Geofile
Soil degradation
Roger and Anne Fielding Smith
January 1996 number 276

Soil degradation

1 Introduction

Plant growth and agriculture generally are dependent upon the maintenance of appropriate physical and chemical conditions in a relatively thin layer of weathered material, soil, at the earth's surface. Poor agricultural practices such as overgrazing can degrade the capability of the soil layer to support vegetation, to the extent that the productivity of the grassland or agricultural ecosystem becomes severely reduced.

Rapid rates of expansion of human populations, particularly in tropical areas, are extending cultivation to regions where soils are less suited to cultivation and rapid degradation is accompanying this expansion of agriculture. A previous **Geofile** on desertification (no.256, January 1995) documented problems associated with wind erosion in drylands and salinisation of soils in irrigated areas. Here the focus will be upon the effects of soil erosion in agricultural systems, the problems associated with the loss of organic matter from soils under cultivation, and other changes associated with continuous cultivation of soils which have the effect of limiting agricultural productivity.

2 Factors influencing soil erosion by water

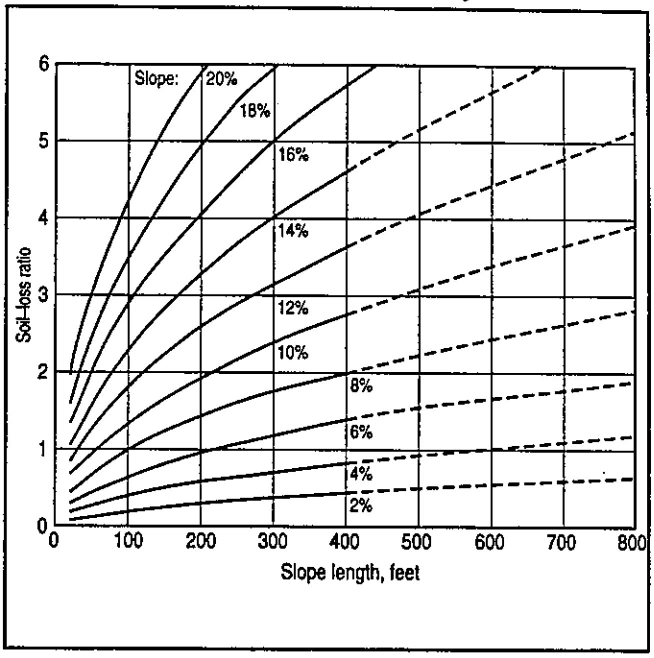
The rate of soil erosion on agricultural land is influenced by rainfall characteristics, soil erodibilty, the nature of the slope at the eroding site and the vegetation cover. Increasingly, computerised mathematical models are being developed to predict rates of soil erosion. One long established model is the Universal Soil Loss Equation (USLE) developed in the United States. This model is recognised to have limitations and its empirical nature means that it has to be adapted to regional conditions, but the model serves to demonstrate the factors influencing erosion rates.

The equation is: $A = RKLSCP$

where

A = soil loss (on a unit area basis) in tons per hectare
R = rainfall factor
K = soil erodibilty factor
L = slope length factor
S = slope gradient factor
C = cropping factor
P = erosion control management factor.

