LAND DEGRADATION & DEVELOPMENT

Land Degrad. Develop. **12**: 519–539 (2001)

DOI: 10.1002/ldr.472

SOIL DEGRADATION BY EROSION

R. LAL*

School of Natural Resources, The Ohio State University, Columbus, Ohio, USA

Received 5 July 2001; Accepted 30 August 2001

ABSTRACT

Soil degradation by accelerated erosion is a serious problem and will remain so during the 21st century, especially in developing countries of the tropics and subtropics. Yet, its extent, severity, and economic and environmental impacts are debatable. Estimates of global and regional land area affected are tentative and subjective. Results of field measurements are often technique-dependent. Considerable progress has been made in modeling soil erosion, yet field validation of these models remains to be done for principal soils and ecoregions. Similar to the land area affected, estimates of erosional impacts on crop yield, productivity and soil quality are tentative and subjective. Further, erosion-induced losses on crop yield are scale-dependent because of the compensatory beneficial effects on yields from depositional sites, and technology-dependent because of the masking effects of input such as fertilizers and irrigation. Erosion caused changes in soil carbon dynamics and non-point source water pollution are important environmental impacts. While erosion (e.g., detachment and transport) can lead to emission of trace gases into the atmosphere, deposition can bury and sequester some of the carbon. In addition to improving the database on the land area affected, there is also a need to assess erosional impacts on productivity and soil C balance at the watershed, regional, and global scale. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: erosion and productivity; soil C dynamics; desertification; crop yields

INTRODUCTION

Soil degradation implies long-term decline in soil's productivity and its environment moderating capacity (Lal, 1994a; 1997). In other words, it means decline in soil quality, or reduction in attributes of the soil in relation to specific functions of value to humans (Doran and Parkin, 1994; Doran and Jones, 1996; Johnson *et al.*, 1997; Karlen *et al.*, 1997; Lal, 1997). It has plagued the earth since the dawn of settled agriculture. In ancient times, soil degradation caused the downfall of several thriving ancient civilizations, e.g., the Harappan and Kalibangan cultures in the Indus Valley, the Mesopotamian and Lydian kingdoms in the Mediterranean region, and the Mayan civilization in Central America (Lowdermilk, 1953; Olson, 1981). During the 20th century, the increase in population has drastically accentuated the risks and extent of soil degradation (Richards, 1991). Available statistics on the extent and severity of soil erosion, at regional and global scales, are questionable. There is a wide range of methods used in data collection and extrapolation. Therefore, data accuracy, reliability, and credibility leave a lot to be desired. Yet, some statistics show that the land area prone to soil degradation is estimated at about 2 billion ha, of which 562 Mha (29·7 per cent) is agricultural land, 685 million ha (34·8 per cent) is permanent pastures and 719 Mha (35·5 per cent) is forest and woodland (Oldeman *et al.*, 1991). Therefore, soil degradation is a serious issue of the modern era (Blakie and Brookfield, 1987), and will remain so during the 21st century.

Soil degradation is a biophysical process exacerbated by socio-economic and political factors. There are three principal soil degradative processes, i.e., physical, chemical, and biological (Figure 1). Soil physical processes involve decline in soil structure leading to an increase in bulk density, decrease in total and macroporosity,

---

*Correspondence to: Prof. R. Lal, School of Natural Resources, The Ohio State University, 2021 Coffey Road, Columbus, OH 43210-1085, USA. E-mail: Lal.1@osu.edu

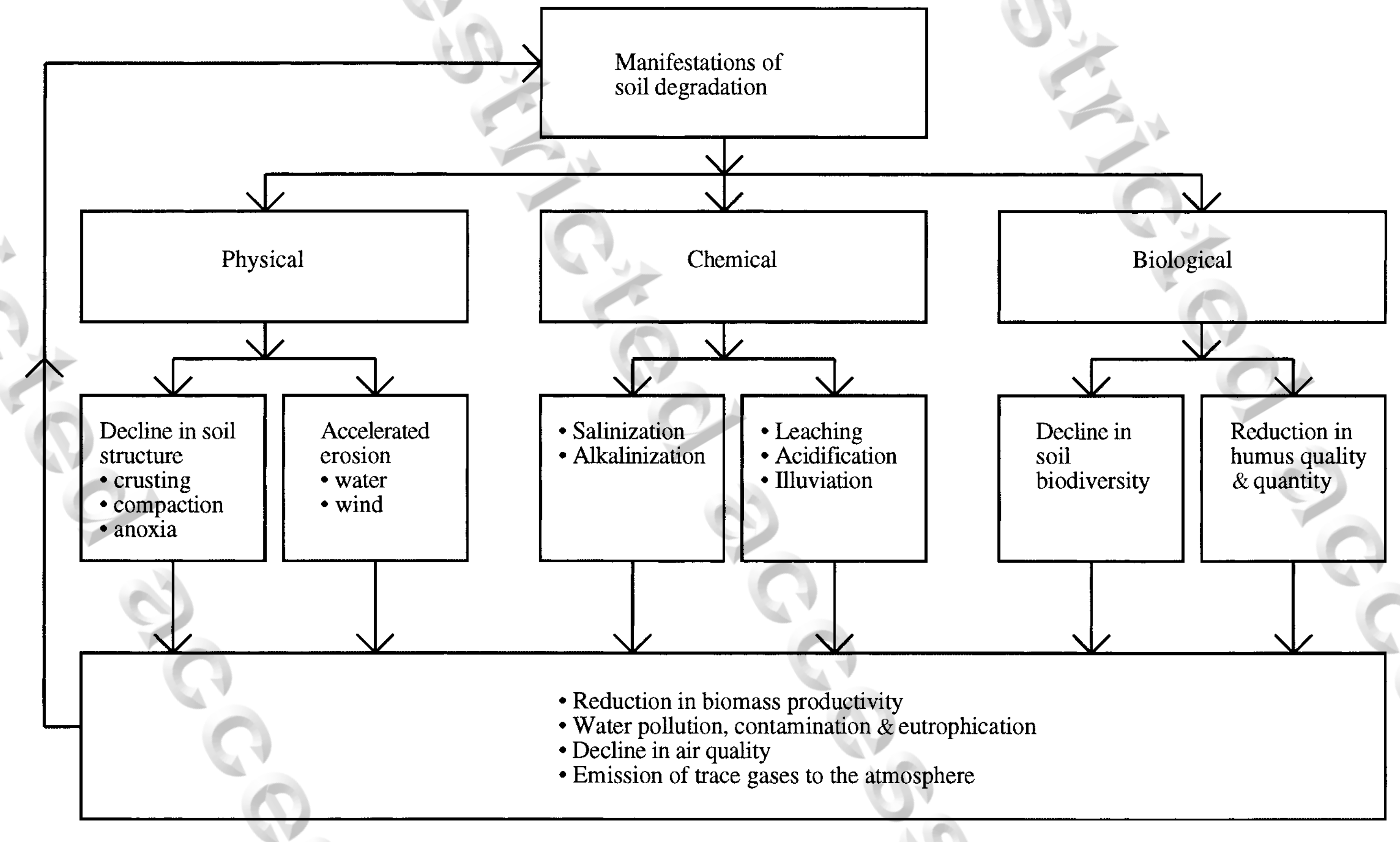

Figure 1. Manifestation of soil degradation

reduction in infiltration, increase in runoff, and exacerbation in erosion by water and wind. The rate of soil degradative processes is governed by numerous natural and anthropogenic factors. Natural factors include soil, climate, vegetation, and other ecoregional characteristics. Important among anthropogenic factors are land use, soil management, farming/cropping systems, land tenure, marketing, and institutional support. Soil degradation is accentuated by poverty, and can cause more serious problems on soils managed for subsistence agriculture with no external input than on those managed for commercial agriculture with science-based input.

Soil degradation is a relative term because, within certain limits, some soil properties can be restored through management. The ability of the soil to restore itself is called soil resilience (Lal, 1994a, 1997). Some soils are more resilient than others. Irreversibly degraded soils have low resilience and cannot be restored. The objective of this paper is to describe soil degradation by erosion and conceptualize erosional impacts on soil productivity, emission of greenhouse gases, and environment quality.

SOIL DEGRADATION AND ACCELERATED SOIL EROSION

Soil erosion exacerbates soil degradation, and vice versa. In some cases decline in soil quality, especially the weakening of structural units, precedes erosion. In others, erosion may lead to decline in soil quality and set in motion the degradative trend. In fact, soil erosion can be a manifestation of soil degradation because it involves physical removal of soil in a vertical and/or horizontal direction and degrades soil quality. It is a natural process that has shaped the landscape and led to formation of fertile alluvial and loess soils. However, the acceleration of the process through anthropogenic perturbations can have severe impacts on soil and environmental quality.

Soil erosion involves 'work' through a three-stage process: (1) detachment, (2) transport, and (3) deposition of soil. Energy for the work is supplied by agents of erosion, and source of the energy determines the type of the erosional process (Figure 2). There are four principal sources of energy: physical such as wind and water, gravity, chemical reactions, and anthropogenic perturbation such as tillage. Tillage implements can be an important source of energy and lead to a substantial transport of soil downslope (Govers *et al.*, 1999). The magnitude and rate of energy dissipation from these four sources determines the severity of erosional processes.

Soil erosion begins with detachment (Ellison, 1947), which is caused by breakdown of aggregates (i.e., organo-mineral complexes leading to formation of domain, microaggregates, and aggregates) by raindrop impact, shearing or drag force of water and wind, or dissolution of cementing agents through chemical reactions. Detached particles and microaggregates are transported by flowing water (overland flow and interflow) and wind and deposited when the velocity of water or wind decreases by the effect of slope or ground cover. Prior to their transport downslope (or down wind), sediments must be detached from the soil mass or be in a detached state. The distance of physical displacement may range from a few millimeters to thousands of kilometers, and the time lapse from detachment to eventual deposition may range from a few seconds to thousands of years.

Because erosion begins with detachment and transport of soil particles, it can be either detachment-limited or transport-limited. Erosion is detachment-limited if all available particles are transported downslope, and it is transport-limited if detached particles accumulate at the site of origin. Some particles are deposited at a short distance from the site of origin (Foster, 1982; Rose, 1985).

The detachment-limited process may occur either in soils of high structural stability in which aggregate strength exceeds that of the raindrop (or wind shear) impact or where slope gradient is too steep to allow sediment accumulation. Deposition happens when the carrying capacity of the overland flow or wind is reduced by decrease in velocity and surface roughness, and presence of vegetation cover or an obstruction. Decrease in stream power may also happen due to loss of turbulence by reduction in slope gradient. Both erosion and deposition are preferential or selective processes, and the size of particles transported or deposited is determined by the Stoke's Law. While the rate and size of particle transported is directly proportional to the velocity, that of deposition is directly related to the concentration and density of sediment size and indirectly to the flow velocity (Hairsine and Rose, 1991).

