# SOIL EROSION AND CONSERVATION

THIRD EDITION

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## CHAPTER 1

# Soil erosion: the global context

Soil erosion costs the US economy between US$30 billion (Uri & Lewis 1998) and US$44 billion (Pimental et al. 1993) annually. The annual cost in the UK is estimated at £90 million (Environment Agency 2002). In Indonesia, the cost is US$400 million per year in Java alone (Magrath & Arens 1989). These costs result from the effects of erosion both on- and off-site.

On-site effects are particularly important on agricultural land where the redistribution of soil within a field, the loss of soil from a field, the breakdown of soil structure and the decline in organic matter and nutrient result in a reduction of cultivable soil depth and a decline in soil fertility. Erosion also reduces available soil moisture, resulting in more drought-prone conditions. The net effect is a loss of productivity, which restricts what can be grown and results in increased expenditure on fertilizers to maintain yields. If fertilizers were used to compensate for loss of fertility arising from erosion in Zimbabwe, the cost would be equivalent to US$1500 million per year (Stocking 1986), a substantial hidden cost to that country's economy. The loss of soil fertility through erosion ultimately leads to the abandonment of land, with consequences for food production and food security and a substantial decline in land value.

Off-site problems arise from sedimentation downstream or downwind, which reduces the capacity of rivers and drainage ditches, enhances the risk of flooding, blocks irrigation canals and shortens the design life of reservoirs. Many hydroelectricity and irrigation projects have been ruined as a consequence of erosion. Sediment is also a pollutant in its own right and, through the chemicals adsorbed to it, can increase the levels of nitrogen and phosphorus in water bodies and result in eutrophication. Erosion leads to the breakdown of soil aggregates and clods into their primary particles of clay, silt and sand. Through this process, the carbon that is held within the clays and the soil organic content is released into the atmosphere as $CO_2$. Lal (1995) has estimated that global soil erosion releases 1.14 Pg C annually to the atmosphere, of which some 15 Tg C is derived from the USA. Erosion is therefore a contributor to climatic change, since increasing the carbon dioxide content of the atmosphere enhances the greenhouse effect.

The on-site costs of erosion are necessarily borne by the farmer, although they may be passed on in part to the community in terms of higher food prices as yields decline or land goes out of production. The farmer bears little of the off-site costs, which fall on local authorities for road clearance and maintenance, insurance companies and all the land holders in the local community affected by sedimentation and flooding. Off-site costs can be considerable. Erosive runoff from arable land in four catchments in the South Downs, England, in October 1987 caused damage equivalent to £660,000 (Robinson & Blackman 1990). Sedimentation ponds to trap sediment and runoff generated from arable land in an area of 5516 $km^2$ in central Belgium cost €38 million to construct and €1.5 million annually to maintain (Verstraeten & Poesen 1999).

Although soil erosion is a physical process with considerable variation globally in its severity and frequency, where and when erosion occurs is also strongly influenced by social, economic, political and institutional factors. Conventional wisdom favours explaining erosion as a response to increasing pressure on land brought about by a growing world population and the abandonment of large areas of formerly productive land as a result of erosion, salinization or alkalinization. In the loess plateau region of China, for example, annual soil loss has increased exponentially since about 220 BC in a simple relationship with total population (Wen 1993). Population pressure forces people to farm more marginal land, often unwisely, especially in the Himalaya, the Andes and many mountainous areas of the humid tropics. In other parts of the world, however, erosion can be seen as a direct response to abandonment of the land associated with rural depopulation. A dramatic example comes from the terraced mountain slopes of the Haraz in Yemen, where land abandonment occurred following droughts in the 1900s, the 1940s and between 1967 and 1973, and then increased markedly in the 1970s as people migrated to Saudi Arabia and the Gulf States. With fewer people on the land, terrace walls were allowed to collapse and erosion is now reducing the depth of the already shallow soil by 1–3 cm yr$^{-1}$ (Vogel 1990). In much of Mediterranean Europe, policies to reduce the number of people employed in agriculture and to increase farm size and the level of mechanization have had a twofold effect. First, traditional terrace structures are left to decay. Second, the increase in farm size is often accompanied by large-scale earth moving and land levelling, which makes the soil more erodible. Almost everywhere that land consolidation programmes have been carried out, rates of soil erosion have increased.