Figure 2: Slope length and gradient graph for determining soil-loss ratio

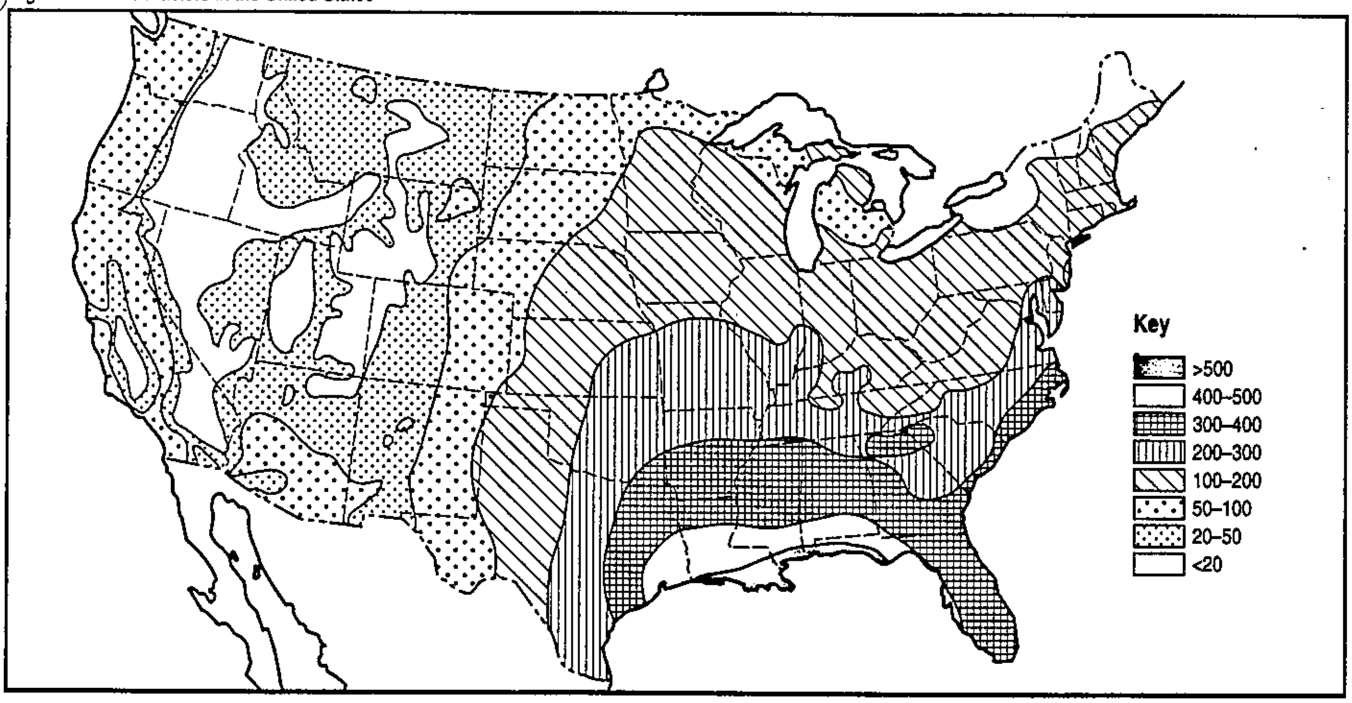


Factor R relates to the erosivity of rainfall. This varies spatially according to the intensity and quantity of rainfall. Figure 1 shows how the rainfall factor varies over the United States. Factors are generally lower in the case of the less intensive rainfall of Western Europe but higher in humid tropical regions. Such variations in rainfall erosivity explain why agricultural practices which result in acceptable rates of soil loss in one area may have disastrous consequences when applied elsewhere.

Soils also vary in their susceptibility to erosion. A number of studies in the British Isles have demonstrated that sandy, silty and loamy soils are more susceptible than clay soils to erosion. In part this is a reflection of different agricultural practice, but the structural instability and lack of cohesion of sandy and silty soils are important factors.

Slope length and slope gradients are important factors. It is estimated that in the United States a doubling of slope length results in about 1.3 times greater soil loss per unit area and an increase in slope gradient increases the velocity of runoff water. Figure 2 shows the influence of these factors. The removal of

Figure 1: Rainfall factors in the United States



hedgerows to produce larger fields has been an important factor influencing soil erosion in parts of southern Britain.

Vegetation cover *(C)* is a critical factor in soil loss. Studies in the United States have shown that in an experimental plot on an 8% slope, soil loss may be 1000 times greater under continuous maize cultivation than under permanent grass. In Britain the move from the cultivation of spring cereals to winter cereals, which has been the result of agricultural intensification under the common agricultural policy, has resulted in widespread erosion problems. The cultivation and planting of soils in the autumn results in the exposure of bare soils to erosion during the season of maximum rainfall.