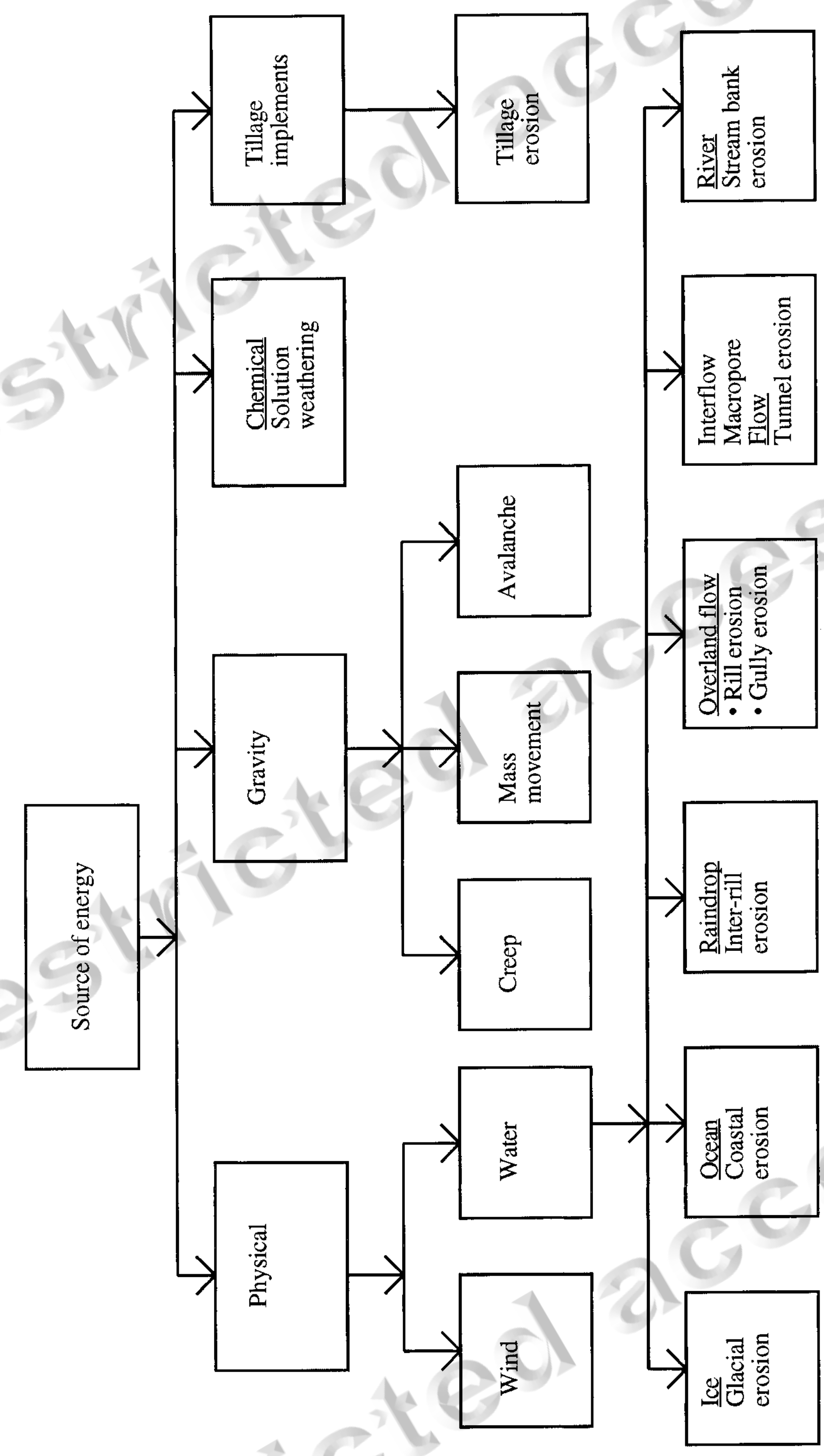

Figure 2. Types or manifestations of soil erosion depend on the source of energy.

Desertification

There is a difference between erosion and desertification. Accelerated erosion by wind and water in drylands is one of many causes of desertification. It refers to a special form of soil degradation in arid, semiarid and dry subhumid areas resulting mainly from adverse human impact (Stewart *et al.*, 1991; UNEP, 1991; Dregne and Chou, 1992; UNDP, 1994; Balba, 1995; Steiner, 1996; Lal *et al.*, 1999). Total drylands area of the world is estimated at 6·08 billion ha. Irrigated land occupies 3 per cent of the drylands, rain-fed cropland about 9 per cent and rangeland about 88 per cent. Dregne and Chou (1992) estimated that about 25 per cent of irrigated land, 50 per cent of the rainfed cropland, and 75 per cent of the rangeland in dry regions is already desertified. Desertification is accentuated by land misuse and soil mismanagement.

Processes Affecting the Rate of Soil Erosion

The natural rate of soil erosion is accelerated by several processes that exacerbate decline in soil structure. These processes are:

(1) Slaking or dispersion: It implies breakdown of soil aggregates.
(2) Compaction: It refers to increase in bulk density or densification.
(3) Crusting: It involves formation of a thin, dense, laminated, and a relatively impermeable layer on the soil surface.

These processes decrease structural stability, reduce soil strength, exacerbate erodibility and accentuate susceptibility to transport by overland flow, interflow, wind, or gravity. These processes are accentuated by soil disturbance (by tillage, vehicular traffic), lack of ground cover (bare fallow, residue removal or burning), and harsh climate (high rainfall intensity and wind velocity).

Factors of Soil Erosion

The effect of processes is modified by biophysical environment comprising soil, climate, terrain and ground cover, and interaction between them (Figure 3). Susceptibility of soil to agents of erosion, soil erodibility, is determined by inherent soil properties, e.g., texture, structure, soil organic matter content, clay minerals, exchangeable cations, and water retention and transmission properties. Soil erodibility is a dynamic property and is influenced by management. Erosivity is influenced by environmental factors primarily climate including drop size distribution and intensity of rain, amount and frequency of rain, runoff amount and velocity, and wind velocity. Another non-climatic environmental factor affecting erosivity is chemical reaction leading to solution weathering. Terrain characteristics have a significant impact on rate of soil erosion by water and gravity agents. Important terrain characteristics include slope gradient, length, aspect, and shape. Ground cover exerts a strong moderating impact on dissipating the energy supplied by agents of soil erosion.

The effect of biophysical processes governing soil erosion is influenced by economic, social and political causes (Figure 3b). Social causes that can accentuate the rate of erosion-induced soil degradation include subsistence or resource-based agriculture, poverty and illiteracy, poor health and malnutrition, political instability, and high demographic pressure (Figure 3b). Social, economic, and policy causes influence mainly the type of land use and management. These causes then influence the rate of soil erosion which determines the severity of soil degradation (Figure 4).

GLOBAL EXTENT OF SOIL DEGRADATION BY EROSION

The total land area subject to human-induced soil degradation is estimated at about 2 billion ha (Table I; GLASOD, 1990; Oldeman *et al.*, 1991). Of this, the land area affected by soil degradation due to erosion is estimated at 1100 Mha by water erosion and 550 Mha by wind erosion (Table I). There are several hotspots of erosion-caused soil degradation. Important among these are South Asia including the Himalayan–Tibetan ecoregion, subSaharan Africa, Central America and the Caribbean, and the Andean region in South America. South Asia is one of the regions where soil erosion by wind (Venkateswarlu, 1994) and water (Singh *et al.*, 1992) is a severe problem. Total

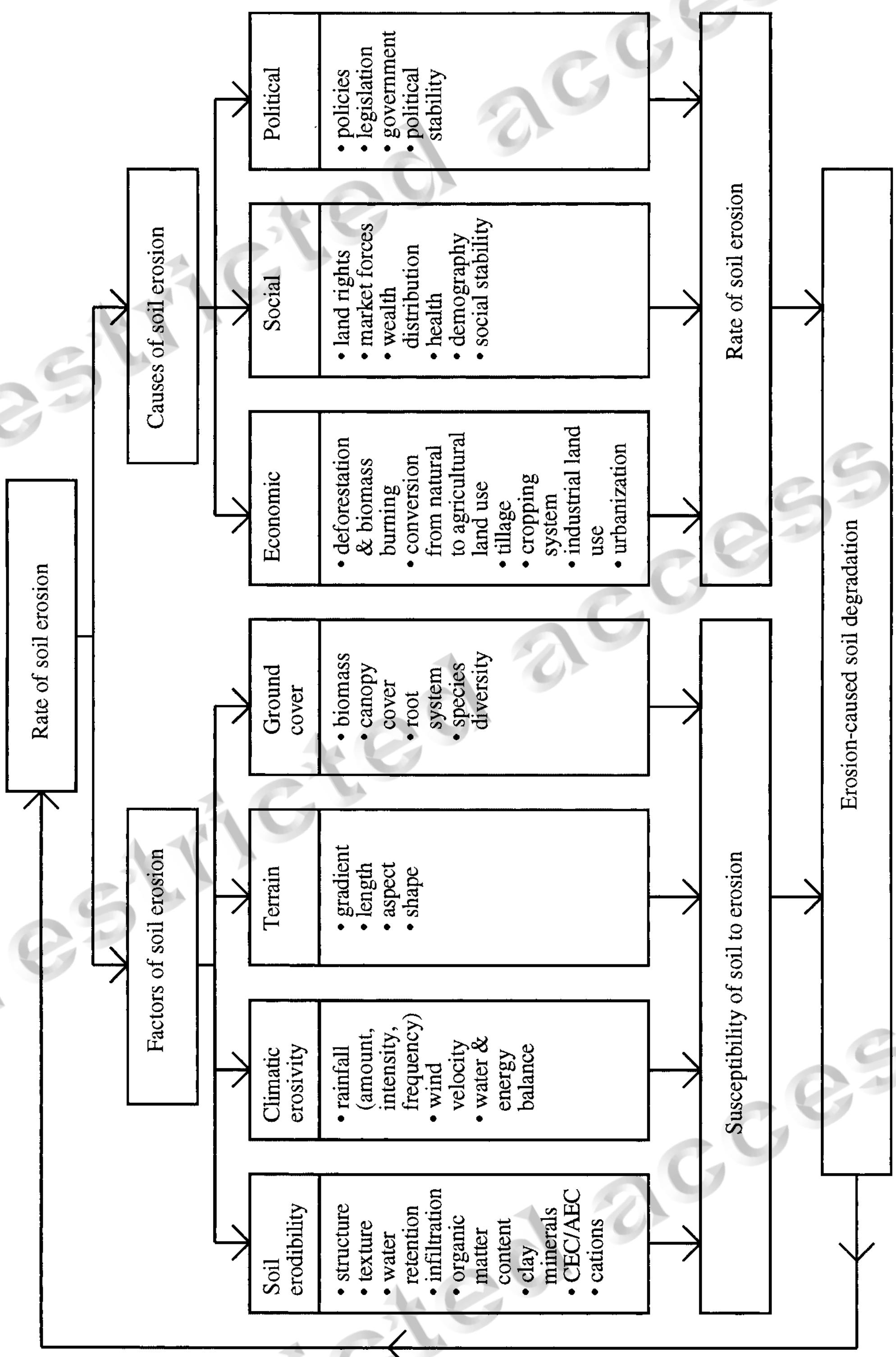

Figure 3. (a) Factors of soil erosion, (b) causes of soil erosion, and (c) interaction between them.