The prevention of soil erosion, which means reducing the rate of soil loss to approximately that which would occur under natural conditions, relies on selecting appropriate strategies for soil conservation, and this, in turn, requires a thorough understanding of the processes of erosion. The factors that influence the rate of erosion may be considered under three headings: energy, resistance and protection. The energy group includes the potential ability of rainfall, runoff and wind to cause erosion. This ability is termed erosivity. Also included are those factors that directly affect the power of the erosive agents, such as the reduction in the length of runoff or wind blow through the construction of terraces and wind breaks respectively. Fundamental to the resistance group is the erodibility of the soil, which depends upon its mechanical and chemical properties. Factors that encourage the infiltration of water into the soil and thereby reduce runoff decrease erodibility, while any activity that pulverizes the soil increases it. Thus cultivation may decrease the erodibility of clay soils but increase that of sandy soils. The protection group focuses on factors relating to the plant cover. By intercepting rainfall and reducing the velocity of runoff and wind, plant cover can protect the soil from erosion. Different plant cover affords different degrees of protection, so that human influence, by determining land use, can control the rate of erosion to a considerable degree.

The rate of soil loss is normally expressed in units of mass or volume per unit area per unit of time. Under natural conditions, annual rates are of the order of 0.0045 t ha$^{-1}$ for areas of moderate relief and 0.45 t ha$^{-1}$ for steep relief. For comparison, rates from agricultural land are in the range of 45–450 t ha$^{-1}$ (Young 1969). These differences have encouraged many researchers and practitioners to distinguish between 'natural' and 'accelerated' erosion, the latter being the result of human impact on the landscape. In practice, such a distinction is often unhelpful because it leads to a view that all unacceptably high rates of erosion must be accelerated, whereas the rates are actually dependent on local conditions. So-called accelerated rates of erosion in lowland England may, in fact, be an order of magnitude lower than the natural rates recorded in the Himalaya, Karakoram or Andes. Theoretically, whether or not a rate of soil loss is severe may be judged relative to the rate of soil formation. If soil properties such as nutrient status, texture and thickness remain unchanged through time, it can usually be assumed that the rate of erosion balances the rate of soil formation. More practically, severity is better judged in relation to the damage caused and the costs of its amelioration.

## 1.1

## Spatial variations

On a world scale, investigations of the relationship between soil loss and climate show that at annual precipitation totals below 450 mm, erosion increases as precipitation increases (Walling & Kleo 1979). But as precipitation increases so does the vegetation cover, resulting in better protection of the soil surface, so that for annual precipitation between 450 and 650 mm, soil loss decreases as precipitation increases. However, as seen in Fig. 1.1, further increases in precipitation are sufficient to overcome the protective effect and erosion then increases until, again, the vegetation responds by becoming sufficiently dense to provide additional protection, causing erosion to decrease. Above 1700 mm, the volume and intensity of the rain outweigh the protective effect of the vegetation and erosion increases with precipitation.

It should be stressed that the general trends described above are often masked by the high variability in erosion rates for any given quantity of precipitation as a result of differences in soil, slopes and land cover (Table 1.1). However, if the rates are grouped into categories of natural vegetation, cultivated land and bare soil, each group follows a broadly similar pattern, with the highest rates associated with semi-arid, semi-humid and tropical monsoon conditions. One exception to this is the humid tropics. Measurements of soil loss from hillslopes in West Africa (Roose 1971), ranging in steepness from 0.3 to 4°, yield mean annual rates of 0.15, 0.20 and 0.03 t ha$^{-1}$ under natural conditions of open savanna grassland, dense savanna grassland and tropical rain forest respectively. Clearance of the land for agriculture increases the rates to 8, 26 and 90 t ha$^{-1}$, while

