.15	59.5	0.34
	CV/1	10-40	19	59	3.09	89.9	0.21
	MS/3	10-45	25	54	1.89	72.9	0.34
Average		10-45	27.20	51	2.07	71.84	0.39

Top-Soil Characteristics for Soil Units within Each Soil Chemical Fertility Class

Source	Soil unit	EROD[Y] Index	Clay (%)	PH	OM %	C %	C/N	Total N %	Total K (ppm)	Total P (ppm)	Avail P (ppm)	Exchangeable (ma/100g) Ca	Mg	K	CBC me/100g	B.S %
CLASS 1																
LUPRD; 1984 (B52)	Hh		7.5	7.35	4.04	2.34					4.5			0.51		
(B53)	"		11.5	6.80	3.83	2.22					4.5			0.51		
(B70)	"		38.9	5.25	9.32	5.41					5.4			0.51		
(B61)	Hhs		16.9	6.25	2.31	1.34					4.5			0.51		
(B63)	"		10.9	5.50	5.76	3.34					3.6			1.53		
(B65)	"		10.9	6.00	1.55	0.90					3.6			1.53		
(B66)	"		20.9	6.45	0.76	0.44					2.7			0.51		
(B68)	"		30.9	6.15	3.62	2.10					5.4			0.51		
Average			18.6	6.22	3.90 m	2.27					4.3 vl			0.77 h-m		

APPENDIX 4(a)

Top-Soil Characteristics for Soil Units Within Each Soil Chemical Fertility Class

Source	Soil Unit	Erod Index[Y]	Clay (%)	PH	OM %	C %	C/N	Total N (ppm)	Total K (ppm)	Total P (ppm)	Avail P (ppm)	Exchangeable (me/100g) Ca	Mg	K	CEC me/100g	B S %
hy, 1968: Shawa, dis Abeba to bra Sina	?	–	–	5.6–6.5	4.3	2.5	13	0.19	–	514	Vl to l	h	h	hm to h		
ing Tech. Services 76, Tigrai (MS5)	Vc		40	7.8	2.24	1.3		0.1	5330	–	1.2	16.9	1.7	0.1	19.0	
0-10 (CSAI/1)	Vc		39	7.5	2.58	1.5		0.2	5870	–	0.0	25.3	3.0	1.1	26.2	
(QE/2)	Vc		35	7.2	3.44	2.0		0.2	2150	–	0.7	20.4	6.9	0.3	29.2	
0-10 (CV1)	Vp	0.17	58	6.6	3.44	2.0		0.2	2980	–	4.6	31.4	10.0	1.0	35.9	
0-10 (MS3)	Vp	0.22	49	7.9	1.03	0.6		0.1	5870	–	1.0	43.2	4.8	1.0	40.0	
rage xclg. (0-15cm) Murphy's)			44	7.4	2.55	1.5		0.16	4440		1.5	27.4	5.3	0.7	30.1	100%
					m	m		l	h	m	vl	vh	h	h		

APPENDIX 4(c)

Top-Soil Characteristics for Soil Units Within Each Soil Chemical Fertility Class