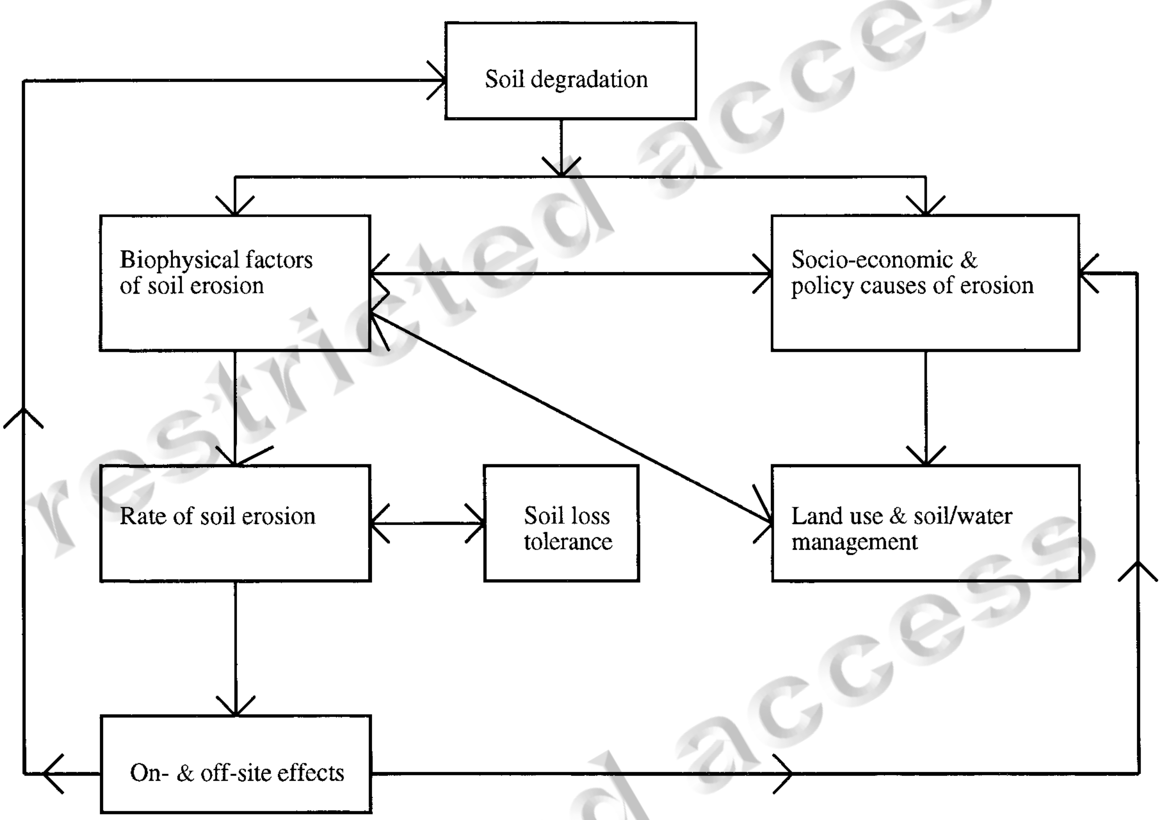

Figure 4. Interaction between biophysical factors and socio-economic and policy causes on rate of soil erosion and severity of soil degradation.

land area affected by water and wind erosion respectively is 32·8 Mha and 11 Mha in India, 26·4 Mha and 35·4 Mha in Iran, 11·2 Mha and 2·1 Mha in Afghanistan, 7·2 Mha and 10·7 Mha in Pakistan, and 81·7 Mha and 59·0 Mha in South Asia (Table II).

The extent and severity of soil erosion depend on ecological factors. Soil erosion by both wind and water are severe in semiarid and subhumid low and mid-latitudes. Risks of soil degradation are accentuated in hot and dry climates in comparison with cold and humid climates (Stewart *et al.*, 1991). Desertification is also severe in arid, semiarid and subhumid climates.

Table I. Global extent of human-induced soil degradation (modified from Oldeman *et al.*, 1991)

World regions	Total land area (10^6 ha)	Human-induced soil degradation (10^6 ha)	Soil erosion (10^6 ha)	
			Water	Wind
Africa	2966	494	227	186
Asia	4256	748	441	222
South America	1768	243	123	42
Central America	306	63	46	5
North America	1885	95	60	35
Europe	950	219	114	42
Oceania	882	103	83	16
World total	13013	1965	1094	548

Table II. Land area affected by soil erosion by water and wind in South Asia (modified from FAO, 1994)

Country	Water erosion (Mha)	Wind erosion (Mha)	Total land area (Mha)
Afganistan	11·2	2·1	65·3
Bangladesh	1·5	0	14·4
Bhutan	0·04	0	4·7
India	32·8	10·8	328·8
Iran	26·4	35·4	163·3
Nepal	1·6	0	14·7
Pakistan	7·2	10·7	79·6
Sri Lanka	1·0	0	6·6
Total	81·74	59·0	677·4

MEASUREMENT AND PREDICTION OF SOIL EROSION

Measurement of Soil Erosion

Erosion measurement may involve assessment of the current rate of soil erosion or that of the historic cumulative soil erosion. Choice of the method for field or *in situ* assessment of the current rate of soil erosion depends on the type of soil erosion to be monitored (Table III), and there is a wide range of techniques used (Lal, 1994b). Field runoff plots are widely used to monitor hillside erosion (Mutchler *et al.*, 1994). However, the design of runoff plots (in terms of plot dimension, runoff and erosion collection system, methods to monitor sediment concentration, etc.) are not standardized. Therefore, results are often technique-dependent. A major problem lies in the design of the collection system, which needs to be based on the return period of the rainstorm, i.e., 50- or 100-year storm. A collection system for runoff plots established at IITA, Ibadan, Nigeria was designed for a rainstorm with a 100-year return period (Lal, 1976). An example of the data collected for excessive rain received in June 1972 is shown in Table IV. Despite the large capacity of the collection system, there was an overflow and the runoff was more than the capacity of the collection system. It is because of the overflow that the runoff from plots with bare fallow treatments for all slopes was equal (e.g., 54·6 mm). There was no overflow in other treatments. In contrast to runoff, there were differences in soil erosion among plots of different slope gradients for the bare fallow treatment. Soil erosion for the bare fallow treatment was 0·8 Mg ha^{-1} for 1 per cent slope, 4·3 Mg ha^{-1} for 5 per cent and 10 per cent slopes and 29·8 Mg ha^{-1} for 15 per cent slope. Soil erosion from maize (plow) treatment was 0·2 Mg ha^{-1} for 1 per cent slope, 0·3 Mg ha^{-1} for 5 per cent slope, 2·6 Mg ha^{-1} for 10 per cent slope, and 5·5 Mg ha^{-1} for 15 per cent slope. There were also differences in erosion due to slope gradient under maize (no-till) treatment in which case soil erosion was 0·03 Mg ha^{-1} for 1 per cent slope, 0·22 Mg ha^{-1} for 5 per cent slope, 1·4 Mg ha^{-1} for 10 per cent slope and 1·6 Mg ha^{-1} for 15 per cent slope plots.

Runoff and sediment collection systems can be different for large agricultural watersheds, which may involve a flume and water stage recorder and sediment sample, or a weir, water stage recorder and sediment sampler. The data in Table V show land-use and management effects on runoff and soil erosion. Mean annual runoff ranged from

Table III. Methods of field assessment of soil erosion

Process	Area (m^2)	Method	Reference
Interrill (splash)	10^{-4}–10^{-3}	Splash cup	Ellison (1947), Elliott *et al.* (1989), Wang (1988), Young and Wiersma (1973)
Rill	10^{-1}–10^{3}	Field plots	Brown *et al.* (1989), Meyer (1994), Nearing *et al.* (1994)
Gully	10^{3}–10^{5}	Field survey	USDA-SCS (1984), Laflen *et al.* (1986)
Agricultural watershed	10^{5}–10^{6}	Flumes, runoff samplers	Mutchler *et al.* (1994), Meyer (1994),
River basin	10^{6}–10^{15}	Weir, bedload and sediment sampler	Walling (1994)

Table IV. Effect of a 105·4 mm rainfall with a maximum intensity of 142·4 mm hr^{-1} on runoff and soil erosion from plots on different slope gradients and under a range of soil and crop management practices (adapted from Lal, 1976)

Slope (%)	Management	Runoff (mm)	Erosion (Mg ha^{-1})
1	Bare fallow	54·6	0·80
	Maize (mulch)	0·0	0·0
	Maize (plow)	34·2	0·2
	Maize (no-till)	6·6	0·03
	Cowpea (plow)	1·8	0·0
5	Bare fallow	54·6	4·3
	Maize (mulch)	7·0	0·01
	Maize (plow)	31·3	0·27
	Maize (no-till)	31·4	0·22
	Cowpea (plow)	34·1	0·1
10	Bare fallow	54·6	4·3
	Maize (mulch)	4·1	0·09
	Maize (plow)	34·3	2·6
	Maize (no-till)	34·2	1·4
	Cowpea (plow)	5·6	0·03
15	Bare fallow	54·6	29·8
	Maize (mulch)	4·0	0·02
	Maize (plow)	34·3	5·5
	Maize (no-till)	35·5	1·6
	Cowpea (plow)	7·3	0·01

5·6–113·1 mm and soil erosion from 0·1–8·3 Mg ha^{-1}. The magnitude of runoff and soil erosion decreased with increase in land area due to deposition over the landscape. The delivery ratio is an important factor to be considered in evaluating soil erosion for watersheds.

There are several techniques for measuring the past or historic soil erosion. The application of radioactive fallout cesium-137 (^{137}Cs) is one such technique (Tamura *et al.*, 1964a,b; McHenry *et al.*, 1973; Ritchie *et al.*, 1975; Ritchie and McHenry, 1990; Hasholt and Walling, 1992; Higgit, 1995). As a result of nuclear weapons testing between the mid-1940s and early 1970s, ^{137}Cs and other radionuclides were deposited on earth's surface as radioactive fallout where these are concentrated in the surface soil layer. Any subsequent movement of ^{137}Cs is attributed to tillage and erosion/deposion processes. The relationship between ^{137}Cs concentration in the surface layer and past soil erosion may be linear, logarithmic or polynomial (Solieau *et al.*, 1990; Oztas *et al.*, 1997; Bajracharya *et al.*, 1998; Hao *et al.*, 2001). Thus, *in situ* validation of the methodology is important. In addition to radionuclides, other tracers have also been used. Important among these are Cu (common ingredients in some pesticides) and charcoal or flyash deposited along the railway lines (Hussain *et al.*, 1998).