The final factor in the USLE relates to the application of measures to control soil erosion, for example contour ploughing, strip cropping on the contour, terrace systems and minimum cultivation practices.

3 The impact of soil erosion on agricultural productivity

Erosion rates inevitably increase when soils are brought under cultivation. If soil degradation is to be avoided then the rate of soil loss from the system should not exceed the rate at which it can be renewed by natural processes of soil formation. There is some uncertainty about natural rates of soil formation, but clearly erosion rates may greatly exceed those at which new soil is formed. In 1987 for example, 10% of the total volume of soil was lost in an erosion event in a 10 ha field on the South Downs (Boardman, 1990). This case may be exceptional, but soil losses are likely to be of greatest consequence where a thin layer of soil overlies parent materials which do not weather quickly to replace soil losses. The extent of the problem is, however, complicated by improvements in agricultural technology, including increased fertiliser application, which can offset topsoil losses. On the South Downs, for example, soils of 20 cm depth over chalk are capable of yielding 6t per ha of winter wheat annually. These yields were economic under the subsidy arrangements in the late 1980s and reflect high fertiliser applications and the ability of the crop to exploit water reserves in the fractured chalk layers underlying the soil. Although soil degradation is occurring, short-term economic losses as a result of erosion may not be apparent to the farmers.

4 Factors resulting in a decrease in soil productivity

The most commonly cited factor reducing crop yield following erosion is the reduction in the plant-available water-holding capacity of the soil. Crops are subject to greater water stress as the topsoil volume is reduced and rooting extends into the subsoil where water availability may be less. The water-holding capacity of the soil is strongly influenced by structural characteristics and organic matter content, both of which are less favourable in the subsoil.

Surface structure is also degraded under eroding conditions; soils become more compact and seedling emergence and rooting are affected. Plant nutrients may be removed in the eroding soil; soil nitrogen for example, is associated with organic matter which is concentrated in the topsoil. Other nutrients may leave the field in solution or attached to mineral soil particles. Finally, soil erosion is typically non-uniform. On the South Downs, for example, Boardman (1990) has observed that the area of individual fields damaged by either erosion or deposition rarely exceeds 5%. Localised effects tend to increase the variability in soil conditions within a field. This influences productivity because fields are managed as uniform units and increased variability makes it more difficult to optimise farming practice.

5 Qualitative and quantitative evidence of reduction of productivity

A Report of the US Commissioner of Patents in 1852 observed that 'twice the quantity of rain falls in the Southern States in the course of a year than falls in England, and it falls in one third of the time....Cotton has destroyed more land than earthquakes, eruptions of burning volcanic mountains or anything else. Witness the red hills of Georgia and South Carolina that have produced cotton till the last dying gasp of the soil forbids any further attempt at cultivation...'.

Bennett (1939) reported that the average yields per hectare of corn and cotton stayed about the same in the United States from 1871 to 1930. This was despite improvements in technology and he attributed the lack of yield increase to the effects of erosion. He further suggested that soil erosion had reduced the agricultural productivity of the United States by 35%, although more recent estimates have ranged from 15% to less than 5%. Such broad estimates are made more difficult by improving farming techniques, including energy subsidies, and changing land uses.

Loss of productivity has been estimated at a more local scale. In the USA it has been suggested that wheat productivity is reduced by between 2% and 10% with the loss of 2.5 cm of topsoil. Where maize is grown on deep, medium-textured soil, removal of the topsoil has been estimated to account for a productivity decline of between 8% and 30%. In Iowa the loss of 25 cm of soil reduced maize yields by about 50%. Reductions have also been observed in tropical areas. On thin soils in Nigeria the loss of 5 cm of soil reduced maize yield by about 50% and in another area the experimental removal of 12 cm of soil gave similar reductions in crops of maize and cow peas. Rates of decrease of yield seem highly variable and the impact of soil loss is very dependent upon the profile characteristics and other factors such as management.