Source	Soil unit	Erod[Y] Index	Clay (%)	PH, H_2O	OM (%)	C (%)	C/N	Total N (%)	Total K (ppm)	Total P (ppm)	Avail P (ppm)	Exchangeable (me/100g) Ca	Mg	K	CEC me/100g	B.S (%)
CLASS 3A																
urphy, 1968; Tigray ligrat to Takazze iver		–	–	6.1-7.3	1.79	1.04	12	0.09		860	vl to l (5)	h (12)	h (6)	hm-h (0.6)		
urphy, 1968, Eritrea smara to Tigray order	?	–	–	6.6-7.3	2.48	1.44	11	0.13		566	h	h	h	vl-h		
unting Tech. Services 976, Tigray (CSA4/6) 0-15	Be	–	14	7.5		0.3		<0.1	870	–	0.2	14.2	4.2	0.1	14.0	
0-10 cm (PG1)	Be	0.17	8	6.4	1.03	0.6	6	0.1	2460	–	6.5	5.2	1.2	0.2	12.5	
0-15 (JS1)	Be	–	14	7.5	0.52	0.3	–	–	–	–	–	14.2	4.2	0.1	14.0	
(MS1)	Be	0.17	31	8.0	1.72	1.0	10	0.1	2150	–	6.9	24.5	4.0	0.4	35.3	
0-15 cm (PE13)	Be	0.27	9	6.7	0.52	0.3		<0.1	980	–	1.9	2.8	0.7	0.1	7.8	
0-15 (CSA4/5)	Be	–	20.3	7.7	3.44	2.0	10	0.2	5470	–	0.5	26.1	1.2	0.6	29.1	
0-20 cm (QE4)	Be	–	10	6.6	0.69	0.4		<0.1	3270	–	0.7	4.3	0.0	0.1	5.8	
0-20 (CSA4/8)	Be	–	36	7.8	3.78	2.2	7	0.3	6890	–	0.4	30.0	1.3	0.8	27.8	
0-15 (QE5)	Be	–	15	6.9	0.69	0.4	4	0.1	3270	–						
0-14 cm (PB1)	Lc	0.22	27	6.1	2.75	1.6	8	0.2	980	–	8.9	15.5	4.8	0.2	18.9	
0-15 (MS14)	Lc	–	7.0	7.0	1.03	0.6		<0.1	1260	–	3.8	12.8	4.3	0.2	18.1	
0-25 (QE8)	Lc	–	22.4	7.1	1.38	0.8	8	0.1	1600	–	17.6	6.4	1.6	0.4	9.2	
UPRD, 1982 (S.R.) 0-30	Lc	–	40.0	6.4	2.48	1.44					1.8				34.0	
rstrom, 1973, Wabi Shabelle	Lo	–		7.7	2.1	1.22	10	0.12	–	2619		7.1	4.0	0.5		
v. exclg. Murphy (0-15 cm)		0.21	19.5	7.1	1.70	0.99	8.3	0.12	2475	(708)	4.2	12.7	2.5	0.3	17.9	87
					l	l		l	m	m	vl	h	m	m		

Top-Soil Characteristics for Soil Units Within Each Soil Chemical Fertility Class

Source	Soil unit	Erod Index[Y]	Clay %	PH, H_2O	OM %	C (%)	C/N	Al.100% / ECEC	ECEC me/100g	Exch.Al me/100g	Avail P (ppm)	Exchangeable (me/100g) Ca	Mg	K	CEC me/100g	B.S, (%)
CLASS 3B																
LUPRD, 1984, Koti (K1)	Nd		26.9	4.70	4.49	2.60		0.9	14.46	0.13	5.4	10	3	1.02	37.6	38
" " " (K2)	Nd		30.9	4.90	4.35	2.52		0	15.89	0	4.5	10	4	1.02	30.4	53
" " " (K3)	Nd		28.9	5.10	3.62	2.10		0	16.89	0	6.3	13	2	1.02	29.8	57
" " " (K4)	Nd		30.9	4.45	4.66	2.70		13.1	8.95	1.17	14.5	5	3	0.51	38.0	24
" " " (K5)	Nd		28.9	5.20	5.14	2.98		0	12.53	0	7.2	6	5	1.53	50.6	26
Average			29.3	4.9	4.45	2.58		3.5	13.74	0.33	7.6	9	3.4	1.02	33.7	40
CLASS 1					m	m					l	m	h	h		

Sub-Soil Characteristics for Soil Units Within Each Soil Chemical Fertility Class

Source	Soil unit	Erod[y] Index	Clay (%)	PH, H_2O	O.M. (%)	C (%)	$\frac{C}{N}$	Total N (%)	Total K (ppm)	Total P (ppm)	Avail P (ppm)	Exchangeable (me/100g) Ca	Mg	K	CEC me/100g	B.S. (%)
CLASS 1																
LUPRD, 1984 (B52)	Hh		9.5	7.05	3.17	1.84					3.6			0.51		
(B53)	Hh		9.5	7.10	2.86	1.66					2.7			0.51		
(B70)	Hh		12.9	5.40	1.24	0.72					7.2			0.26		
(B61)	Hhs		20.9	6.25	2.14	1.24					5.4			0.51		
(B63)	"		10.9	5.15	5.59	3.24					5.4			1.02		
(B65)	"		24.9	6.15	1.41	0.82					3.6			0.77		
(B66)	"		26.9	6.70	0.69	0.40					2.7			0.51		
(B68)	"		28.9	5.95	3.76	2.18					1.8			0.51		
Average			18.1	6.2	2.61	1.51					4.1			0.58		
					M						VL			h-m		