Table V. Land-use and management effects on runoff and soil erosion from agricultural watersheds of 2–4 ha each in western Nigeria (Lal, 1996)

Treatment	Runoff (mm)	Erosion (Mg ha^{-1})
Manual clearing, plow-till	43·5	0·6
Manual clearing, no-till	5·6	0·1
Shear blade, no-till	43·2	1·5
Tree pusher, plow-till	113·1	8·3
Tree pusher, no-till	68·3	5·1
Traditional farming	5·7	0·2
Rainfall	1319·9	

Note: Runoff and soil erosion are annual means for three years from 1979 to 1981.

There are other techniques of estimating soil erosion on a landscape scale using field surveys, buried nail or plate techniques, exposure of plant roots, and depth of deposition of sediments along fence lines, etc. Details of such techniques, along with their potential and constraints, are given in Lal (1990) and other reviews.

In addition to soil degradation by water erosion, large areas of arid and semiarid regions are prone to wind erosion (Oldeman *et al.*, 1991). Areas susceptible to wind erosion include much of North Africa and the Near East, parts of southeastern Africa, parts of southern and eastern Asia, the Siberian Plain, South America, semiarid and arid parts of North America, and the drylands of Australia. Factors and causes affecting wind erosion are similar to that of water erosion (Figures 3 and 4). However, field and laboratory methods of measuring wind erosion are not as advanced as that for water erosion. Indirect methods of measuring wind erosion include assessment of soil properties (e.g., texture, wind resistance of soil aggregates) microrelief, ground cover, wind velocity, and climate aridity. There are standard techniques of measuring wind erosivity and soil erodibility (Skidmore *et al.*, 1994). Satellite imagery can also be used to assess extent of wind erosion hazard. In contrast, direct methods of assessing wind erosion are based on techniques involving measurement of drift and the quantity of particles entrained by wind (Lal, 1990).

Modeling Soil Erosion

Development of USLE

Soil erosion prediction has been a challenge to scientists since the 1930s and several models have been developed (Table IV). Baver (1933) proposed an empirical equation for estimating soil erosion involving parameters such as soil dispersion, infiltration rate, soil permeability, and particle size. Zingg (1940) related soil erosion to slope gradient. Similar empirical equations were developed by Horton (1945) and Ellison (1947). Smith and Whitt (1948) added more factors into Zingg's equation to incorporate the influence of cover and management. The major forerunner of the universal soil loss equation (USLE) was a model proposed by Musgrave (1947). He developed a parametric model relating erosion to soil erodibility (K), vegetation cover (C), slope gradient (S), slope length (L) and the maximum 30 minute intensity (I_{30}). It was this equation that was then modified by Wischmeier and Smith (1958) that became known as the USLE.

The USLE has been widely used, and several adaptations and changes have been made since its development. The USLE was developed as a regression equation to predict soil erosion from cropland on a hillslope. It was modified during 1970s and 1980s to predict soil erosion under other conditions. The modified universal soil loss equation (MUSLE) was developed to estimate erosion on a single storm basis (Foster *et al.*, 1977a,b), sediment yield from watersheds (Williams and Berndt, 1972; Williams, 1975; Cooley and Williams, 1985), erosion and

Table VI. Empirical models for predicting soil erosion

Parameter	Reference
Slope gradient	Zingg (1940)
Slope, rainfall, and soil factor	Musgrave (1947), Smith and Whitt (1948)
Slope, rainfall, soil and management (USLE)	Wischmeier and Smith (1958, 1978)
Soil loss tolerance	Stamey and Smith (1964)
RUSLE (revised universal soil loss equation)	Renard *et al.* (1991)
MUSLE (modified universal soil loss equation)	Williams and Berndt (1977), Williams (1982)
CREAMS (chemical, runoff, and erosion from agricultural management systems)	Knisel (1980), Foster *et al.* (1980)
SPUR (simulation of production and utilization of rangeland)	Wight and Skiles (1987)
SWRRB (simulator for water resources in rural basins)	Williams *et al.* (1985)
ANSWERS (areal nonpoint source watershed environment response simulator)	Beasley *et al.* (1980)
Kineros (kinematic runoff and erosion model)	Woolhiser *et al.* (1990)
AGNPS (agricultural non-point source)	Young *et al.* (1987)
SLEMSA (soil loss estimation system for southern Africa)	Elwell (1977), Elwell and Stocking (1982)

sediment yield from rangelands (Renard *et al.*, 1974), soil erosion from forest lands (Dissmeyer and Foster, 1985) and from flatlands (Mutchler and Murphree, 1981).

In addition, USLE was revised to update the database. The revised universal soil loss equation (RUSLE) updates the information on data acquired after the 1978 USLE release, and incorporates several concepts from process-based erosion models. Incorporation of these concepts provides basis for estimating values of different factors including *L*, *S* and *C* (Renard *et al.*, 1991, 1994, 1996, 1997). Equations used to arrive at the factor values in RUSLE are different than those used in USLE. Similar to USLE, however, RUSLE remains to be a regression equation.

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \ldots \tag{1}$$

A principal modification is in factor *R* which includes both rainfall and runoff erosivity factor (runoff erosivity also includes snow melt where such runoff is significant). There are also changes in factor *C* which is based on computation of subfactor called soil loss ratios (SLR). The SLR depends on *S* subfactors: prior land use, canopy cover, surface cover, surface roughness and soil moisture (Renard *et al.*, 1996).

Development of other parametric models

In addition to USLE some regional parametric models have also been developed to predict soil erosion from cropland. Hudson (1961) proposed a parametric prediction equation similar to USLE (Equation 2),

$$A = TSLPMR \ldots \tag{2}$$

where A is erosion, T is the soil type, S is the slope gradient, L is the slope length, P is the agricultural practice, M is the mechanical protection and R is the rainfall. Specific modification in erosivity index were made to substitute this factor R for $KE > 1$ by Hudson (1961), AI_m by Lal (1976) and p^2/P by Fournier (1956) and Fournier and Henin (1959) and FAO (1979). Elwell (1977) and Elwell and Stocking (1982) developed yet another empirical model called the soil loss estimation for Southern Africa (SLEMSA) (Equation 3),

$$A = KCX \ldots \tag{3}$$

where A is the predicted mean annual soil loss, K is the mean annual soil loss from a standard field plot 30×10 m on a $4 \cdot 5$ per cent slope with soil of known erodibility under fallow, C is the crop management factor and X is the slope length factor.

Process-based models of predicting soil erosion

Empirical models (e.g., USLE and SLEMSA) have constraints of applicability limited to ecological conditions similar to those from which data were used in their development. Further, because USLE cannot deal with deposition, its application precludes large areas and watersheds. Based on these considerations, several process-based models have been developed (e.g., EUROSEM, LISEM). A process-based model widely used is the Water Erosion Prediction Project (WEPP) (Foster, 1991; Nearing *et al.*, 1994; Renard *et al.*, 1996). The WEPP model computes erosion by rill and interrill processes. The sediment delivery to rills from interrill areas is computed by Equation 4,

$$D_i = K_i I_e^2 G_e C_e S_f \ldots \tag{4}$$

where D_i is the delivery of sediment from interrill areas to rill (kg m^{-2} s^{-1}), K_i is the interrill erodibility (Kg m^{-4} s^{-1}), I_e is the effective rainfall intensity (m s^{-1}), G_e is the ground cover adjustment factor, C_e is the canopy cover adjustment factor, and S_f is the slope adjustment factor calculated as per Equation 5.

$$S_f = 1 \cdot 05 - 0 \cdot 85 \exp\,(-4 \sin a) \ldots \tag{5}$$

where a is the slope of the surface toward nearby rill (Renard *et al.*, 1996). In comparison, rill erosion is the detachment and transport of soil particles by concentrated flowing water (Eq. 6),

$$D_c = K_r(\tau - \tau_c)\ldots \tag{6}$$

where K_r is the rill erodibility ($\mathrm{s}^{-1}\ \mathrm{m}^{-1}$), τ is the hydraulic shear of flowing water (Pa) and τ_c is the critical hydraulic shear that must be exceeded before rill detachment can occur (Pa).

Rose (1994) adopted a different basic approach to sediment erosion and transport. He computed sediment (q_s) and water (q) fluxes across a sloping, planar land surface using the mass balance approach. He calculated soil loss from the land area during an erosion event by Equation 7,

$$q_s = qc\ldots \tag{7}$$

where q_s is the soil loss ($\mathrm{kg\ m^{-1}\ s^{-1}}$), q is water flux ($\mathrm{m^3 m^{-1}\ s^{-1}}$) and c is the sediment concentration (mass of sediments per unit volume of suspension). Therefore, assessment of soil erosion involves the quantification of hydrology of surface flow and of the erosional processes that increase sediment concentration C and the depositional processes that decrease it.

Similar to the water erosion, process-based models have also been developed for wind erosion (Skidmore, 1994), which is a significant factor in arid and semiarid regions, and reliable predictive models can be useful in developing mitigation strategies. Comparable to the USLE, a wind-erosion model was proposed by Woodruff and Siddoway (1965) as shown in Equation 8.

$$E = f(I, K, C, L, V)\ldots \tag{8}$$

where I is the soil erodibility index, K is the soil ridge-roughness factor, C is the climatic factor, L is the unsheltered median travel distance of wind across a field, and V is the equivalent vegetative cover. This equation has been widely adopted and used for estimating erosion hazards in drylands (Wilson, 1975; USDA, 1984).

EROSIONAL EFFECTS ON PRODUCTIVITY

Accelerated soil erosion has adverse economic and environmental impacts (Lal, 1998). Economic effects are due to loss of farm income due to on-site and off-site reduction in income and other losses with adverse impact on crop/animal production. The environmental impacts are due to pollution of natural waters. Productivity effects of soil erosion are both on-site and off-site. The on-site productivity loss due to soil erosion is attributed to three interacting effects (Figure 5): short-term productivity effects, long-term productivity effects and reduction in soil quality. The most severe effect is due to loss of topsoil depth in soils with a root-restrictive layer. In addition to erosion by water and wind, tillage erosion is also an important determinant of loss of topsoil depth in cultivated landscapes of rolling terrain (Lewis and Nyamalinda, 1996; Turkelboom *et al.*, 1997; Thapa *et al.*,1999; Quine *et al.*, 1999). On-site loss of productivity caused by all types of erosion can be partly compensated by additional input of fertilizers (especially N) and supplemental irrigation. Increase in input reduces profit margin even though crop yield remains the same. Off-site effects on productivity may be positive or negative. Crop yields are an expression of historical production, whereas productivity is a measure of potential yield (Tengberg and Stocking, 1997). Yield can remain constant or even increase as soils become degraded (Stocking, 1994; Dregne, 1995). Soil degradation may also influence quality of crop produced (Johnson and Lewis, 1995). Numerous field experiments have documented increase in crop yields on depositional sites (Fahnestock *et al.*, 1995), especially in seasons with below-normal rains and periods of prolonged drought stress. Reduction in crop yields on depositional sites is often due to crop burial, runon of pesticides, and inundation leading to anaerobiosis. Similar to the on-site effects, the off-site effects of accelerated erosion also comprise short-term effects, long-term effects, and changes in land/soil quality (Figure 6).