6 Soil erosion in tropical areas

Okigbo (1977) suggests that under traditional natural fallow systems erosion is minimised by the retention of some cover during clearing and by growing a number of crops in association, which protects the soil and minimises the need for weeding. Economic and demographic expansion, however, increases population pressure, shortens fallow periods and introduces new agricultural practices which are detrimental to soil resources. He presents a classification of farming systems and associated erosion hazards.

- Shifting cultivation involving nomadic herding: here with increasing livestock numbers overstocking results in increased erosion hazard around waterholes.
- Shifting cultivation or bush fallowing: erosion hazard is low except along footpaths and in compounds.
- Rudimentary sedentary agriculture: erosion hazard slightly increased, especially where there is a decrease in frequency and duration of fallow.
- Intensive sedentary agriculture or compound farming: here the length of fallow is often less than four years and erosion hazard is high on slopes, footpaths and compounds.
- Terrace farming and floodplain agriculture: here erosion hazard is low on flat lowlands. In terrace systems erosion hazard is high on footpaths and where terrace walls break down.
- Mixed farming involving livestock (cattle, sheep, goats) in combination with crops: erosion hazard is high, particularly in savanna where there is no adequate cover at the end of the dry season.
- Livestock ranching: in these systems erosion hazard is associated with poor range management, overstocking and overgrazing. Gully erosion is serious along animal trails and around waterholes.
- Intensive livestock production: in these systems erosion tends to be absent or localised.
- Large-scale plantations: here the lowest hazard is associated with tree crop plantations but erosion hazard may be high with large-scale mechanised food and arable crop farms and row crops.
- Specialised horticulture including market gardening: where fruit trees are grown in plantations with cover crops erosion is minimised, but irrigation systems on slopes may cause erosion problems. Mulching and alignment of crops with the contour also minimise hazard.

Okigbo suggests that, overall, traditional systems do not involve serious erosion hazard as long as fallow periods are reasonably long, vegetation cover is maintained and population pressure low. With increasing population pressure and intensification, however, erosion can become a serious hazard. Sheet erosion tends to be an important process in tropical soil erosion and may selectively remove organic and mineral colloids and nutrient elements from the upper 20 cm where they tend to be concentrated in tropical soils.

7 Soil structure and cultivation

Soil structure is the aggregation of the primary mineral clay, silt and sand particles in a soil into larger units called peds. This aggregation is best developed in soil containing some clay. Sandy soils often show little structural development and silty soils tend to have rather unstable structures. In topsoils structural development is generally associated with organic activity and organic matter; in lower horizons larger structures result from swelling and shrinking of the clay component with changing water content. The interacting variables are initial soil texture (particle size), organic material content, physical processes and soil management (Tidy, 1990). In agriculture, soil management is an important influence on structure. Structural development influences the nature and size of pores between and within structural units, which in turn influences the permeability of the soil to air and water and the ability of the soil to hold water in smaller pores against drainage induced by gravitational force. Such water is available to plants in dryer periods.

A good structure allows root penetration, free drainage and adequate water

Figure 3: The effect of grazed lays and arable cropping on soil organic matter –after Tidy (1990)