APPENDIX 5 (a)

Sub-Soil Characteristics for Soil Units Within Each Soil Chemical Fertility Class

Source	Soil unit	Erod[y] Index	Clay (%)	PH H_2O	O.M. (%)	C (%)	$\frac{C}{N}$	Total N (%)	Total K (ppm)	Total P (ppm)	Avail P (ppm)	Exchangeable (me/100g) Ca	Mg	K	CEC me/100g	B.S. (%)
CLASS 2																
Hunting Tech. Servives, 1976, Tigrai																
15-40 (MS5)	Vc		46	7.9		1.3		0.10	5180	–	0.8	23.5	4.7	0.8	29.1	
10-30 (CSA1/1)	Vc		48	7.8		1.2		0.20	6010	–	0.9	21.0	5.9	0.1	26.5	
8-75 cm (QE/2)	Vc		48	7.8		0.67		0.10	2150	–	0.2	17.2	6.1	0.1	29.6	
10-40 (CV1)	Vp	0.18	59	6.6		1.8		0.20	2690	–	1.4	34.0	10.0	0.6	45.8	
10-45 (MS3)	Vp	0.22	54	8.0		1.1		0.10	6890	–	1.1	48.6	6.5	0.8	44.0	
Average (15-45 cm)		0.20	51	7.6	2.06	1.2	8.6	0.14	4524		0.9	30.9	6.6	0.5	35.0	100%
					l-m	l-m		l	h		vl	vh	h	m		

Sub-Soil Characteristics for Soil Units Within Each Soil Chemical Fertility Class

Source	Soil unit	Erod[y] Index	Clay (%)	PH H_2O	O.M. (%)	C (%)	C/N	Total N (%)	Total K (ppm)	Total P (ppm)	Avail P (ppm)	Exchangeable (me/100g) Ca	Mg	K	CEC me/100g	B.S. (%)
CLASS 3A																
Hunting Tech. Services 1976, Tigray																
15-35 (CSA4/6)	Be		16	7.4		0.2		<0.1	460	–	0.0	19.5	5.5	<0.1	18.4	
" 10-30 cm (PG1)	Be	0.15	14	6.4		0.5		0.10	4060	–	11.6	5.7	0.9	0.2	9.6	
" 15-75 (JS1)	Be		16	7.4		0.2		–	–	–	–	19.5	5.5	<0.1	18.4	
" 6-30 (MS1)	Be	0.21	36	7.9		0.8		0.10	1060	–	7.1	32.9	5.3	0.2	40.9	
" 15-30 cm (PE13)	Be	0.36	22	6.7		0.4		0.10	1620	–	2.3	5.8	2.0	0.2	12.3	
" 15-74 (CSA4/5)	Be		46	7.7		2.0		0.20	7330	–	0.4	30.2	1.7	1.0	28.9	
" (CSA4/8)	Be		–	–	–	–	–	–	–	–	–	–	–	–	–	
" 20-50 cm(QE/4)	Be		13	6.2		0.2		<0.1	1200	–	0.7	5.4	1.1	<0.1	8.2	
" 15-45 cm(QE/5)	Be		40	7.0		0.5		0.10	4640	–	0.3	8.2	3.7	0.5	15.0	
" 14-65 cm(PB1)	Lc	0.22	43	7.0		0.6		0.06	900	–	1.0	12.9	6.2	0.2	21.7	
" 15-75 (MS14)	Lc		33	7.3		0.8		<0.1	900	–	1.5	23.3	7.3	0.1	31.7	
" 25-40 cm(QE8)	Lc		35	6.9	–	–	–	0.10	1170	–	3.0	10.9	4.3	0.2	17.2	
LUPRD, 1982 (S.R.)	Lc		52	6.65	1.38	0.8					2.7				32.8	
Orstrom, 1973, Wabi Shabelle – 40-100	Lo			7.5	1.2	0.7	9	0.08		1746	–	11.8	6.0	0.3		
Average (15-50 cm)		0.24	31	7.1	1.1	0.64	6.4	0.1	2334	(1746)	2.7	15.5	4.1	0.31	21.3	93%
					l	l		vl	m	?	vl	h	h	m		