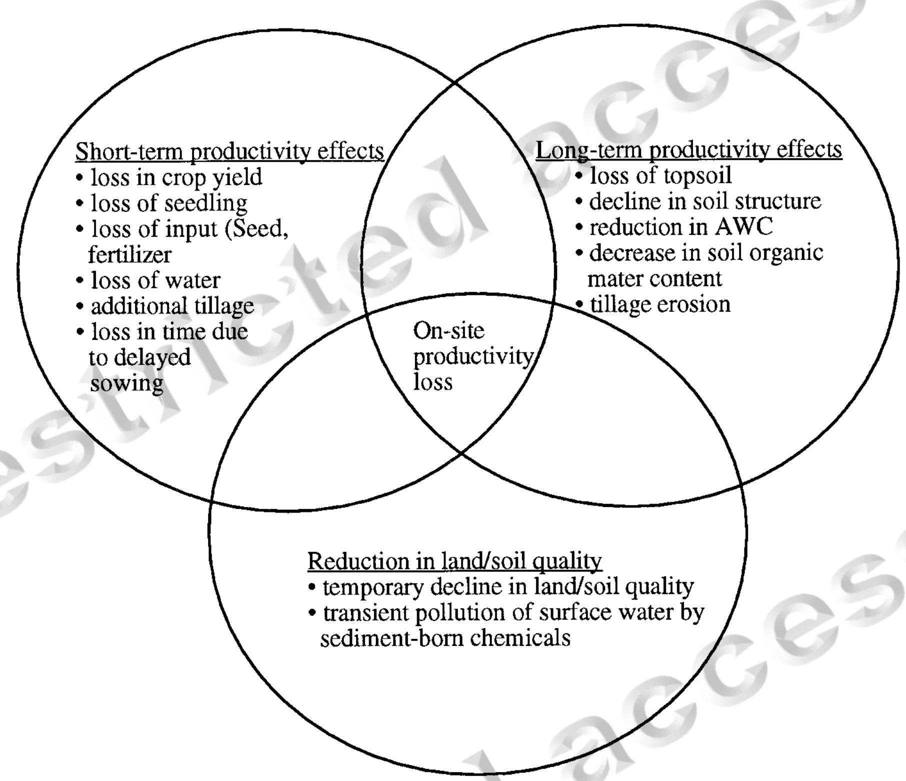

Figure 5. On-site effects of soil erosion on productivity are due to short-term and long-term effects, and on decline in soil quality.

It is difficult to assess the loss of agronomic productivity due to soil erosion, because of the confounding effects of rainfall and other climatic factors during the growing season, and that of management. There is also a scaling problem for extrapolation of data from plot scale to regional, national or global scale. There are few estimates of productivity loss at regional scales. Qualitative estimates of the effects on irreversible soil productivity losses from water erosion were reported for several regions of Africa (Dregne, 1990), Asia (Dregne, 1992a,b), Australia and New Zealand (Dregne, 1995), and North America (Den Biggelaar *et al.*, 2001). Lal (1995) estimated yield losses due to past erosion in Africa, and reported that losses may range from 2–40 per cent, with a mean loss of 9 per cent for the continent and 6·6 per cent for subSaharan Africa (Table VII). It was estimated that if accelerated erosion continues unabated, yield reductions by 2020 may be 16·5 per cent for the continent and 14·5 per cent for subSaharan Africa. Annual reduction in total production for 1989 due to accelerated erosion in the continent of Africa was 8·2 million Mg of cereals, 9·2 million Mg of roots and tubers, and 0·6 million Mg of pulses. The reduction in total production for 1989 for subSaharan Africa was estimated at 3·6 milion Mg for cereals, 6·5 million Mg for roots and tubers, and 0·36 million Mg for pulses (Lal, 1995). Lal (1998) reported risks of global loss of crop yields due to erosion by 10 per cent in cereals, 5 per cent in soybeans, 5 per cent in pulses, and 12 per cent in root and tubers (Table VIII). Accordingly, total production losses on a global scale in 1995 may have been 192 million Mg for cereals, 6 million Mg for soybeans, 3 million Mg for pulses, and 73 million Mg for roots and tubers. Estimates of regional losses in crop production showed total loss in food production at 31 million Mg for Africa, 190 million Mg for Asia, and 18 million Mg for tropical America (Table IX). Den Biggelaar *et al.* (2001) estimated erosional losses on crop yields in North America. The amount of production decline resulting from erosion in North America was estimated at $234 \cdot 5 \times 10^3$ Mg yr^{-1} for maize, $60 \cdot 2 \times 10^3$ Mg yr^{-1} for soybeans, $75 \cdot 0 \times 10^3$ Mg yr^{-1} for wheat and $1 \cdot 9 \times 10^3$ Mg yr^{-1} for cotton. The total economic value of erosion-induced loss in crop yields (using 2000 prices) was US $41·2 million, of which US $37·9 million were in the United States and the remainder in Canada.

Table VII. Erosion effects on grain production in Africa in 1989 (Lal, 1995)

Commodity	Actual production in 1989[a]		Expected production if there was no soil erosion	
	Yield (kg ha^{-1})	Total production (10^6 Mg)	Yield[b] Mg ha^{-1})	Total production (10^6 Mg)
African continent (51 countries)				
Cereals	1228	91	1338	99
Roots and tubers	7231	103	7882	112
Pulses	584	7	637	7
SubSaharan Africa[c] (44 countries)				
Cereals	1140	55	1215	59
Roots and tubers	6460	98	6886	105
Pulses	514	5	548	6

[a] Actual production data were obtained from the Food and Agriculture Organization (1989).
[b] Estimated yield reduction due to erosion is 9% for continent of Africa and 6.6% for subSaharan Africa.
[c] SubSaharan Africa does not include Algeria, Egypt, Libya, Mauritania, Morocco, South Africa and Tunisia.

Table VIII. World food production in 1995 with and without erosion (Lal, 1998)

Commodity	Net production[a] (10^6 Mg)	Estimated production loss (%)	Estimated production if there were no erosion (10^6 Mg)
Cereals	1896	10	2086
Soybeans	126	5	132
Pulses	56	5	59
Roots and tubers	609	12	682
Total	2687	32	2959

[a] Net production figures are from FAO (1995).

Table IX. Regional food production statistics for 1995 with (A) and without (B) soil erosion

	Cereals (10^6)		Soybeans (10^6)		Pulses (10^6)		Roots and tubers (10^6)	
Region	A	B	A	B	A	B	A	B
North Central America	358	376 (5)	61	64 (5)	6	6 (5)	28	29 (5)
Europe	268	281 (5)	1	1 (5)	6	6 (5)	80	84 (5)
Oceania	27	28 (10)	—	—	2	2 (15)	3	3 (10)
Africa	100	110 (10)	0·5	0·6 (20)	7	8 (20)	135	155 (15)
Asia	929	1068 (15)	21	23 (10)	27	31 (15)	248	293 (18)
South America	90	99 (10)	41	45 (10)	4	4 (10)	46	51 (12)
Others	*124*	*130 (5)*	*3*	*3 (5)*	*4*	*4 (5)*	*69*	*72 (5)*
Total	1896	2092	126	136	50	61	609	687

Notes: Numbers in parenthesis indicates the assumed percent decline in production for each region.
Production statistics from FAO (1995).

These estimates of global loss of crop yields are to be considered with caution. These are merely the estimates of yield losses that may occur under the worst case scenario. The actual yield loss during any growing season due to past erosion may depend on numerous factors already described in this section.

In addition to productivity loss, there are other off-site economic impacts of accelerated soil erosion (Figure 6). These economic impacts are due to siltation of waterways and reservoirs, and adverse impacts on aquatic ecosystems and recreational facilities (Lal, 1998; Pimentel *et al.*, 1995).

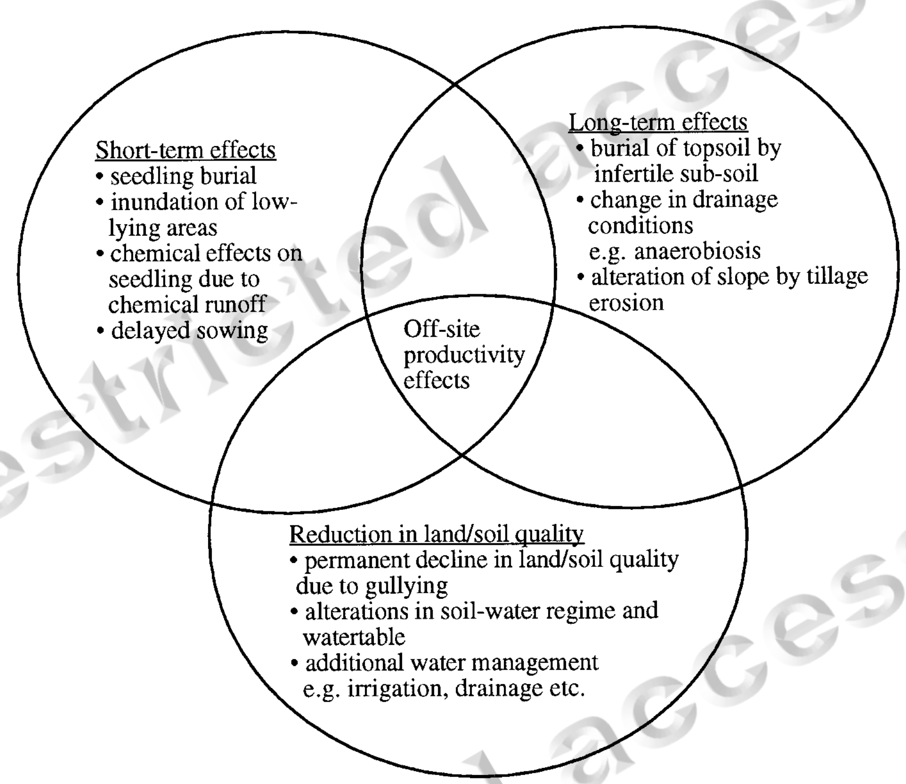

Figure 6. Off-site effects of soil erosion on productivity may be short term or long term and due to decline in land/soil quality.

SOIL EROSION AND THE GREENHOUSE EFFECT

The atmospheric concentration of CO_2 and other radiatively-active gases is steadily increasing. Concentration of CO_2 has risen from 280 ppmv from about 1850 to 365 ppmv in 1995, and is increasing at the rate of 0·5 per cent yr^{-1} (IPCC, 1995). At this rate of increase, CO_2 concentration is expected to reach 600 ppmv during the 21st century. The concentration of CH_4 has increased from 0·8 to 1·74 ppmv and is increasing at the rate of 0·75 per cent yr^{-1}, and that of N_2O has increased from 288 ppbv to 311 ppbv and is increasing at 0·25 per cent yr^{-1} (IPCC, 1995). In addition to fossil fuel, another recognized anthropogenic source of atmospheric increase in CO_2 concentration is land-use change and agricultural activities. These activities lead to emission of C from the soil to the atmosphere.

