PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Degradation and resilience of soils

R. Lal

Phil. Trans. R. Soc. Lond. B 1997 **352**, 997-1010
doi: 10.1098/rstb.1997.0078

Degradation and resilience of soils

R. LAL

School of Natural Resources, The Ohio State University, 2021 Coffey Road, Columbus OH 43210-1085, USA

SUMMARY

Debate on global soil degradation, its extent and agronomic impact, can only be resolved through understanding of the processes and factors leading to establishment of the cause-effect relationships for major soils, ecoregions, and land uses. Systematic evaluation through long-term experimentation is needed for establishing quantitative criteria of (i) soil quality in relation to specific functions; (ii) soil degradation in relation to critical limits of key soil properties and processes; and (iii) soil resilience in relation to the ease of restoration through judicious management and discriminate use of essential input. Quantitative assessment of soil degradation can be obtained by evaluating its impact on productivity for different land uses and management systems. Interdisciplinary research is needed to quantify soil degradation effects on decrease in productivity, reduction in biomass, and decline in environment quality through pollution and eutrophication of natural waters and emission of radiatively-active gases from terrestrial ecosystems to the atmosphere. Data from long-term field experiments in principal ecoregions are specifically needed to (i) establish relationships between soil quality versus soil degradation and soil quality versus soil resilience; (ii) identify indicators of soil quality and soil resilience; and (iii) establish critical limits of important properties for soil degradation and soil resilience. There is a need to develop and standardize techniques for measuring soil resilience.

1. INTRODUCTION

Soil degradation has raised some serious debate, and it is an important issue in the modern era (Blaikie & Dregne 1985; Brookfield 1987; UNEP 1991, 1992; Oldeman 1994; Johnson & Lewis 1995; Gardner 1996). Some believe that erosion and soil degradation have disastrous effects on agricultural productivity (Brown 1995; Pimentel *et al.* 1995; Scherr & Yadav 1996). Others argue that productivity loss due to erosion and soil degradation is hardly 5% (Crosson & Anderson 1992; Crosson 1995). Further, statistics on soil degradation are often based on subjective methodology, and not related to productivity, soil and crop management, or land use.

Freshwater is now scarce in many regions of the world (Lvovitch 1971; Postel 1992; Postel *et al.* 1996). It constitutes only 2.5% of the total volume of water on Earth, and only about one-third of this water (0.77% of the total) is held in aquifers, soil, lakes, swamp, rivers, plant life and the atmosphere (Colenbrander 1973, 1978; Dooge 1973). The number of countries with scarcity of freshwater for human consumption (including agricultural and industrial use) was 20 in 1990, and will increase to 30–35 by 2025 (Engelman & LeRoy 1993). Between 1990 and 2025, the number of people affected by water scarcity will increase from 130 million to about one billion.

Soil and water degradation are also related to overall environmental quality, of which water pollution and the 'greenhouse effect' are two major concerns of global significance. The atmospheric concentration of CO_2 has increased by 30%, from 280 ppm in 1850 to 360 ppm in 1995 (IPCC 1995). The increase has occurred due to two principal anthropogenic activities, namely land use and fossil fuel burning. The global release of soil organic carbon (SOC) from agricultural activities has been estimated at 800 Tg C yr^{-1} (T = tera = 10^{12}) (Schlesinger 1990). Soil biological degradation—decreases in SOC and biomass carbon contents—is an important factor leading to C emission from soil to the atmosphere, and is closely linked to soil quality. The latter is defined as the capacity of soil to produce economic goods and services and to perform environmental regulatory functions (Lal 1993; Doran & Parkin 1994; Doran *et al.* 1996). In addition to CO_2, other important greenhouse gases include CH_4 and N_2O. Atmospheric concentration of CH_4 has increased from 0.8 ppm in 1750 to 1.72 ppm in 1990, and of N_2O from 290 ppb in 1750 to 310 ppb in 1990 (Engelman 1994; IPCC 1995). A large part of these gaseous emissions is due to soil related processes.

Increase in the human population has increased demands on soil resources for numerous other functions, and has been a principal cause of global deforestation and conversion to agricultural land use (Richards 1990). In addition to production of food, fuel, fibre and building materials, soils are increasingly used for: (i) biomass production for industrial use; (ii) environmental regulation through buffering biochemical transformations–bioremediation; (iii) retention of a large gene pool; (iv) engineering and military uses; (v) aesthetic and cultural uses; and (vi) archaeological functions. Soil degradation and resilience must be evaluated in terms of all of these functions.