APPENDIX 5 (c)

PPENDIX 5 (a)

Sub-Soil Characteristics for Soil Units Within Each Soil Chemical Fertility Class

Source	Soil unit	Erod Index[y]	Clay (%)	PH, H_2O	O.M. (%)	C (%)	C/N	Al.100%/ECEC	ECEC me/100g	Exch.Al me/100g	Avail P (ppm)	Exchangeable (me/100g) Ca	Mg	K	CEC me/100g	B.S. (%)
CLASS 3B																
LUPRD, 1984, Kati (K1)	Nd		34.9	4.35	3.45	2.0		11.5	12.57	1.44	8.1	6	4	0.26	36.0	31
" " " (K2)	Nd		38.9	4.65	1.38	0.8		2.6	8.16	0.21	3.6	5	2	0.51	36.4	26
" " " (K3)	Nd		54.9	4.60	1.73	1.0		2.3	10.18	0.23	1.8	7	2	0.51	33.0	30
" " " (K4)	Nd		42.9	4.30	2.42	1.4		17.7	8.44	1.49	12.6	5	1	0.51	37.2	19
" " " (K5)	Nd		28.9	4.60	3.07	1.78		1.9	11.86	0.22	6.3	6	4	0.71	40.00	29
Average			40.1	4.5	2.41	1.40		7.2	10.24	0.72	6.5	6	2.6	0.51	35.3	27
					m	m					1	m	m	m		

APPENDIX 6

Selected Soil Chemical and Physical Properties of the Generalised Soil Chemical Fertility Classes[g]

Class (source)	Top Soil / Sub Soil	Soil Units[a]	Erod Index[b]	Clay %	pH, H_2O	O.M. %	C %	C/N	Total N %	Total K ppm	Avail P ppm[c]	Exchangeable Bases[d] me/100/g Ca	Mg	K	CEC[d] me/100g	Al/ECEC %	Base Sat. %
1 LUPRD, 1984 (B52,B53,B70,B61, B63,B65,B66,B68)	Top	Hh and	–	19	6.2	m 3.9	m 2.3	f (10)	m f (0.23)	–	vl 4.3	–	–	h 0.8	–	0	–
	SUB	Hhs	–	18	6.2	m 2.6	m 1.5	f (10)	l f (0.15)	–	vl 4.1	–	–	h–m 0.6	–	0	–
2 (Huntings, 1976: MS/5, CSA1/1QE/2, CV/1, MS/3)	Top	Vc and	0.20	44	7.4	m 2.55	m 1.5	9.4	l 0.16	h 4440	vl 1.5	vh 27.4	h 5.3	h 0.7	30.1	0	vh 100
	SUB	Vp	0.20	51	7.6	m 2.06	m 1.2	8.6	l 0.14	h 4524	vl 0.9	vh 30.9	h 6.6	m 0.5	35.0	0	vh 100
3a (Huntings, 1976: CSA4/6 CSA4/6, PG/1, JS/1, MS/1,PE/13,CSA4/5, CSA4/8,QE/4,QE/5, PB/1,MS/14,QE/8, LUPRD,1982(S.R.) ORSTROM, 1973.	Top	Be and	0.21	19.5	7.1	l 1.70	l 1.0	8.3	l 0.12	m 2475	vl 4.2	h 12.7	m 2.5	m 0.3	17.9	0	vh 87
	SUB	Lc and Lo	0.24	31	7.1	l 1.10	l 0.6	6.4	l 0.10	m 2334	vl 2.7	h 15.5	h 4.1	m 0.3	21.3	0	vh 93
3b (LUPRD, 1984: K1, K2, K3, K4, K5)	Top	Nd	–	29	4.9	m 4.45	m 2.6	f (12)	l f (0.2)	–	l 7.6	m 9	h 3.4	h 1.0	e 33.7	vl* 3.5	m 40
	SUB		–	40	4.5	m 2.41	m 1.4	f (10)	l f (0.14)	–	l 6.5	m 6	m 2.6	m 0.5	e 35.3	l 7.2	l 27

(cont'd)

a. Symbols according to those given in the legend of the Soil Map of the World (FAO) UNESCO, 1974)

b. Determined by use of the nomograph in Wischmeier and Smith (1978)

c. Determined by Olsen extraction

d. Determined with $N.NH_4$ Acetate at pH7.0

e. Unreliable, should have determined Effective Cation Exchange Capacity

f. Estimated Values

g. These values represent average values of soils from the specified sources.

h. With respect to CEC determined with $N.NH_4$ Acetate at pH7.