The soil C pool is the third largest global C pool. The oceanic pool is estimated at 38 000 Pg C, the geologic pool containing fossil fuel at 5000 Pg, the soil C pool at 3200 Pg (and likely to be as high as 3500 Pg), the atmospheric C pool at 760 Pg and the biotic C pool at 560 Pg (Batjes, 1996; Schlesinger, 1997). The soil C pool comprises both soil organic carbon (SOC) and soil inorganic carbon (SIC) components. The SOC component to 2 m depth is estimated at about 2450 Pg, and the SIC component to 1 m depth at 750 Pg. Thus, the soil C pool is about 4·2 times the atmospheric pool and 5·7 times the biotic pool. The atmospheric C pool is increasing at the rate of 3·3 Pg C yr^{-1} primarily at the expense of the soil and the biotic pools. The historic C loss is estimated at 50–100 Pg C from soils, and 100–150 Pg from the biotic C pools. The depletion of soil C pool is accentuated by soil erosion and other degradative processes (Lal, 1999a).

Soil erosion is a multi-stage process involving detachment, redistribution over the landscape, deposition in depressional sites, and transport to aquatic ecosystems in water erosion and to depressional sites in wind erosion (Figure 8). Disruption or breakdown of aggregates exposes the C to climatic elements and microbial decomposition which was previosuly encapsulated within the aggregates and buffered against mineralization. Some of the C

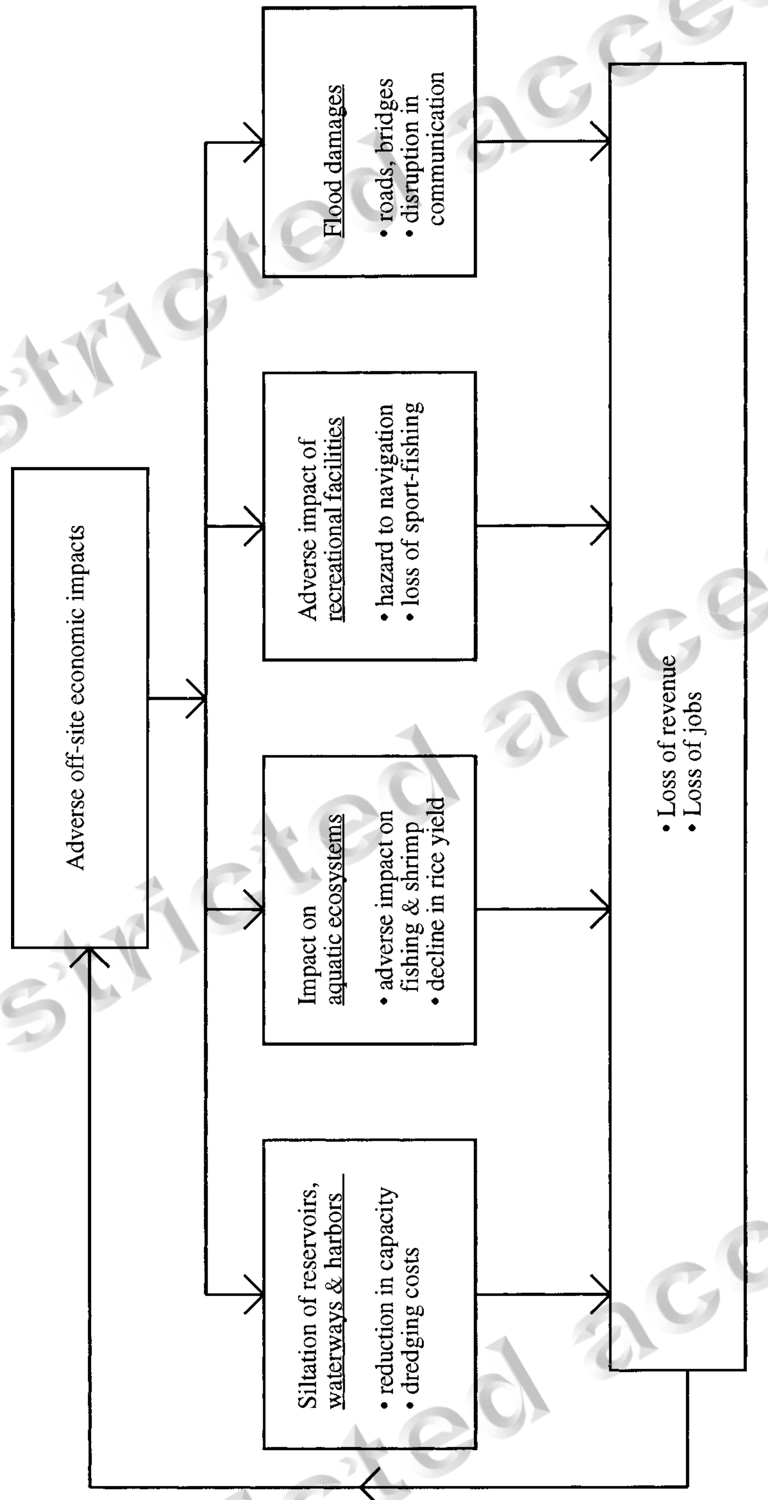

Figure 7. Off-site economic impact of accelerated soil erosion.

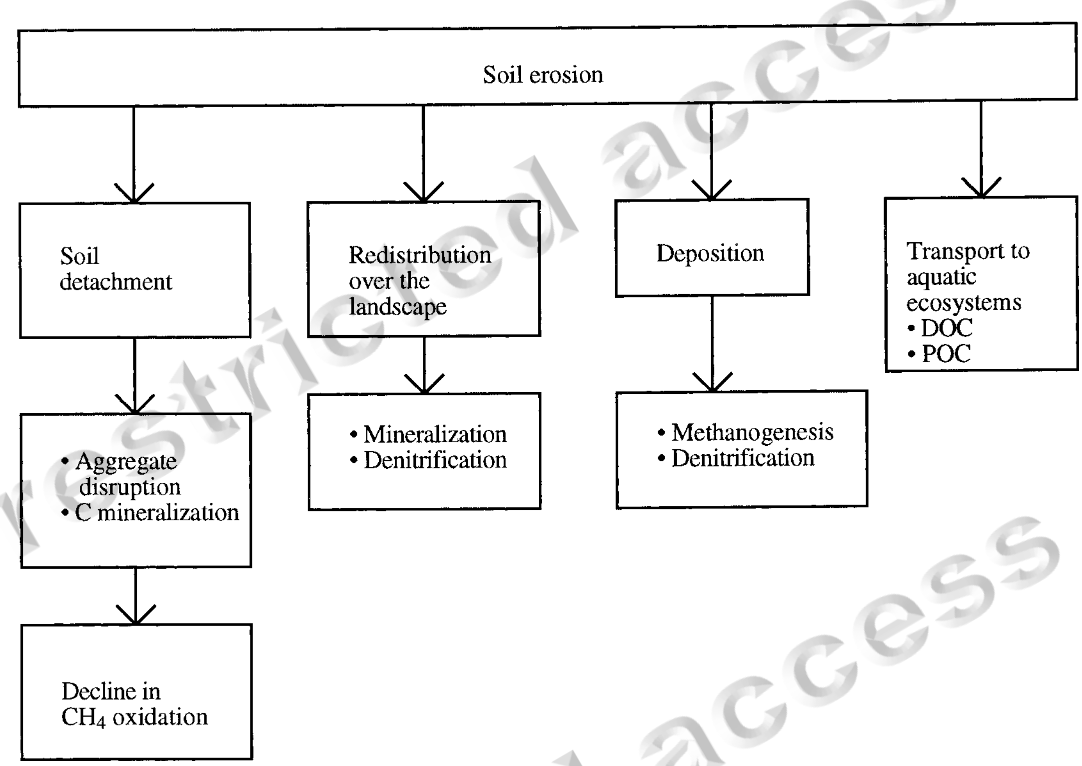

Figure 8. Soil erosion and gaseous emissions.

is redistributed over the landscape and is also prone to mineralization. The C deposited in depressional sites and carried to aquatic ecosystems may be buried and sequestered (Stallard, 1998). Redistribution of C transported with eroded sediments affects several processes that accentuate emission of greenhouse gases from landscape to the atmosphere. It is often assumed that as much as 20 per cent of the carbon displaced by soil erosion is emitted into the atmosphere and 10 per cent deposited in depressional sites (Lal, 1995). It is estimated that as much as 1.14 Pg C may be emitted into the atmosphere due to water erosion and related processes. Lal *et al.* (1999) estimated annual C loss due to desertification of drylands at the rate of 0·2–0·9 Pg C yr^{-1}.

It is difficult to asses the historic loss of C due to past erosion. Using the available data on land area affected by erosion (Oldeman *et al.*, 1991), Lal (1999b) estimated that 21 Pg C has been lost due to water erosion and 4 Pg due to wind erosion (Table X). These estimates, crude as these may be, provide a reference point with regard to the potential of C sequestration through erosion control and restoration of degraded soils. It is assumed that 60–75 per cent of the historic C loss can be recovered through adoption of soil restorative techniques.

Table X. World soil C depletion due to accelerated soil erosion (Lal, 1999b)

	Water erosion			Wind erosion			
Severity	Area (Mha)	C depletion (Mgha)	C loss (Pg)	Area (Mha)	C depletion (Mgha)	C loss (Pg)	Total loss (Pg)
Light	343	5	1·7	269	2·5	0·7	2·4
Moderate	527	20	10·5	254	10	2·5	13·0
Strong and extreme	224	40	9·0	26	20	0·5	9·5
Total	—	—	21·2	—	3·7	24·9	—

Erosion-induced changes in soil C dynamics are complex and not very well understood. An important factor affecting soil C dynamics is the activity and species diversity of soil fauna which influence microbial processes. Microbial processes affect humification, aggregation, and mineralization. Effects of erosion/deposition cycles on these processes need to be studied.

CONCLUSIONS

Soil degradation by accelerated erosion has been a chronic problem ever since the dawn of settled agriculture. The problem has been exacerbated by increase in human and animal population, cultivation of marginal lands, and adoption of extensive, resource-based and subsistence farming methods. Soil erosion is a physical process driven by socio-economic, cultural, and political causes. Effectiveness of biophysical measures to mitigate soil erosion can be enhanced by due consideration to soil, political and cultural variables.

Estimates of the global extent of soil erosion are tentative and subjective, and need to be improved by using remote sensing, GIS and other modern techniques. Developing a credible data base is crucial to identifying management strategies. Erosional hot spots of the world (Himalyan–Tibetan ecoregion, subSaharan Africa, Central America and the Caribbean, and the Andean region) are in need of coordinated efforts at the global scale to restore degraded ecosystems.

The measurement of soil erosion is still more of an art than science, and a wide range of techniques are used to monitor soil erosion. There is a strong need to standardize methods of measurement of soil erosion rates at field, hillside and watershed scales.

Accelerated soil erosion has adverse economic and environmental impacts. Yield reduction by erosion-induced decline in soil quality may be high in regions with predominantly subsistence agriculture based on low external input.