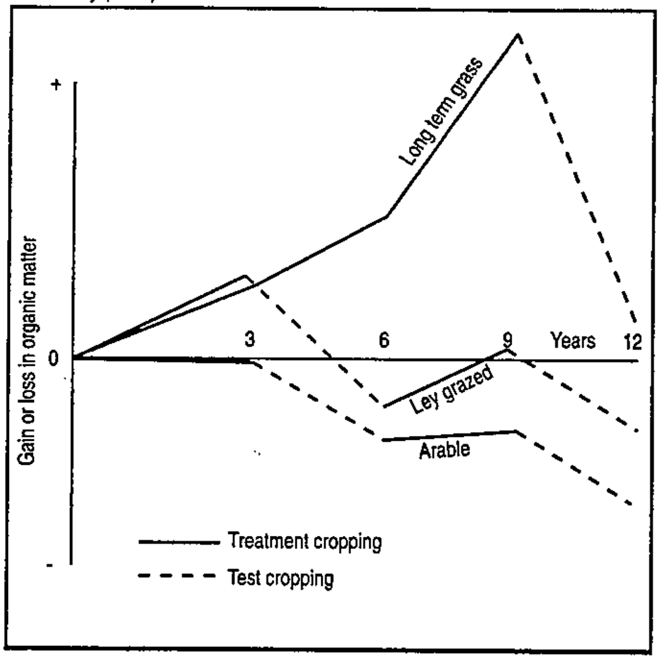
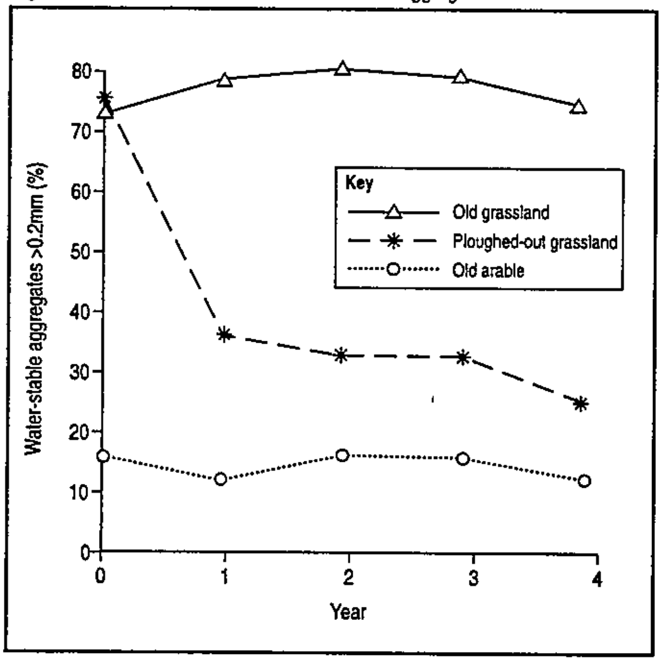