The objective of this paper, therefore, is to discuss basic concepts of soil degradation and resilience, describe the economic impact of soil degradation, explain methods of assessment and prediction of soil resilience, and identify research and development priorities for soil restoration and environmental quality enhancement.

2. SOIL DEGRADATION

(*a*) *Basic concepts*

Soil degradation is the loss of actual or potential productivity or utility as a result of natural or anthropogenic factors (Lal 1994*c*). Essentially, it is the decline in soil quality or reduction in its productivity and environmental regulatory capacity. Soil degradative processes, mechanisms that set in motion the degradative trends, include physical, chemical and biological processes (figure 1). Important among the physical processes is decline in soil structure, leading to crusting, compaction, erosion, desertification, anaerobiosis, environmental pollution, and unsustainable use of natural resources. Significant chemical processes include acidification and leaching, salinization, reduction in CEC and loss of fertility. Biological processes include reduction in total and biomass carbon, and decline in soil biodiversity (figure 1). Soil structure is the important property that affects all three degradative processes.

Factors affecting soil degradation are biophysical environments, which determine the kind of degradative processes, such as erosion and salinization. These include soil quality, which is affected by its intrinsic properties, climate, terrain and landscape position, and climax vegetation and biodiversity, especially the soil biodiversity. Causes of soil degradation are the agents that determine the rate of soil degradation. These are biophysical (land use and soil management, including deforestation and tillage methods), socio-economic (e.g. land tenure, marketing, institutional support, income and human health), and political (e.g. incentives, political stability) forces that influence the effectiveness of processes and factors of soil degradation.

Soil degradation is a biophysical process driven by socioeconomic and political causes (see figure 2). High population density is not necessarily related to soil degradation. What the population does to itself and to the soil that it depends on determines the extent of soil degradation. People can be a major asset in reversing the degradative trend (Tiffen *et al.* 1994). However, subsistence agriculture, poverty and illiteracy are important causes of soil and environmental degradation. People must be healthy and politically and economically motivated to care for the land.

Susceptibility to degradative processes can be grouped into five classes (table 1). Soils, depending on their inherent characteristics and climatic conditions, range from highly resistant or stable to extremely sensitive and fragile. Fragility, extreme sensitivity to