* Some soils give extreme values of 13.3 & 17.7% Al saturation of the ECEC. in the top soil and sub-soil respectively.

h - high, m - medium, l - low, vl - very low.

Relationship between Soil Nutrient Levels and Soil Chemical Ratings

Soil Chemical Ratings	Soil Chemical Values				
	OM(%)[a]	Total N(%)[b]	Avail. P(ppm)[c]	Exch. K(me/100g)[d]	Al. Sat. (%)[e]
Very low	<1	<0.1	<5	<0.2	1.5
Low	1–2	0.1–.2	5–10	0.2–0.3	5.10
Medium	2–5	0.2–0.3	10–25	0.3–0.6	10–15
High	5–10	0.3–0.4	25–50	0.6–1.2	15–25
Very high	>10	>0.4	>50	>1.2	>25

[a] Determined by the Walkley Black method

[b] Determined by the Kjeldahl method

[c] Determined by Olsen extraction method

[d] Determined by N.NH_4 Acetate extraction at pH7.0

[e] Determined as Al/ECEC as a percentage, Values given refer to Al intolerant crops only such as sorghum, and cotton.

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SOIL CHEMICAL VALUES AND RATINGS FOR SOILS OCCURRING WITHIN SHEET AND RILL EROSION RATE CLASSES VI to VIII

a) DYSTRIC NITOSOLS

Horizon	Source	Soil unit	Depth	pH	OM	C	Al 100% / ECEC	Total N	Available P(ppm)	me/100g Exchange K
	LUPRD, 1984 kati									
1st	K_1	Nd	0–25	4.70	4.49	2.60			5.42	1.02
	K_2	Nd	0–30	4.90	4.35	2.52			4.51	1.02
	K_3	Nd	0–20	5.10	3.62	2.10			6.32	1.02
	K_4	Nd	0–15	4.45	4.66	2.70			14.46	0.51
	K_5	Nd	0–20	5.20	5.14	2.98			7.23	1.53
Average			0–22	4.87	4.45 m	2.58	3.5 vl	(0.22) est	7.58 l	1.02 h
2nd	K_1	Nd	25–50	4.35	3.45	2.0			8.13	0.26
	K_2	Nd	30–50	4.65	1.38	0.80			3.61	0.51
	K_3	Nd	20–45	4.60	1.73	1.00			1.80	0.51
	K_4	Nd	15–40	4.30	2.42	1.40			12.65	0.51
	K_5	Nd	20–50	4.60	3.07	1.78			6.32	0.77
Average			22–50	4.50	2.41 m	1.39	7.2 l	(0.16) est	6.50 l	0.51 m
3rd	K_1	Nd	50–110	4.45	1.07	0.62	0.81		1.80	1.02
	K_2	Nd	50–90	4.75	0.41	0.24	1.9		9.03	1.02
	K_3	Nd	45–80	4.45	1.90	1.10	2.3		9.79	0.77
	K_4	Nd	40–80	5.20	0.69	0.40	1.4		5.42	1.53
	K_5	Nd	50–110	4.90	1.48	0.86	3.9		9.94	1.28
			50–110	4.75	1.11 l	0.64	2.1 vl	(0.06) est	7.19 l	1.12 h