Figure 4: The effect of land use on water-stable aggregate

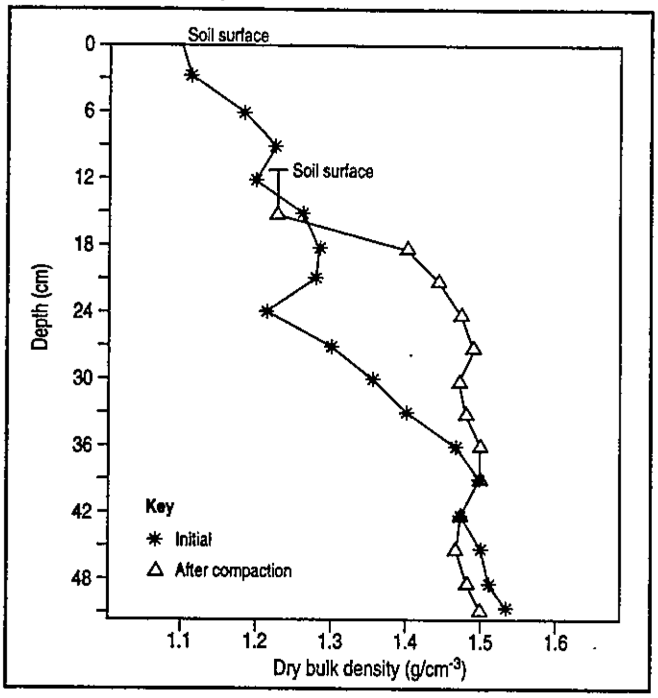


storage. An ideal structure has pores above 0.1 mm in size which allow root growth, air movement and water movement and pores less than 0.05 mm which hold water. The structure should allow rapid infiltration of water and rooting to depths of about 1m; compaction in the subsoil should be absent. Clay is a significant influence on soil structure development, but well-decomposed organic matter is an even more important structural agent. Larger structures tend to be less stable than smaller structures and, in soils of temperate areas, structure is best developed under grassland where the fine roots of grasses accompanied by the activity of soil organisms promote structural development.

When soils are continuously cropped organic matter levels fall; when they fall to 4% in fine sandy and silty soils and 2.6% in clays, structural stability may be affected (Tidy, 1990). Figure 3 shows the influence of grazed lays (grassland) and arable cropping on soil organic matter and Figure 4 shows the effect of land use on water-stable aggregates. These are aggregates which are resistant to cycles of wetting and drying. Aggregate stability generally declines with decreasing organic matter and is most poorly developed in silty soils and fine sandy loams. This is one reason why such soils are susceptible to erosion, aggregates slake (break down) and the soil surface becomes sealed by fine particles. Infiltration is reduced and overland flow occurs, leading to erosion.

Cultivation increases the exposure of soil organic matter to decomposition, and earthworm populations and soil fungi are reduced. Both are important in structure

Figure 5: Effects of passage of vehicles over soils



formation. Pressure from the wheels of agricultural machinery also disrupts soil structure and can lead to the formation of compressed zones, or plough pans, below the plough layer. These denser layers inhibit vertical movement of soil water and air and inhibit root development. Figure 5 shows the effect of the passage of vehicle wheels resulting in the depression of the soil surface and an increase in bulk density of the soil (bulk density is the density of a volume of soil including pore space – an increase in bulk density therefore indicates a reduction in pore volume). A field may be passed over by wheeled vehicles more than ten times during a growing season in the course of activities such as rolling, harrowing and the application of fertiliser and pesticides. Modern practice is to try to confine such passes to fixed routes but this may exacerbate soil erosion in that it provides passage ways for surface water which may develop into gullies. This is particularly the case on steeper slopes where, for safety reasons, cultivation is normally up and downslope. Figure 6 shows the effect on bulk density of the passage of different vehicles over the soil surface. Loaded wheeled trailers have the greatest effect. In severe cases of compaction techniques of deep cultivation are used to break up plough pans.

In an attempt to reduce disturbance to the soil's natural structure and to overcome problems with accelerated loss of soil organic matter, techniques such as zero tillage and direct drilling have been developed. Here crop seeds are placed into the soil surface which is not otherwise disturbed or only receives shallow cultivation. This generally has beneficial effects upon soil structure, but there are different problems in that weed control is reliant upon herbicide applications rather than the physical effects of the plough and the less soluble nutrients (phosphorous and potassium) may become concentrated in the upper soil layers and be less available to the crop.