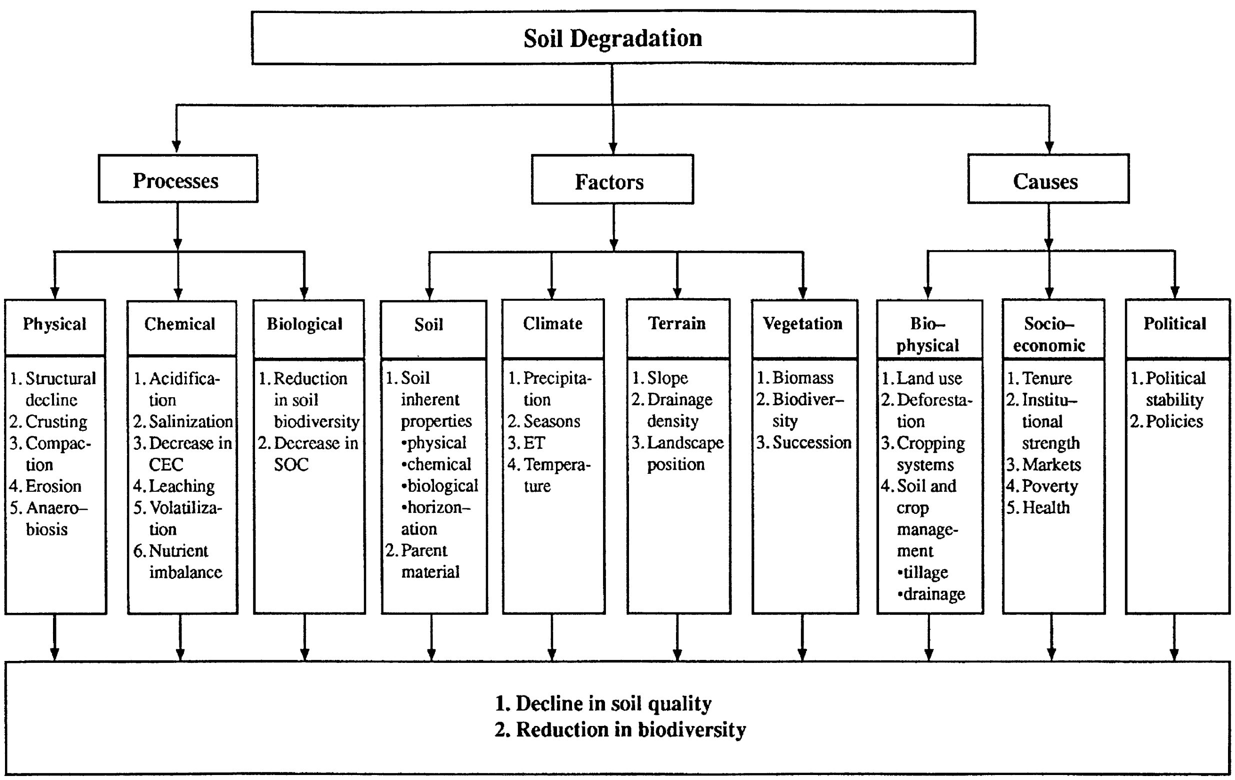

Figure 1. Processes, factors, and causes of soil degradation.

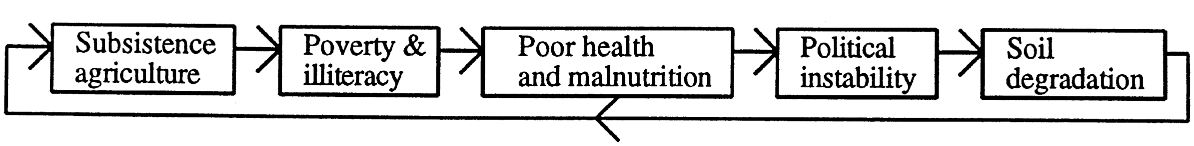

Figure 2. Socio-economic and political causes of soil degradation.

Table 1. *Soil degradative classes*

class	susceptibility to degradation	description
0	resistant	extremely resistant to stress and very stable
1	slight	resistant to stress and stable
2	moderate	susceptible to stress and moderately stable
3	severe	highly susceptible to stress and unstable
4	extreme	extremely susceptible and fragile

degradative processes, may refer to the whole soil, a degradative process (e.g. erosion) or a property (e.g. soil structure).

Stable or resilient soils do not necessarily resist change. They are in stable equilibrium with the new environment. Fragile soils degrade to a new equilibrium under stress, and the altered state is unfavourable to plant growth and environmental regulatory capacity.

(*b*) *Regional and global effects of soil degradation on productivity*

Information on the economic impact of soil degradation by different processes on a global scale is not available. Some information for local and regional scales is available. In Canada, for example, on-farm effects of soil degradation were estimated to range from $700 to $915 million in 1984 (Girt 1986). The economic impact of soil degradation is extremely severe in densely populated South Asia (Tolba & El-Kholy 1992; UNEP 1994), and sub-Saharan Africa (Lal 1995).

Soil compaction is a worldwide problem (Soane & Ouwerkerk 1994), especially so with the adoption of mechanized agriculture. Severe compaction has caused yield reductions of 25–50% in some regions of Europe (Ericksson *et al*. 1974) and North America (Raghavan *et al*. 1978, 1990), and 40–90% in some parts of West Africa (Charreau 1972; Kayombo & Lal 1994). In Ohio, Lal (1996*a*) reported reductions in crop yields by 25% in maize, 20% in soybeans, and 30% in oats over a seven-year period. On-farm losses due to soil compaction in the United States alone have been estimated at $1.2 billion per year (Gill 1971).