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b) Haplic phaeozems

Horizon	Source	Soil unit	Depth	PH	OM	C	Total N %	Available P(ppm)	me/100g Exchange K
	LUPRD, 1984								
1st	B52	Hh	0–10	7.35	4.04	2.34		4.5	0.51
	B53	Hh	0–10	6.80	3.83	2.22		4.5	0.51
	B61	Hh	0–15	6.25	2.31	1.34		4.5	0.51
	B63	Hh	0–30	5.50	5.76	3.34		3.6	1.53
	B65	Hh	0–30	6.00	1.55	0.90		3.6	1.53
	B66	Hh	0–15	6.45	0.76	0.44		2.7	0.51
	B68	Hh	0–15	6.15	3.62	2.10		5.4	0.51
	B70	Hh	0–20	5.25	7.32	5.41		5.4	0.51
Average			0–18	6.21	3.64	2.26	(0.22)	4.3	0.80
					m		est	vl	h
2nd	B52	Hh	10–20	7.05	3.17	1.84		3.6	0.51
	B53	Hh	10–40	7.10	2.86	1.66		2.7	0.51
	B61	Hh	15–80	6.25	2.14	1.24		5.4	0.51
	B63	Hh	30–55	5.15	5.59	3.24		5.4	1.02
	B65	Hh	30–75	6.15	1.41	0.82		3.6	0.77
	B66	Hh	15–40	6.70	0.69	0.40		2.7	0.51
	B68	Hh	15–50	5.95	3.76	2.18		1.8	0.51
	B70	Hh	20–35						
Average			18–50	6.33	2.80	1.62	(0.16)	3.60	0.62
					m		est	vl	h
3rd	B52	Hh	20–65	6.85	2.31	1.34		2.7	0.51
	B53	Hh	40–70	7.15	1.28	0.74		1.8	0.51
	B61	Hh	80–110						
	B63	Hh	55–90	6.55	4.38	2.54		4.5	0.26
	B65	Hh	75–145	6.50	0.66	0.38		2.7	0.51
	B66	Hh	40–60	6.70	0.66	0.38		2.7	
	B68								
	B70	Hh	35–55	5.40	1.24	0.72		7.2	0.26
Average			50–85	6.53	1.75	1.01	(<0.10)	3.60	0.41
					(1)		est	vl	m

c) Chromic Luvisols

Horizon	Source	Soil Unit	Depth	pH	Total N(%)	Available P(ppm)	me/100gm Exch.K	OM %	C (%)
	Hunting Tech. Service 1976 Tigray								
1st	PB1	Lc	0-14	6.1	0.2	8.9	0.2	2.75	1.6
	MS 14	Lc	0-15	7.0	<0.1	3.8	0.2	1.03	0.6
	QE 8	Lc	0-25	7.1	0.1	17.6	0.4	1.38	0.8
	LUPRD (S.R)	Lc	0-30	6.4	-	1.8	-	2.48	1.44
	Orstrom, 1973, Wabi Shebeli								
Average			0-20	6.65	0.13 l	8.02 l	0.26 l	1.91 ll	1.11
2nd	PB1	Lc	14-65	7.0	0.06	1.0	0.2	1.03	0.6
	MS14	Lc	15-45	7.3	<0.1	1.5	0.1	1.37	0.8
	QE8	Lc	25-40	6.9	0.10	3.0	0.2		
	(S.R)	Lc	30-90	6.65	-	2.67	-	1.38	0.8
	Orstrom 1973 Wabi Shebeli								
Average			20-60	6.70	0.08 vl	2.04 vl	0.16 vl	1.26 l	0.73
3rd	PB_1	Lc	65-95	7.4	0.06	1.0	0.2	1.03	0.6
	MS 14	Lc	45-75	7.5	<0.1	1.5	0.1	1.37	0.8
	QE 8	Lc	40-145	6.9	0.1	3.0	0.2	-	-
	(S.R)	Lc	90-130	6.60		3.61	-	1.38	0.8
Average			60-110	7.10	0.08 vl	2.27 vl	0.16 vl	1.26 l	0.73