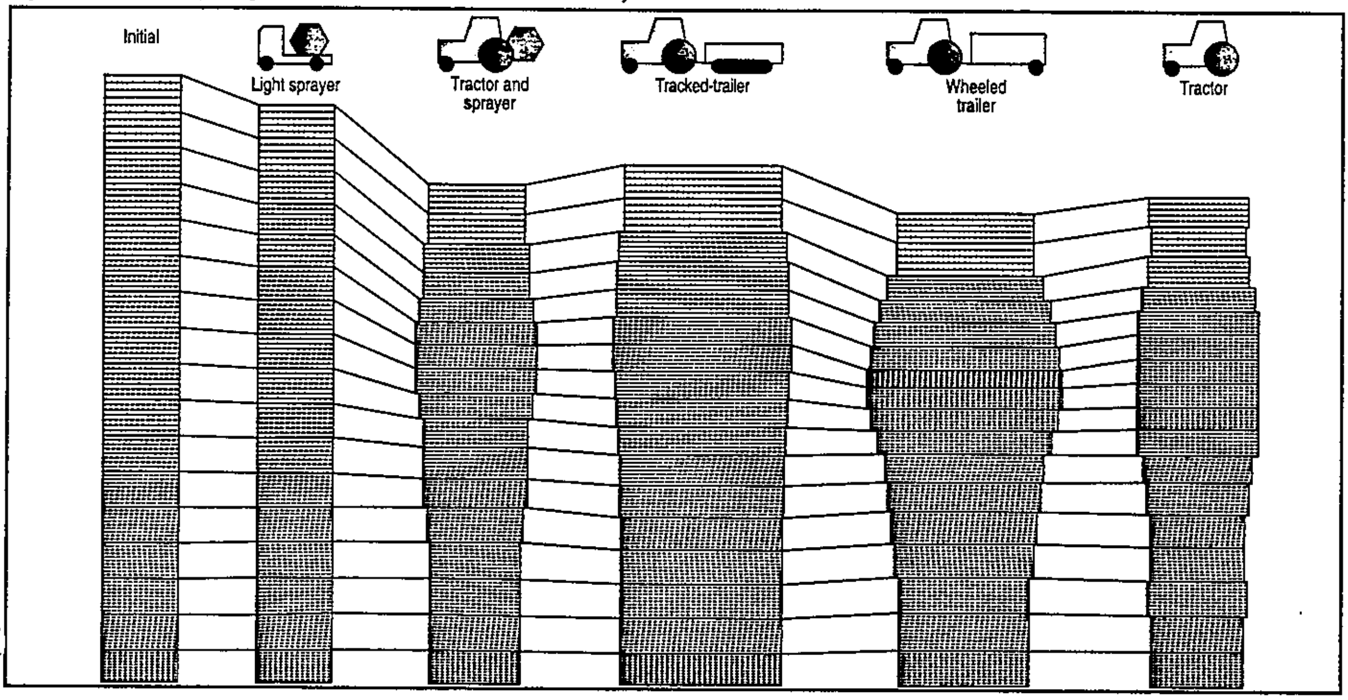
8 Organic matter in tropical soils

In tropical soils which have been strongly weathered the soil organic matter is a store of plant nutrients and plays a significant role in holding nutrients by ion retention and maintaining good soil structure (Ross, 1993). Organic matter decomposition rates are generally faster in tropical soils and deforestation results in losses of soil carbon and nitrogen which is held in soil organic matter and released by accelerated decomposition. Organic matter therefore makes a very significant contribution to the fertility of tropical soils and a decline in fertility following deforestation results from accelerated soil erosion, reduction in litter fall and increases in decomposition and nutrient release rates. In tropical forests organic matter contributes to the maintenance of a good soil structure which aids soil aeration and water infiltration. In addition a leaf litter layer at the soil surface and a surface root mat mean that soils under forest will resist soil erosion, even under rainfall intensities considerably higher than those of temperate areas.

Forests are cleared by clearfelling and burning, bulldozing and selective logging. These differing methods result in differences in the extent of soil organic matter and nutrient loss. Carbon, nitrogen and sulphur are lost in smoke during burning but much of this comes from the vegetation.

Nevertheless following forest burning there is a large fall in the carbon:nitrogen ratio of soils due to high losses of N compared to C during the fire, fast release of N by organic matter decomposition and nitrate and nitrogen losses by leaching (Ross,

Figure 6: Effects of the passage of different farm vehicles on soil bulk density



1993). Ash returned to the soil surface contains basic cations and may result in an increase of soil organic matter in the short term and an increase in pH, but ash may be lost in soil erosion before vegetation regrowth occurs.