Accelerated soil erosion is another principal cause of soil degradation (Lal 1984, 1989*a*). As with compaction, few attempts have been made to assess the global economic impact of erosion. On plot and field scales, erosion can cause yield reductions of 30–90% in some root-restrictive shallow soils of West Africa (Mbagwu *et al*. 1984; Lal 1987). Yield reductions of 20–40% have been measured for row crops in Ohio (Fahnestock *et al*. 1995; Changere & Lal 1995) and elsewhere in the mid-west USA (Gantzer & McCarty 1987; Mokma & Sietz 1992; Olson & Nizeyimana 1988; Schumacher *et al*. 1994). In the Andean region of Colombia, Reining (1992), Ruppenthal (1995) and others from the University of Hohenheim, Germany, have observed severe losses due to accelerated erosion on some soils. On a global scale, Dregne (1990) observed that productivity of some soils in Africa has declined by 20% due to soil erosion and desertification. Lal (1995) reported that yield reduction in Africa due to past soil erosion may range from 2–40%, with a mean loss of 8.2% for the continent. If accelerated erosion continues unabated, yield reductions by the year 2020 may be 16.5%. Annual reduction in total production for 1989 due to accelerated erosion was 8.2 million tonnes (Mt) for cereals, 9.2 Mt for roots and tubers, and 0.6 Mt for pulses (Lal 1995). There are also serious (20%) productivity losses due to erosion in Asia, especially in India, China, Iran, Israel, Jordan, Lebanon, Nepal and Pakistan (Dregne 1992). In South Asia, annual loss in cereal productivity caused by water erosion is estimated to be 36 Mt, equivalent to $5400 million, with a further $1800 million loss due to wind erosion (UNEP 1994). Pimentel *et al*. (1995) estimated the total annual cost of erosion from agriculture in the USA to be about $44 billion per year, about $100 per acre of crop land and pasture. Globally, the annual loss of 75 billion tonnes of soil costs (at $3 per tonne of soil for nutrients and $2 per tonne of soil for water) the world about $400 billion per year, or more than $70 per person per year.

Nutrient depletion is another principal process of soil degradation, with severe economic impact at a global scale, especially in sub-Saharan Africa. Stoorvogel *et al*. (1993) estimated the nutrient balances for 38 countries in sub-Saharan Africa. Annual soil fertility depletion rates were estimated at 22 kg of N, 3 kg of P and 15 kg of K ha^{-1}. Stocking (1986) estimated the economic costs of the nutrient loss (N, P and K) by soil erosion in Zimbabwe. The annual losses of N and P alone totalled $1.5 billion. In South Asia, annual economic loss is estimated at $600 million for nutrient loss by erosion, and $1200 million due to soil fertility depletion (UNEP 1994).

Salt-affected soils occupy an estimated 950 million ha of land in arid and semi-arid regions, nearly 33% of the potentially arable land area of the world (Gupta & Abrol 1990). Productivity of irrigated lands is severely threatened by build-up of salt in the root zone. In South Asia, annual economic loss is estimated at $500 million from waterlogging, and $1500 million from salinization (UNEP 1994). The potential and actual economic impacts on global scale are not known. Soil acidity, and the resultant toxicity caused by high concentrations of aluminium and manganese in the root zone, are serious problems in sub-humid and humid regions (Oldeman 1994). Once again, the economic impact on a global scale is not known.

In the context of these global economic and environmental impacts, and deterioration of numerous soil functions of value to humans, soil degradation and resilience concepts are relevant. They are especially important in developing technologies for reversing soil degradative trends and mitigating the greenhouse effect through soil and ecosystem restoration. Soil resources are essentially non-renewable. Hence, it is necessary to adopt a positive approach to sustainable management of these finite resources.

(*c*) *Degradation of an Alfisol in western Nigeria*

Alfisols, the predominant soils of the sub-humid regions of West Africa, are easily degraded with continuous cultivation. Several experiments were conducted on Alfisols at IITA, Ibadan, Western Nigeria, to evaluate agricultural sustainability of a wide range of land use and soil management systems (Lal 1976*a*, *b*; 1989*a*, *b*, *c*, *d*). The management systems evaluated included tillage systems, mulch farming, agroforestry, cover crops and ley farming. SOC content was selected as an indicator of soil degradation or quality. An eight-year tillage experiment in which two crops were grown each year, using recommended fertilizer rates, showed that maize grain yield (equation (1)), SOC content (equation (2)) and the C : N ratio (equation (3)) followed a quadratic function. These parameters are interrelated: they increased for the first four years and then declined with continuous cultivation.

$$Y = 1.03 + 1.56\ T - 0.18\ T^2,\ R^2 = 0.9, \quad (1)$$

$$\mathrm{SOC} = 5.02 + 4.11\ T - 0.48\ T^2,\ R^2 = 0.7, \quad (2)$$

$$\mathrm{C{:}N} = 4.60 + 2.02\ T - 0.15\ T^2,\ R^2 = 0.6, \quad (3)$$

where Y is grain yield in Mt ha^{-1} yr^{-1}, T is time in years since deforestation, and SOC and N contents are in g kg^{-1}. Grain yield was significantly correlated with SOC and clay contents (Lal 1997*a*, *b*), which declined with cultivation duration.