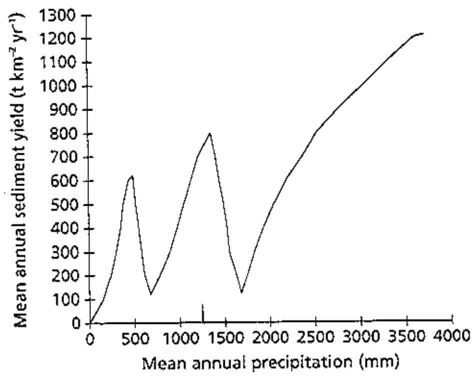

**Fig. 1.1** Relationship between sediment yield and mean annual precipitation (after Walling & Kleo 1979).

**Table 1.1** Annual rates of erosion in selected countries (t ha$^{-1}$)

| | Natural | Cultivated | Bare soil |
|---|---|---|---|
| China | 0.1–2 | 150–200 | 280–360 |
| USA | 0.03–3 | 5–170 | 4–9 |
| Australia | 0.0–64 | 0.1–150 | 44–87 |
| Ivory Coast | 0.03–0.2 | 0.1–90 | 10–750 |
| Nigeria | 0.5–1 | 0.1–35 | 3–150 |
| India | 0.5–5 | 0.3–40 | 10–185 |
| Ethiopia | 1–5 | 8–42 | 5–70 |
| Belgium | 0.1–0.5 | 3–30 | 7–82 |
| UK | 0.1–0.5 | 0.1–20 | 10–200 |

*Sources:* Browning et al. (1948), Roose (1971), Fournier (1972), Lal (1976), Bollinne (1978), Jiang et al. (1981), Singh et al. (1981), Morgan (1985a), Boardman (1990), Edwards (1993), Hurni (1993).

leaving the land as bare soil produces rates of 20, 30 and 170 t ha$^{-1}$ respectively. Thus, removal of the rain forest results in much greater rises in erosion rates than does removal of the savanna grassland. These measurements emphasize the high degree of protection afforded by the rain forest but also reflect the erosive capacity of the high rainfalls in the humid tropics when that protection is destroyed. The rates of removal of tropical rain forests over the past twenty years are therefore of major concern with respect to present and future erosion problems.

Many attempts have been made to produce maps of erosion at a global scale. Since some 70 per cent of the sediment delivered by the river systems to the oceans each year is carried in suspension, these maps are based largely on measurements of suspended sediment yields, with extrapolations to provide estimates in areas of sparse data. The results are subject to errors associated with inadequate extrapolation procedures, the different methods used to sample the sediment and process the data and differences between the river basins in their degree of human impact. In addition, suspended sediment yield is strongly influenced by the size of the catchment because of the greater opportunity for sediment to be deposited with increasing distance of transport and therefore with basin size. Thus a map based on data for drainage basins of 1000 km$^2$ in size would be very different from one based on data for basins of 10,000 km$^2$. Figure 1.2 shows the global pattern of suspended sediment yield for catchments between 1000 and 10,000 km$^2$ in area (Walling & Webb 1983). More recent assessments (Lvovich et al. 1991; Dedkov & Mozzherin 1996) have served to confirm this pattern, emphasizing the vulnerability to erosion of the semi-arid and semi-humid areas of the world, especially in China, India, the western USA, central Asia and the Mediterranean. The problem of soil erosion in these areas is compounded by the need for water conservation and the ecological sensitivity of the environment, so that removal of the vegetation cover for cropping or grazing results in rapid declines in the organic content of the soil, followed by soil exhaustion and the risk of desertification. Other areas of high erosion rates include mountainous terrain, such as much of the Andes, the Himalaya and the Karakoram, parts of the Rocky Mountains and the African Rift Valley; and areas of volcanic soils, such as Java, the South Island of New Zealand, Papua New Guinea and parts of Central America.