A study of soil organic matter status in the Amazon region of Peru showed that slash and burn had no effect upon soil organic matter status, while different methods of bulldozing reduced levels by 16–21%. The study showed that crushing and compaction by heavy vehicles, soil organic matter removal and more rapid decomposition rates following tree removal, were responsible for changes affecting soil structures.

Clearance by bulldozer always results in greater soil degradation and poorer subsequent crop yields than slash and burn. Once the canopy is removed, litter and soil organic matter are lost by overland flow and erosion. Data from Nigeria (Figure 7) show the influence of slope on rates of soil organic matter and nitrogen loss following forest clearance.

Figure 7: The influence of slope on rates of soil organic matter and nitrogen loss following forest clearance (Ross, 1993)

Location	Vegetation	Slope	Erosional losses (kg per ha per yr) Soil organic matter	Total soil nitrogen
Nigeria	Bare fallow	1%	416.5	36.7
		5%	2317.0	186.2
		10%	3631.7	310.4
		15%	3781.0	313.5
Nigeria	Maize (ploughed)	1%	57.4	5.1
		5%	250.0	20.8
		10%	168.2	13.4
		15%	587.6	75.3
Nigeria	Cowpeas + maize (ploughed)	1%	31.3	3.1
		5%	187.3	16.7
		10%	174.8	14.1
Nigeria	Maize + mulch	15%	1071.7	101.1
		(all)	<0.1	<0.1kg
N. Brazil	Terra firma forest	Topslope 4°	257.1*	2.211*
		Midslope 13°	302.1*	3.36*
		Footslope 4°	138.1*	2.28*
N. Brazil	Part cleared forest (<1.5m tall)	Topslope 4°	218.9*	3.603*
		Midslope 13°	379.7*	5.052*
		Footslope 4°	51.6*	3.84*
N. Brazil	Total cleared forest	Topslope 4°	203.6*	3.081*
		Midslope 13°	273.1*	11.691*
		Footslope 4°	386.0*	12.543*
Philippines	Primary forest	nd	45.0	nd
	Tree fallow	nd	65.2	nd
	Logged over forest	nd	836.1	nd
	New maize plantation	nd	447.4	7.78
	New rice plantation	nd	278.6	5.77
	Second-year-old rice	nd	890.7	22.05
	12-year-old rice	nd	12127.4	243.5

Note: *Annual data calculated from three month data, assuming active erosion occurs in only 6 out of 12 months.

Ross (1993) observes that the sustainability of natural tropical ecosystems depends, in many cases, on efficient nutrient cycling with minimal nutrient loss. The sustainable use of tropical soil resources depends on the management of tropical cultivation systems along similar lines. There are particular problems in the prevailing situation of tropical forest conversion to agricultural land. This severely disrupts soil–plant interactions, with significant impacts on soil organic matter on which tropical soils strongly depend for nutrient supply and retention and the maintenance of their structural characteristics.

Bibliography

Bennett, H. (1939) *Soil Conservation*, McGraw Hill.

Boardman, J. (1990) 'Soil erosion on the South Downs: A review', in *Soil Erosion on Agricultural Land*, eds J. Boardman, I.D.L. Foster and J.A. Dearing, John Wiley and Sons.

Foth, H.D. (1990) *Fundamentals of Soil Science*, John Wiley and Sons.

Okigbo, B.N. (1977) 'Farming systems and soil erosion in West Africa' in *Soil Conservation and Management in the Humid Tropics*, ed D.J. Greenland, John Wiley and Sons.

Ross, S.M. (1993) 'Organic matter in tropical soils: current conditions, concerns and prospects for conservation', *Progress in Physical Geography* vol.17, no.3, pp. 265–305.

Tidy, J. (1990) *Agricultural Ecology*, Longman.

Acknowledgements
GEOFILE researched and written by Roger and Anne Fielding Smith
Maps and diagrams: Mike Ormond, Micrographics, Llandudno, Gwynedd
Printed by The Baskerville Press, Salisbury, Wiltshire

ISSN 0267-7563