Another long-term tillage and residue management experiment conducted over a five-year period showed that total SOC content was more for no-till (equation (4)) than plow till (equation (5)), and the rate of SOC decline with time also differed among tillage methods.

$$\mathrm{SOC_{NT}} = 10.2 + t^{-0.54},\ R^2 = 0.97, \quad (4)$$

$$\mathrm{SOC_{PT}} = 2.38 + \mathrm{e}^{-0.22t},\ R^2 = 0.96, \quad (5)$$

where t is time in months. An experiment conducted with different mulch rates showed that SOC content decreased linearly with duration after deforestation, and the rate of decline in 0–10 cm depth was 0.045, 0.043, 0.042, 0.036 and 0.036 kg m^2 month^{-1} for mulch rates of 0, 2, 4, 6 and 12 Mt ha^{-1} season^{-1}, respectively (Lal *et al*. 1980).

Cropping/farming systems also have a significant impact on soil degradation. An eight-year watershed management experiment showed that the SOC content was lower under alley cropping (equation (6)) than mucuna fallow (equation (7)) or ley farming (equation (8)) (Lal 1996*b*, *c*):

$$\mathrm{SOC} = 2.11 + \mathrm{e}^{-0.26t},\ R^2 = 0.74, \quad (6)$$

$$\mathrm{SOC} = 2.22 + r^{-0.052t},\ R^2 = 0.67, \quad (7)$$

$$\mathrm{SOC} = 2.23 + \mathrm{e}^{-0.056t},\ R^2 = 0.78, \quad (8)$$

where t is time in months.

Severe problems of soil degradation in west Africa are due to land misuse and soil mismanagement, harsh climate, the susceptibility of the soil to degradation, and predominance of resource-based and exploitative agricultural systems based on low external input and soil-mining systems. Decline in soil structure is the major problem, and this is accentuated by a reduction in SOC content (Nye & Greenland 1960) and depletion of soil fertility. Unless soil structure is improved, application of fertilizers alone is not sufficient to curtail the soil degradative processes.

Rapid SOC decline, despite high rates of organic mulch application, may be due to lack of essential nutrients N, P and S. If SOC content is to be increased by 10 000 kg ha^{-1}, it would require about 67 Mt of crop residues, 833 kg of N, 200 kg of P and 143 kg of S (Himes 1997). Here lies one of the important reasons for severe soil degradation observed in low-input or subsistence agricultural systems, widely practised in sub-Saharan Africa. Along with substantial and regular applications of biomass, the addition of plant nutrients as inorganic fertilizers and organic amendments is also essential to improve soil quality and restore productivity of degraded soils.

3. SOIL RESILIENCE

Resilience is an ecological concept that involves several attributes that govern responses to disturbance or stress (Holling 1973; Patten 1974; May 1976, 1978; Holdgate & Woodman 1978; Mitchell 1979; Pimm 1984; Hill 1987; Mortimore 1988, 1989; Barrow 1991; Peters 1991). Several terms used in ecology with relevance to soil resilience are: (i) resilience, the ability to resist change or recover to the initial state; (ii) resistance, the ability to resist displacement from the antecedent state; (iii) elasticity, the rate of recovery; (iv) amplitude, the range of change in a property from which recovery is possible; (v) hysteresis, the divergence in the recovery path or pattern; and (vi) malleability, the difference in the new versus the antecedent state.

These ecological concepts have been applied to natural ecosystems, e.g. forest resilience (Whitaker 1975; Westman 1978; Jordan 1987; Scott 1987), and to soils and their management (Blum 1990, 1994; Blum & Aguilar 1994; Szabolcs 1994*a*, *b*; Lal 1994*a*, *b*). Therefore, soil resilience refers to the ability of soil to resist or recover from an anthropogenic or natural perturbation. Most soils do not offer resistance to perturbation, but are able to recover. The extent and the rate of recovery are high for a resilient soil. Resilient soils have high elasticity and amplitude, and low malleability. Some resilient soils may also be hysteretic because of inherent soil properties that influence the recovery path.