d) Eutric Cambisols

Horizon	Source	Soil unit	Depth	PH	Total N(%)	Avail P(ppm)	me/100g exch.K	OM %	% C
	Hunting Tech. Serv. 1976, Tigray								
1st	CSA4/6	Be	0–15	7.5	◁ 0.1	0.2	0.1		0.3
	PG/1	Be	0–10	6.4	0.1	6.5	0.2	1.03	0.6
	JS/1	Be	0–15	7.5	–	–	0.1	0.52	0.3
	MS/1	Be	0–6	8.0	0.1	6.9	0.4	1.72	1.0
	PE/13	Be	0–15	6.7	◁ 0.1	1.9	0.1	0.52	0.3
	CSA4/8	Be	0–20	7.7	0.2	0.5	0.6	3.44	2.0
	QE/4	Be	0–20	6.6	◁ 0.1	0.7	0.1	0.69	0.4
Average			0–15	7.19	0.08 vl	3.10 vl	0.40 m	1.14 l	0.41
2nd	CSA4/6	Be	15–35	7.4	◁ 0.1	0.0	◁ 0.1	0.34	0.20
	PG/1	Be	10–30	6.4	0.10	11.0	0.2	0.86	0.50
	JS/1	Be	15–35	7.4	–	–	◁ 0.1	0.34	0.2
	MS/1	Be	6.31	7.9	0.10	7.1	0.2	1.37	0.8
	PE/13	Be	15–30	6.7	0.10	2.3	0.2	0.68	0.4
	CSA4/5	Be	15–75	7.7	0.20	0.4	1.0	3.44	2.0
	CSA4/8	Be	–	–	–	–	–	–	–
	QE/4	Be	20–50	6.2	◁ 0.10	0.7	◁ 0.1	0.34	0.2
Average			15–40	7.10	0.10 vll	3.58 vl	0.27 l	1.05 l	0.60
3rd	CSA4/6		35–90	7.8	0.1	0.0	0.0	0.34	0.20
	PG/1	Be	30–50	6.5			0.2		–
	JS/1	Be	35–90	7.8			◁ 0.1		
	MS/1	Be	30–52	7.9			0.1		
	PE/13	Be	30–60	6.5			0.2		
	CSA4/5	Be	40–75	7.0	0.20	0.4	1.0	–	2.0
	CSA4/8	Be	–	7.8	–	–	0.2		
	QE/4	Be	50–75	7.0	◁ 0.10	0.7	◁ 0.1	0.34	0.2
				7.3	0.13 vl	0.55 vl	0.30 l	0.34 vl	1.0

The Influence of Current Sheet and Rill Erosion Rate Classes on Reductions In Effective Soil Depth and Changes in Soil Depth Classes over 25 years

Sheet and Rill Erosion rate class	Soil Depth Reduction (cm)	Soil Depth Class changes*
1 and I	0.6	–
11 and II	1.9	–
111 and III	4.4	–
1V	8.1	E → F
		F → R
V	13.1	D → E
		E → F
		F → R
V1	28.8	B → C
		C → D
		D → F
		E → R
		F → R
V11	51.9	A → B
		B → C
		C → E
		D → R
		E → R
		F → R
V111	62.5	A → B
		B → D
		C → R
		D → R
		E → R
		F → R

* See Table 8 for relationship between effective soil depth and depth class.

AVAILABLE WATER CAPACITY DATA CALCULATED USING DIFFERENT FIELD CAPACITY VALUES FOR DIFFERENT SOIL UNITS

Soil Unit (FAO/UNESCO, 1974)	Source	Profile Number	Texture		Bulk Density Top Soil / Sub Soil (g/cm³)	FC = 0.1 BAR		F.C. = 0.3 BAR		FC = 0.2 BAR (EST'D)	
			Top Soil	Sub Soil		Top soil	Sub soil	Top soil	Sub Soil	Top soil	Sub soil
Mollic Andosol	Sogreah, 1982, Meki and Galana		sil	sil-l				27.4	26.3		
Vitric Andosol	Sogreah, 1982; Meki and Galana		sil	sil-sl				24.6	24.4		
Haplic Phaeozem	Sogreah, 1982; Meki and Galana							18.2	21.7		
Luvic Phaeozem	Sogreah, 1982; Meki and Galana							26.2	18.4		
Chromic Vertisol	Huntings Tech. Services 1976, Tigrai	MS/5	sic	sic-c	1.16 / 1.50	21.3	14.9	14.5	11.7	17.9	13.3
"	"	CSA1/1	Sicl	c	1.37 / 1.39	23.7	14.4	16.9	11.3	20.3	12.9
"	"	CSA4/9	c	cl	1.33 / 1.39	22.1	19.9	20.7	18.2	21.4	19.1
"	"	QE/2	cl	c	1.29 / 1.48	27.4	17.6	17.4	14.2	22.4	15.9
"	Halcrow, ULG, 1962, Dabus River	K43	c	c				10.8	13.3		