A further area of high erosion risk, not discernible from Fig. 1.2, occurs where the landforms and associated soils are relics of a previous climate. Over much of southern Africa, stratigraphical evidence shows sequences of periods of comparative stability in the landscape, indicated by the development of humic layers and stone lines, and periods of instability, represented by colluvial sediments, often up to 5 m thick. Throughout much of Swaziland and Zimbabwe, present-day gully erosion is particularly severe on these colluvial deposits, which are often fine sandy or silty in nature and, therefore, inherently highly erodible (Shakesby & Whitlow 1991). Gullying is also extensive worldwide in areas of deeply weathered regoliths or saprolite, overlying granites and granodiorites. The deep weathered mantle was probably formed during a more humid tropical climate when the surface was protected from erosion by a dense vegetation cover. Clearance of the vegetation has led to an increase in runoff and erosion. Once the upper soil layers have been removed, the underlying, highly weathered, often very fine substrate is exposed. This offers limited resistance and rapidly becomes deeply dissected (Scholten 1997). Such conditions occur not only in southern Africa but also on the margins of the savanna lands in West Africa, Brazil and southern China.

**Fig. 1.2** A tentative map of global variations in suspended sediment yield (after Walling & Webb 1983).

Within relatively small areas, rainfall characteristics are reasonably uniform and erosion varies spatially in relation to soils, slopes and land use. Boardman (1990) found that between 1982 and 1987 in the area between Brighton and Lewes in the South Downs, England, most erosion occurred in fields on the sides of major dry valleys where the relief was greater than 100 m and the land was under winter cereals. Not all the sediment eroded from hillslopes finds its way into the river system. Some of it is deposited on footslopes and in flood plains, where it remains in temporary storage, sometimes until the next storm, or, at other times, as in the case of much colluvial and alluvial material, for millions of years. Larger drainage basins tend to have a larger proportion of these sediment sinks, which explains why erosion rates expressed per unit area are generally higher in small basins and decrease as the catchment becomes bigger. The proportion of the sediment eroded from the land surface that discharges into the river is known as the sediment delivery ratio. Research has shown that this can vary from about 3 to 90 per cent, decreasing with greater basin area and lower average slope (Walling 1983).

## 1.2

## Temporal variations

Typically, data on erosion rates for individual events or years for given locations show a highly skewed distribution (Fig. 1.3), with a large number of very low magnitude events producing moderate amounts of soil loss and a small number of higher magnitude events. Over a long period of time, most erosion takes place during events of moderate frequency and magnitude simply because extreme or catastrophic events are too infrequent to contribute appreciably to the quantity of soil eroded. Experimental studies by Roose (1967) in Senegal showed that, between 1959 and 1963, 68 per cent of the soil loss took place in rain storms of 15–60 mm, events that occur about ten times a year. Studies in mid-Bedfordshire, England (Morgan et al. 1986) indicated that, in the period 1973–9, 80 per cent of the erosion occurred in 13 storms, the greatest soil loss, comprising 21 per cent of the erosion, resulting from a storm of 57.2 mm. These storms have a frequency of between two and four times a year. In contrast, Hudson (1981) emphasized the role of the more dramatic event. Quoting from research in Zimbabwe, he stated that 50 per cent of the annual soil loss occurs in only two storms and that, in one year, 75 per cent of the erosion took place in ten minutes. Moderate events also account for most of the erosion carried out by wind. Studies on coastal dunes at Cape Moreton, New South Wales, showed that most sand transport occurred in strong winds of about 14 m s$^{-1}$, with relatively little in winds of gale force and above because their greater competence was compensated for by their rarity (Chapman 1990). The frequency of the dominant erosion event may vary for different erosion processes. For example, for shallow debris slides and mudflows on cultivated fields and grassland in the Mgeta area of Tanzania the dominant event has a return period of once in five years (Temple & Rapp 1972).