Soil degradation in general and accelerated erosion in particular also affect water quality and emission of radiatively-active gases to the atmosphere. The strategy of controlling soil erosion and restoring degraded soils and ecosystems has a potential to sequester carbon in vegetation and soil, and reduce the rate of enrichment of atmospheric concentration of CO_2 and other gases.

Technology for mitigating soil erosion is known, and have been proven effective on experimental plots. However, adoption of these technologies requires fine tuning at local scales with due consideration to socio-economic, political and cultural factors.

REFERENCES

Bajracharya RM, Lal R, Kimble JM. 1998. Use of radioactive fallout cesium-137 to estimate soil erosion on three farms in west central Ohio. *Soil Science* **163**: 133–142.

Balba AM. 1995. *Management of Problem Soils in Arid Ecosystem.* CRC/Lewis Publishers: Boca Raton, FL, 250 pp.

Batjes NH. 1996. Total C and N in soils of the world. *European Journal of Soil Science* **47**: 151–163.

Baver LD. 1933. Some factors affecting soil erosion. *Agricultural Engineering* **14**: 51–52.

Beasley DB, Huggins LF, Monke EJ. 1980. ANSWERS: a model for watershed planning. *Transactions of ASAE* **23**: 938–944.

Blaikie P, Brookfield H. 1987. *Land Degradation and Society.* Methuen: London.

Brown LC, Foster GR, Beasley DB. 1989. *Transactions of ASAE* **32**: 1967–1978.

Cooley KR, Williams JR. 1985. Applicability of the USLE and modified USLE to Hawaii. In *Soil Erosion and Conservation*, El-Swaify SA, Moldenhauer WC, Lo A (eds). Soil Conservation Society of America: Ankeny, IA; 509–522.

Den Biggelaar C, Lal R, Wiebe K, Breneman V. 2001. Impact of soil erosion on crop yields in North America. *Advances in Agronomy* **72**: 1–52.

Dissmeyer GE, Foster GR. 1985. Modifying the USLE for forest lands. In *Soil Erosion and Conservation*, El-Swaify SA, Moldenhauer WC, Lo A (eds). Soil Conservation Society of America: Ankeny, IA; 480–495.

Doran JW, Parkin TB. 1994. Defining and assessing soil quality. In *Defining Soil Quality for Sustainable Environment*, Doran JW *et al.* (eds). Special Publication No. 35. Soil Science Society of America: Madison, WI; 3–21.

Doran JW, Jones AD (eds). 1996. *Methods for assessing soil quality.* Special Publication No. 49. Soil Science Society of America: Madison, WI.

Dregne HE. 1990. Erosion and soil productivity in Africa. *Journal of Soil Water Conservation* **45**: 431–437.

Dregne HE. 1992a. Erosion and soil productivity in Asia. *Journal of Soil Water Conservation* **47**: 8–13.

Dregne HE. 1992b. *Degradation and Restoration of Arid Lands.* Texas Technical University: Lubbock, TX.

Dregne HE. 1995. Erosion and soil productivity in Australia and New Zealand. *Land Degradation & Rehabilitation* **6**: 71–78.

Dregne HE, Chou N-T. 1992. Global desertification: dimensions and costs. In *Degradation and Restoration of Arid Lands*, Dregne HE (ed.). Texas Technical University: Lubbock, TX; 249–282.

Elliott WJ, Laflen JM, Kohl KD. 1989. Effect of soil properties on soil erodibility. ASAE Paper No. 89–2150, ASAE: St Joseph, MI.

Ellison WD. 1947. Soil erosion studies. *Agricultural Engineering* **23**: 146–156, 197–201, 245–248, 297–300, 349–351, 402–405, 442–444.

Elwell HA. 1977. Soil loss estimation for southern Africa. Research Bulletin 22. Department of Conservation and Extension: Harare, Zimbabwe.

Elwell HA, Stocking MA. 1982. Developing a simple yet practical method of soil loss estimation. *Tropical Agriculture* **59**: 43–48.

Fahnestock P, Lal R, Hall GF. 1995. Land use and erosional effects on two Ohio Alfisols. *Journal of Sustainable Agriculture* **7**: 85–100.

FAO/UNEP/UNESCO. 1979. A provisional methodology for soil degradation assessment. FAO: Rome.

FAO. 1989. *Yearbook in Agriculture*. FAO: Rome.

FAO. 1994. *Land Degradation in South Asia: 1st Severity, Causes and Effects Upon the People.* World Soil Resources Report 78. FAO: Rome.

FAO. 1995. *Yearbook of Production.* FAO: Rome.

Foster GR. 1982. Modeling the soil erosion process. In *Hydrologic Modeling of Small Watershed*, Haan CT (ed.). ASAE Monograph No. 5. ASAE: St Joseph, MI; 297–379.

Foster GR. 1991. Advances in water and wind erosion prediction. *Journal of Soil Water Conservation* **46**: 27–29.

Foster GR, Lane LJ, Nowloin JD, Laflan JM, Young RA. 1980. A model to estimate sediment yield from field-sized areas: development of model. In *CREAMS: Field-Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems*, Knisel WG (ed.). Conservation Research Report No. 26, US Deapartment of Agriculture: Washington, DC.

Foster GR, Meyer LD, Oustad CA. 1977a. An erosion equation derived from basic erosion principles. *Transactions of ASAE* **20**: 678–682.

Foster GR, Meyer LD, Oustad CA. 1977b. A runoff erosivity factor and variable slope length exponents for soil loss estimates. *Transactions of ASAE* **20**: 683–687.

Fournier F. 1956. The effect of climatic factors on soil erosion: estimates of solids transported in suspension in runoff. Publication No. 38. Association of International Hydrology: Wallingford.

Fournier F, Henin S. 1959. A new climatic formula for evaluating the specific degradation of soil. *CR Academy of Science* **248**: 1694–1699.

GLASOD. 1990. Global assessment of soil degradation. *World Maps.* ISRIC: Wageningen.

Govers G, Lobb DA, Quine TA. 1999. Tillage erosion and translocation: emergence of a new paradigm in soil erosion research. *Soil Tillage Research* **51**: 167–174.

Hairsine PB, Rose CW. 1991. Rainfall detachment and deposition: sediment transport in the absence of flow–driven processes. *Soil Science Society of America Journal* **55**: 320–324.

Hao Y, Lal R, Izaurralde RC, Ritchie JC, Owens LB, Hothem DL. 2001. *Soil Science* **166**: 116–126.

Hasholt B, Walling DE. 1992. Use of caesium-137 to investigate sediment sources and sediment delivery in a small glacierized mountain drainage basin in eastern Greenland. In *Erosion, Debris Flows and Environment in Mountain Regions.* Proceedings of the Chendu Symposium, China. IAHS Publication No. 209, Wallingford; 87–100.

Higgitt DL. 1995. The development and application of caesium-137 measurements in erosion investigations. In *Sediment and Water Quality in River Catchments*, Forster IDL, Gurnell AMB, Webb BW (eds). Wiley: Chichester; 287–305.

Horton RE. 1945. Erosional development of streams and their drainage basins: hydrological approach to quantitative morphology. *Geological Society of America Bulletin* **56**: 275–370.

Hudson NW. 1961. An introduction to the mechanics of soil erosion under conditions of sub-tropical rainfall. *Rhodesia Science Association Proceedings* **49**: 14–25.

Hussain I, Olson K, Jones RL. 1998. Flyash and erosion patterns on cultivated and uncultivated hillslopes in southern Illinois. *Soil Science* **164**: 726–738.

IPCC. 1995. *Climate Change.* Working Group 1. Cambridge University Press: Cambridge.

Johnson DL, Lewis LA. 1995. *Land Degradation: creation and destruction.* Blackwell: Cambridge, MA.

Johnson DL, Ambrose SH, Bassett TJ, Bowen ML, Crummey DE, Isaacson JS, Johnson DN, Lamb P, Saul M, Winter-Nelson AE. 1997. Meaning of environmental terms. *Journal of Environment Quality* **26**: 581–589.

Karlen DL, Mausbach MJ, Doran JW, Cline RG, Harris RF, Schuman GE. 1997. Soil quality: a concept, definition, and framework for evaluation. *Soil Science Society of America Journal* **61**: 4–10.

Knisel WG. 1980. *CREAMS: A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems.* Conservation Research Report No. 25. US Department of Agriculture: Tucson, AZ.

Laflen JM, Watson DA, Franti TG. 1986. Ephemeral gully erosion. In *Proceedings of 4th Federal Interagency Sedimentation Conference.* Las Vegas, NV; 3–29–3–37.[Q9]

Lal R. 1976. *Soil erosion problems on Alfisols in western Nigeria and their control.* Monograph No. 1, IITA: Ibadan.

Lal R. 1990. Erosion measurement and evaluation. In *Soil Erosion in the Tropics: Principles and Measurement*. McGraw Hill: New York; 183–223.

Lal R. 1994a. Sustainable land use systems and soil resilience. In *Soil Resilience and Sustainable Land Use*, Greenland DJ, Szabolcs I (eds). CAB International: Wallingford; 41–67.

Lal R. 1994b. *Soil Erosion Research Methods.* Soil Water Conservation Society. St Lucie Press: Delray Beach, FL.

Lal R. 1995. Erosion-crop productivity relationships for soils of Africa. *Soil Science Society of America Journal* **59**: 661–667.

Lal R. 1996. Deforestation and land use effects on soil degradation and rehabilitation in western Nigeria. III. Runoff, soil erosion and nutrient loss. *Land Degradation & Development* **7**: 99–119.

Lal R. 1997. Degradation and resilience of soils. *Philosophical Transaction of the Royal Society London* **352**: 997–1010.

Lal R. 1998. Soil erosion impact on agronomic productivity and environment quality. Critical Review. *Plant Science* **17**: 319–464.

Lal R. 1999a. Soil management and restoration for carbon sequestration to mitigate the accelerated greenhouse effect. *Progress in Environmental Science* **1**: 307–326.

Lal R. 1999b. Soil erosion control for C sequestration and greenhouse effect mitigation. Background paper for *Sustaining the Global Farm*, White Paper, 10th ISCO Conference, 23–28 May 1999. Purdue University: W. Lafayette, IN.

Lal R, Hassan HM, Dumanski JW. 1999. Desertification control for C sequestration to mitigate the greenhouse effect. In *Carbon Sequestration in Soils: Science, Monitoring and Beyond*, Rosenberg NJ, Izaurralde RC, Malone EL (eds). Battelle Press: Columbus, OH; 83–137.

Lewis LA, Nyamalinda V. 1996. The critical role of human activities in land degradation in Rwanda. *Land Degradation & Development* **7**: 47–56.

Lowdermilk WC. 1953. Conquest of the land through 7000 years. USDA-SCS. Agricultural Information Bulletin 99. US Department of Agriculture: Washington, DC.

McHenry JR, Ritchie JC, Gill AC. 1973. Accumulation of fallout cesium-137 in soil and sediments in selected watersheds. *Water Resources Research* **9**: 676–686.