APPENDIX 10

Soil Unit (FAO/UNESCO, 1974)	Source	Profile Number	Texture		Bulk Density Top Soil / Sub Soil (g/cm³)	FC=0.1 BAR		F.C.=0.3 BAR		FC=0 2 BAR(EST'D)	
			Top Soil	Sub Soil		Top soil	Sub soil	Top soil	Sub soil	Top soil	Sub soil
Pellic Vertisol	Hunting Tech. Services, 1976, Tigrai	MS/3	c	c	1.27 / 1.28	21.1	13.9	16.6	10.4	18.9	12.2
"	Halcrow-ULG,1962, Dabus River	PASD/16	c	c				11.1	14.9		
"	"	PASD/10	c	c				9.1	13.0		
Eutric Cambisol	Hunting Tech. services, 1976 Tigrai	CSA4/6	1.52	1.60	sl/scl	23.9	14.5	17.0	10.7	20.5	12.6
"	"	CSA4/5	1.43	1.44	c /cl	24.2	16.3	17.3	12.8	20.8	14.6
Dystric Nitosol	Holcrow-ULG,1962 Dabus River	PASD/16			sc / c			8.4	8.2		
Chromic Luvisol	Huntings Tech. Services 1976;Tigray	QE/8	1.36	1.36	1 1	24.7	20.1	19.7	15.6	22.2	17.9
	"	MS/14	1.33	1.43	1 cl-sl	24.4	25.2	14.6	18.8	19.5	22.0
Chromic Arenosol	"	QE/1	1.75	1.79	ls ls-sl	20.3	8.5	9.6	11.1	15.0	9.8

ESTIMATED ANNUAL NUTRIENT LOSSES FROM DIFFERENT SHEET AND RILL EROSION RATE CLASSES AND DIFFERENT SOIL CHEMICAL FERTILITY CLASS

Sheet and Rill Erosion Rate Class	Average Soil Loss mm/yr	Organic Matter[a] (t/ha/yr) Chemical Fertility Class				Total Nitrogen[a] (t/ha/yr) Chemical Fertility Class				Exchangeable Potassium[a] (kg/ha/yr) Chem.Fert.Class				Olsen-Extractable Phosphorus[b] (kg/ha/yr) Chemical Fert.Class			
		1	2	3a	3b	1	2	3a	3b	1	2	3a	3b	1	2	3a	3b
I	0.25	0.24	0.16	0.10	0.26	0.01	0.01	0.01	0.01	1.9	1.6	0.7	2.3	0.03	0.01	0.03	0.05
II	0.75	0.70	0.46	0.30	0.80	0.04	0.03	0.02	0.04	5.6	4.9	2.1	7.0	0.09	0.03	0.09	0.16
III	1.75	1.6	1.0	0.7	1.8	0.10	0.07	0.05	0.09	13	11	4.9	16	0.22	0.07	0.21	0.38
IV	3.25	3.0	1.9	1.3	3.4	0.19	0.13	0.10	0.16	24	21	9.1	30	0.40	0.14	0.39	0.71
V	5.25	4.9	3.2	2.1	5.6	0.30	0.21	0.16	0.26	39	34	14	49	0.65	0.22	0.63	1.1
VI	11.5	10	7.0	4.7	12	0.67	0.46	0.35	0.58	86	75	32	100	1.4	0.49	1.4	2.5
VII*	20.75	17	12	7.6	19	1.0	0.80	0.59	0.95	140	120	58	160	2.5	0.79	2.3	4.3
VIII*	> 25	> 19	14	>8.7	> 21	>1.2	>0.95	>0.70	> 1.1	>160	>140	> 70	>180	> 3.0	> 0.90	> 2.5	>5.1

*At these erosion rates the nutrient contents in the 0-15cm and 15-45cm horizons are used in the calculations.

[a] An enrichment ratio of 2.0 has been used

[b] An enrichment ratio of 2.4 has been used

APPENDIX 11