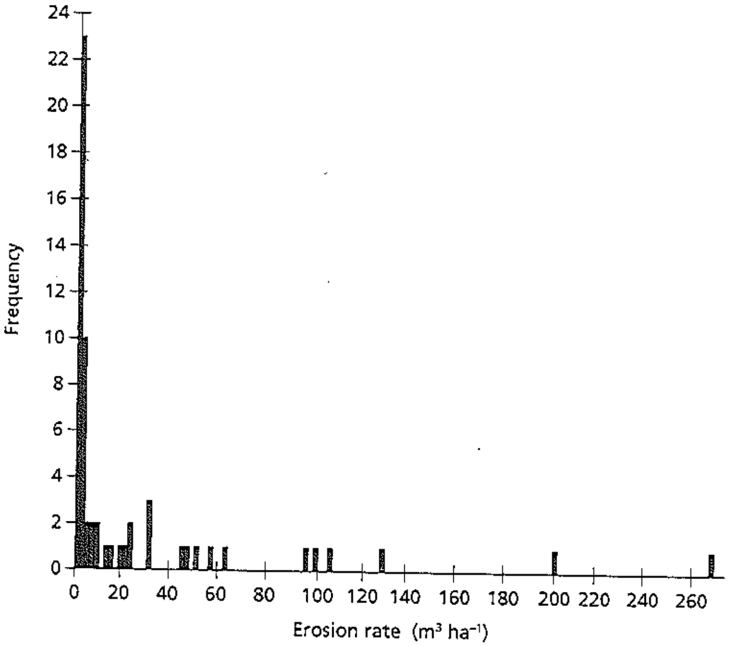

**Fig. 1.3** Typical frequency distribution of annual erosion rates based on measurements at 270 field sites on arable land in England and Wales (after McHugh personal communication).

The more dramatic events may become important where erosion is not a function of climate alone but depends on the frequency at which potentially erosive events coincide with ground conditions that favour erosion. Analysis of 28 years of data for nine small catchments under a four-year rotation of maize–wheat–grass–grass at Coshocton, Ohio (Edwards & Owens 1991) showed that the three largest storms, all with return periods of 100 years or more, accounted for 52 per cent of the erosion and that 92 per cent of the soil loss occurred in the years when the land was under maize. Extreme events may also produce landscape features that are both dramatic and long lasting. A slow-moving equatorial storm deposited 631 mm of rain on 28 December 1926 and 1194 mm between 26 and 29 December in the Kuantan area of Malaysia, resulting in extensive gully erosion and numerous landslides. The scars produced in the landscape were still visible 35 years later (Nossin 1964).

In addition to the variations in erosion associated with the frequency and magnitude of single storms, rates of erosion often follow a seasonal pattern. This is best illustrated with reference to a rainfall regime with a wet and dry season (Fig. 1.4). The vegetation growth follows a similar pattern but peaks later than the rainfall. The most vulnerable time for erosion is the early part of the wet season when the rainfall is high but the vegetation has not grown sufficiently to protect the soil. Thus the erosion peak precedes the rainfall peak.

Somewhat more complex seasonal patterns occur with less simple rainfall regimes or where the land is used for arable farming. Generally, the period between ploughing and the growth of the crop beyond the seedling stage contains an erosion risk if it coincides with heavy rainfall or strong winds. Thus, in western Europe, the period in spring before the crop cover reaches 20 per cent is often a peak time for erosion when rainfall degrades the bare soil surface, causing the development of a surface seal (Cerdan et al. 2002a).

Longer-term spatial variations in erosion occur in relation to changes in land cover. A typical sequence of events is described by Wolman (1967) for Maryland, where soil erosion rates increased with the conversion of woodland to cropland after AD 1700 (Fig. 1.5). They declined as the urban fringe extended across the area in the 1950s and the land reverted to scrub when the farmers sold out to speculators, before accelerating rapidly, reaching annual rates of 7000 t ha$^{-1}$, when the area was laid bare during housing construction. With the completion of urban development, runoff from concrete surfaces is concentrated into gutters and sewers, and annual soil loss falls below 4 t ha$^{-1}$.