Meyer LD. 1994. Rainfall simulators for soil erosion research. In *Soil Erosion Research Methods*, Lal R (ed.). St Lucie Press: Delray Beach, FL; 83–103.

Musgrave GW. 1947. The quantitative evaluation of factors in water erosion, a first approximation. *Journal of Soil Water Conservation* **2**: 133–138.

Mutchler CK, Murphree CE. 1981. Prediction of erosion on flatlands. In *Soil Conservation*, Morgan RPC (ed.). Wiley: Chichester; 321–327.

Mutchler CK, Murphree CE, McGregor KC. 1994. Laboratory and field plots for erosion research. In *Soil Erosion Research Methods*, Lal R (ed.). Soil Water Conservation Society, St Lucie Press: Delray Beach, FL; 11–37.

Nearing MA, Lane LJ, Lopes VL. 1994. Modeling soil erosion. In *Soil Erosion Research Methods*, Lal R (ed.). Soil Water Conservation Society: Ankeny, IA; 127–157.

Oldeman LR, Hakkeling RTA, Sombroek WG. 1991. World map of the status of human-induced soil degradation. An explanatory note. ISRIC: Wageningen.

Olson GW. 1981. Archaeology: Lessons on future soil use. *Journal of Soil Water Conservation* **36**: 261–264.

Oztas T, Jones AJ, Mielke LN, Grossman RB. 1997. Parabolic method to predict soil erosion from cesium-137 activity. *Nebraska Agricultural Experiment Station Journal* Series. Linclon, NE.

Pimentel D, Harvey C, Resodudarmo P, Sinclair K, Jurz D, McNair M, Crist S, Shpritz L, Fitton L, Saffouri R, Blair R. 1995. Environmental and economic costs of soil erosion and conservation benefits. *Science* **267**: 1117–1123.

Quine T, Walling D, Chakela Q, Mandiringana O, Zhang X. 1999. Rates and patterns of tillage and water erosion on terraces and contour strips: evidence from cesium-137 measurements. *Catena* **36**: 115–142.

Renard KG, Simanton JR, Osborn HB. 1974. Applicability of the USLE to semi-arid rangeland conditions in the Southwest. In *Hydrology and Water Resources in Arizona and the Southwest*, Vol. 4. Amerian Water Resources Association, 18–31.

Renard KG, Foster GR, Weesies GA, Porter JP. 1991. RUSLE: revised universal soil loss equation. *Journal of Soil Water Conservation* **46**: 30–33.

Renard KG, Laflen JM, Foster GR, McCool DK. 1994. The revised universal soil loss equation. In *Soil Erosion Research Methods*, Lal R (ed.). Soil Water Conservation Society: Ankeny, IA; 105–125.

Renard KG, Foster GR, Lane LJ, Laflen JM. 1996. Soil loss estimation. In *Soil Erosion, Conservation and Rehabilitation,* Agassi M (ed.). Marcel Dekker: New York; 169–202.

Renard KG, Foster GR, Weesies GA, McCool DK, Yoder DC. 1997. *Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation.* USDA Handbook No. 703, USDA: Washington, DC.

Richards JF. 1991. Land transformation. In *The Earth as Transformed by Human Action: Global and Regional Changes in Biosphere Over the Past 300 Years*, Turner BL, Clark WC, Kate RW, Richards JF, Mathews JT, Mayer WB (eds). Cambridge University Press: New York; 163–178.

Ritchie JC, Spraberry JA, McHenry JR. 1974. Estimating soil erosion from the distribution of fallout ^{137}Cs. *Soil Science Society of America Proceeding* **38**: 137–139.

Ritchie JC, Hawks PH, McHenry JR. 1975. Deposition rates in valleys determined using fallout cesium-137. *Geological Society of America Bulletin* **86**: 1128–1130.

Ritchie JC, McHenry JR. 1990. Application of radioactive fallout cesium-137 for measuring soil erosion and sediment accumulation rates and patterns: a review. *Journal of Environmental Quality* **19**: 215–233.

Rose CW. 1985. Developments in soil erosion and deposition models. *Advances in Soil Science* **2**: 1–63.

Rose CW. 1994. Research progress on soil erosion processes and a basis for soil conservation practices. In *Soil Erosion Research Methods*, Lal R (ed.). Soil Water Conservation Society: Ankeny, IA; 159–180.

Schlesinger WH. 1997. *Biogeochemistry: An Analysis of Global Change.* Academic Press: New York.

Singh G, Babu R, Narain P, Bhushan LS, Abrol IP. 1992. Soil erosion rates in India. *Journal of Soil Water Conservation* **47**: 93–95.

Skidmore EL. 1994. Wind erosion. In *Soil Erosion Research Methods*, Lal R (ed.). Soil Water Conservation Society: Ankeny, IA; 265–293.

Skidmore EL, Hagen LJ, Armbrust DV, Durar AA, Fryrear DW, Potter KN, Wagner LE, Zobeck TM. 1994. Methods for investigating basic processes and conditions affecting wind erosion. In *Soil Erosion Research Methods*, Lal R (ed.). Soil Water Conservation Society: Ankeny, IA; 295–330.

Smith DD, Whitt DM. 1948. Evaluating soil losses from field areas. *Agricultural Engineering* **29**: 394–396.

Soileau JM, Hajek BF, Touchton JT. 1990. Soil erosion and deposition evidence in a small watershed using fallout cesium-137. *Soil Science Society of America Journal* **54**: 1712–1719.

Stallard RF. 1998. Terrestrial sedimentation and the carbon cycle: coupling weathering and erosion to carbon burial. *Global Biogeochemcial Cycles* **12**: 231–257.

Stamey WL, Smith RM. 1964. A conservation definition of erosion tolerance. *Soil Science* **97**: 183–186.

Steiner KG. 1996. *Causes of Soil Degradation and Development Approaches to Sustainable Soil Managment.* Margraf Verlag: Reiskinchen.

Stewart BA, Lal R, El-Swaify SA. 1991. Sustaining the resource base of an expanding world agriculture. In *Soil Management for Sustainability*, Lal R, Pierce FJ (eds). Soil Water Conservation Society: Ankeny, IA; 125–144.

Stocking M. 1994. Soil erosion and conservation: a place for soil science? In *Soil Science and Sustainable Land Management in the Tropics*, Syers JK, Rimmer DL (eds). CAB International: Wallingford; 40–58.

Tamura T. 1964a. Reaction of Cesium-137 and Strontium-90 with Soil Minerals and Sesquioxides. In *8th International Congress of Soil Science, Bucharest, Romania, 31 August–9 September.* International Society of Soil Science: Wageningen; 465–478.

Tamura T. 1964b. Selective sorption reaction of cesium with mineral soils. *Nucl. Saf.* **5**: 262–268.

Tengberg A, Stocking M. 1997. Erosion-induced loss in soil productivity and its impact on agricultural production and food security. FAO/AGRITEX Expert Consultation on Integrated Soil Management for Sustainable Agriculture and Food Security in Southern and Eastern Africa. Harare, Zimbabwe, 8–12 December. FAO: Rome.

Thapa BB, Cassel DK, Garrity D. 1999. Assessment of tillage erosion rates on steepland Oxisols in the humid tropics using granite rocks. *Soil Tillage Research* **51**: 233–244.

Turkelboom F, Poesen J, Ohler I, Van Keer K, Ongprasert S, Vlassak K. 1997. Assessment of tillage erosion rates on steep slopes in northern Thailand. *Catena* **29**: 29–44.

UNDP. 1994. Land degradation in South Asia: its severity, causes and effect upon people. FAO: Rome.

UNEP. 1991. Status of desertification and the implementation of United Nations Plan of Action to combat desertification. UNEP: Nairobi.

USDA. 1984. National Resource Inventory. Washington, DC.

USDA-SCS. 1984. Study of erosion from ephemeral gullies on cropland—1983. Report to St John-Aroostock RC&D Steering Committee, Central Aroostock Soil & Water Conservation District by USDA-SCS: Orono, ME.

Venkateswarlu J. 1994. Managing extreme stresses in arid zone of western Rajisthan, India. In *Stressed Ecosystem and Sustainable Agriculture*, Varmani SM, Katyal JC, Eswaran H, Abrol IP (eds). Oxford & IBH Publishing: New Delhi; 161–171.

Walling DE. 1994. Measuring sediment yield from river basins. In *Soil Erosion Research Methods*, R Lal (ed.). St Lucie Press: Delray Beach, FL; 39–82.

Wang Y. 1988. Effect of slope steepness, bulk density and surface roughness on interrill soil erosion. MS thesis, University of Minnesota: MN.

Wight JR, Skiles JW (eds). 1987. *SPUR: Simulation of Production and Utilization of Rangelands. Document and User Guide. ARS 63, USDA-ARS: Washington, DC.*

Williams JR. 1975. Sediment yield prediction with USLE using runoff energy factor. In *Present and Prospective Technology for Predicting Sediment Yields and Sources*, ARS-S-40, USDA: Washington, DC; 244–252.

Williams JR. 1982. Sediment-yield prediction with universal equation using runoff energy factor. In *Proceedings of Workshop on Estimating Erosion and Sediment Yield on Range-Lands*, ARM-W-26, USDA-ARS: Washington, DC; 244–252.

Williams JR, Berndt HD. 1972. Sediment yield prediction based on watershed hydrology. Paper 76–2535. ASAE, St Joseph, MI.

Williams JR, Berndt HD. 1977. Sediment yield prediction based on watershed hydrology. *Transactions of ASAE* **20**: 1100–1104.

Williams JR, Nicks AD, Arnold JG. 1985. Simulator for water resources in rural basins. *Journal of Hydraulic Engineering ASCE* **111**: 970–986.

Wilson L. 1975. Application of the wind erosion equation in air pollution surveys. *Journal of Soil Water Conservation* **30**: 215–219.

Wischmeier WH, Smith DD. 1958. Rainfall energy and its relationship to soil loss. *Transactions of AGU* **39**: 285–291.

Wischmeier WH, Smith DD. 1978. *Predicting Rainfall Erosion Losses.* Agriculture Handbook No. 537, US Department of Agriculture, Government Printers: Washington, DC.

Woodruff NP, Siddoway FH. 1965. A wind erosion equation. *Soil Science Society of America Proceedings* **29**: 602–608.

Woolhiser DA, Smith RE, Goodrich DC. 1990. *KINERUS. A Kinematic Runoff and Erosion Model: Documentation and User Manual.* ARS-77, USDA-ARS: Washington, DC.

Young RA, Wiersma JL. 1973. The role of rainfall impact in soil detachment and transport. *Water Resources Research* **9**: 1629–1639.

Young RA, Onstad CA, Bosch DD, Anderson WP. 1987. AGNPS: Agricultural non-point source pollution model: a watershed analysis tool. Conservation Research Report No. 35, USDA-ARS: Washington, DC.

Zingg AW. 1940. Degree and length of slope as it affects soil loss in runoff. *Agricultural Engineering* **21**: 59–64