Based on stratigraphical and archaeological evidence of valley floor deposits and archival material, Bork (1989) reconstructed the history of soil erosion in Niedersachsen, Germany. From the early Holocene, when soils developed under the natural woodlands, up to the early Middle Ages, erosion rates were extremely low. With the clearance of forest for agriculture between AD 940 and 1340, erosion increased and reached annual rates of about 10 t ha$^{-1}$. Between 1340 and 1350, annual erosion rates rose dramatically to 2250 t ha$^{-1}$ as a result of gully erosion induced by extreme climatic events such as that on 21 July 1342, when the largest flood ever

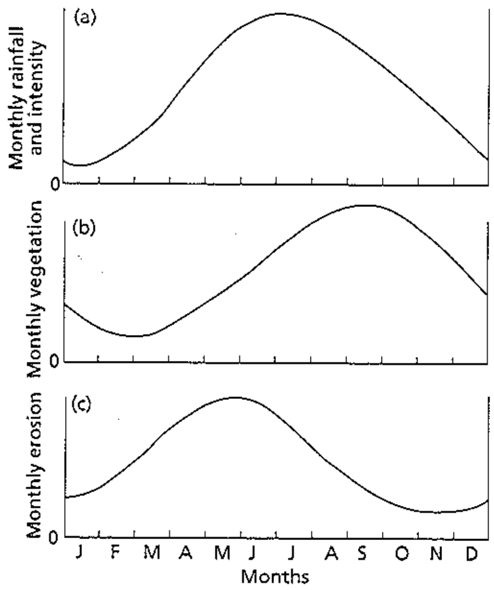

**Fig. 1.4** Seasonal cycles of rainfall, vegetation cover and erosion in a semi-humid climate (after Kirkby 1980a).

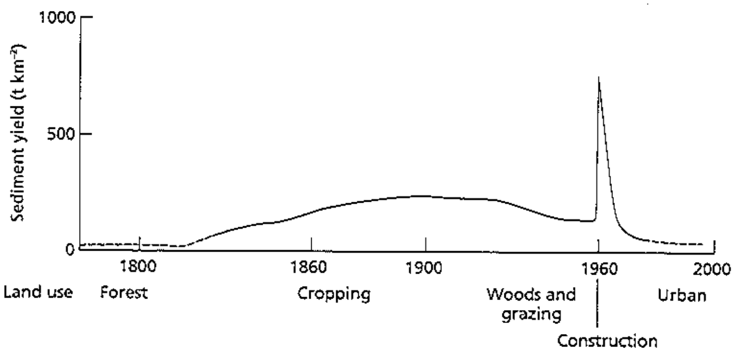

**Fig. 1.5** Relationship between sediment yield and changing land use in the Piedmont region of Maryland, USA (after Wolman 1967).

recorded in central Europe occurred (Bork et al. 1998). Erosion declined afterwards, partly as a result of a decrease in the area under arable as land was abandoned due to impoverishment by erosion. The rate of erosion did not return to early mediaeval levels but remained at an average annual rate of around 25 t ha$^{-1}$. The higher rate reflected sheet erosion on the land remaining in arable as production went over to the three-field system, with one-third of the land in fallow at any one time. The period between 1750 and 1800 saw a second episode of gullying, with an average annual soil loss around 160 t ha$^{-1}$, in response to an increase in the frequency of heavy rainfall events. The soil loss did not reach mid-fourteenth-century levels, however, because of the establishment of terraces, the use of contour ploughing and grass strips and a higher proportion of the land under grass and trees. Since 1800 annual soil loss has averaged 20 t ha$^{-1}$ but it has increased in recent years following land consolidation, which has resulted in larger fields, removal of terraces and grass strips and land levelling. A similar history of fluctuating rates of soil erosion in relation to changes in land use has been reconstructed for the Wolfsgraben in northern Bavaria, Germany (Dotterweich et al. 2003). In periods when the land was under arable cultivation, annual erosion rates averaged 2.8 t ha$^{-1}$ and sedimentation occurred on the valley floors. In extreme rainfall events in the early fourteenth century and again in the late eighteenth century, these sediments were cut through by gullies, up to 5 m deep. Whenever land was taken out of cultivation and reverted to forest, erosion rates were very low and the gullies were infilled.

These historical studies indicate the complex nature of soil erosion. Although erosion is a natural process and, therefore, naturally variable with climate, soils and topography, human impact can make the landscape either more or less resilient to climatic events. Rates of erosion quickly accelerate to high levels whenever land is misused.

Box 1

## Erosion, population and food supply

Only 22 per cent of the earth's land area of 14,900 million hectares is potentially productive (El-Swaify 1994). Since this has to provide 97 per cent of the food supply (3 per cent comes from oceans, rivers and lakes), it is under increasing pressure as world population numbers continue to grow. The fear is that meeting the greater demand for food through more intensive use of existing agricultural land and expansion of agriculture on to more marginal land will substantially increase erosion. Failure to control erosion will therefore seriously endanger global food security. Concern about the future is based upon:

- very high rates of erosion measured from agricultural land, with annual rates often 20 to over 100 t ha$^{-1}$;
- declines in the productivity of the soil by as much as 15–30 per cent annually;
- the difficulty of restoring severely degraded land because of the loss of fertility;
- an estimated loss of some 6 million hectares annually as a result of degradation by erosion and other causes (Pimental et al. 1993).

Unfortunately, it is impossible to know whether the above data represent a realistic picture because they ignore important issues. First, the data on erosion rates are highly selective and often based on short periods of measurement; it is statistically invalid to extrapolate them over large areas. Pimental et al. (1995) estimated that Europe was losing soil at an annual rate of 17 t ha$^{-1}$ but, according to Lomborg (2001), this figure is largely based on extrapolating measurements from a 0.1 hectare plot of land in Belgium. Second, most studies of productivity in relation to erosion come from low-input

*Continued*

3,300 mha
−6 m ha/yr degraded

agriculture and therefore ignore the effects of improved farming practices, including greater use of irrigation, pesticides and fertilizers. In much of Western Europe and the USA, annual increases of 1–2 per cent in productivity can more than offset the effects of erosion, which, locally, are generally in the 0.1–0.5 per cent range (Crosson 1995). In these areas, agricultural production has allowed increasing numbers of people to be fed despite the proportion of the population directly employed on the land falling to below 10 per cent.

In order to gain a better understanding of the global situation, more information is required on the status of the earth's land resource and how fast soil is being lost by erosion. An accurate assessment of land degradation is not straightforward. Statements on the area affected by erosion can be misleading unless supported by field observations. In order to provide a systematic method, UNEP co-sponsored a Global Assessment of Soil Degradation (GLASOD) using over 200 experts to assess the state of degradation in their own countries against clearly defined criteria. The results (Table B1.1; Oldeman 1994) indicated that soil erosion accounted for 82 per cent of human-induced soil degradation, affecting some 1643 million hectares, but only 0.5 per cent of this had reached an irreversible stage. It should be stressed that there is considerable uncertainty about these figures since there appears to have been no control over how the experts interpreted the various grades of land degradation. The grades were more often interpreted in relation to conditions within each country rather than to any consistent world standard. Nevertheless, the GLASOD survey represents the only global scale assessment available at present.

This analysis of the global situation would appear to indicate that soil erosion should not be a threat to the ability of the world to feed itself. The greater proportion of the world's arable land remains productive. Changes in farming practice can more than offset the effects of erosion and feed more people from a unit area of land. Studies in Nigeria and Kenya (Bridges & Oldeman 2001) indicate that, even in developing countries, high population densities can lead to higher productivity and better soil protection. Against this, there are many areas of the world where soil erosion presents major problems that need to be addressed. In addition, this global analysis ignores the environmental impacts of erosion with respect to water quality, flooding and carbon emission. There is, therefore, a clear need for soil protection, but the case for it needs to be made with reference to local on-site problems and off-site effects.

**Table B1.1** Extent of human-induced soil degradation by erosion (million hectares)

| | Light | Moderate | Strong | Extreme | Total |
|---|---|---|---|---|---|
| Water erosion | 343 | 527 | 217 | 7 | 1094 |
| Wind erosion | 269 | 254 | 24 | 2 | 549 |
| Total | 612 | 781 | 241 | 9 | 1643 |

Light: somewhat reduced productivity which can be restored by local farming systems.
Moderate: greatly reduced productivity which can be restored by use of structural measures such as terracing and contour banks.
Strong: land cannot be reclaimed at farm level; restoration requires major engineering works.
Extreme: land is unreclaimable.
*Source:* after Oldeman (1994).