There are a number of processes, factors and causes of soil resilience which are analogous to soil degradation (figure 3). Processes of soil resilience refer to mechanisms that influence ability and rate of recovery. Important among these are the rates of new soil formation, aggregation, SOC accumulation, nutrient cycling and transformation, leaching of excess salts,

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

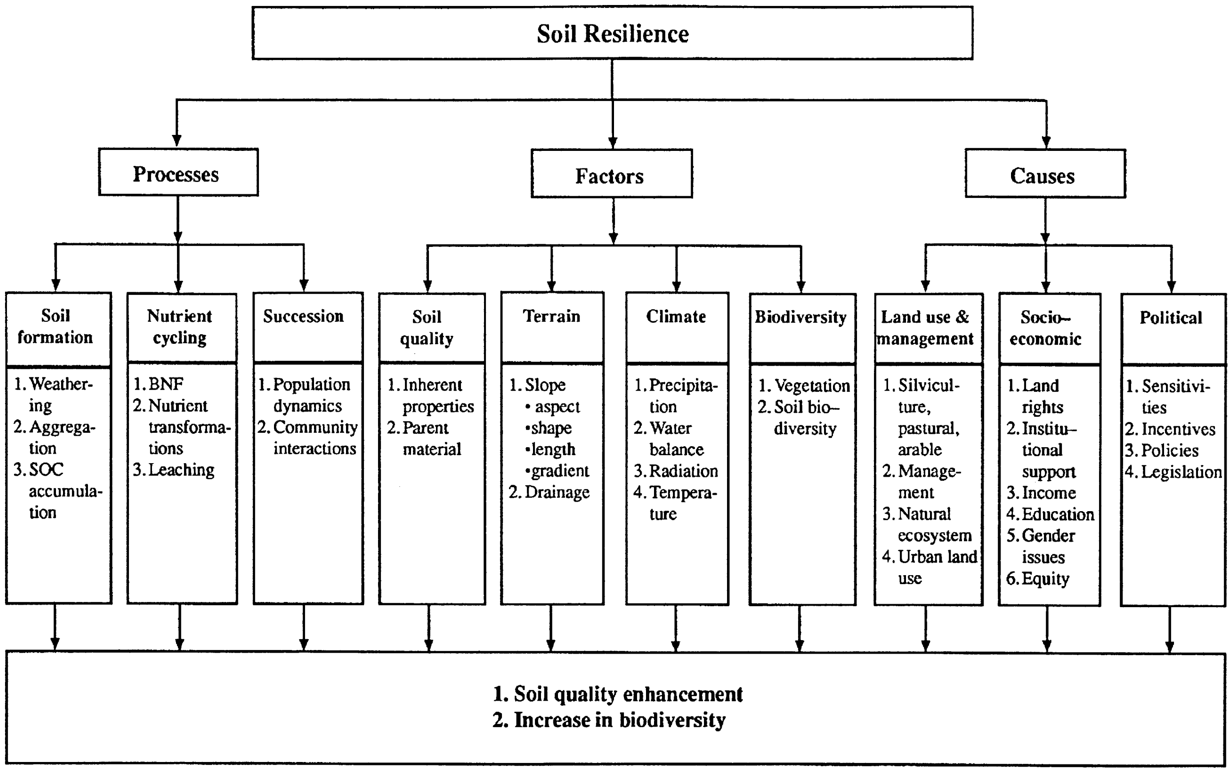

Figure 3. Processes, factors and causes of soil resilience (SOC: soil organic carbon; BNF: biological nitrogen fixation)

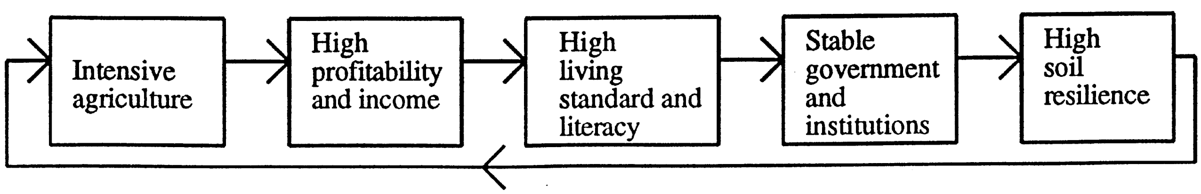

Figure 4. Socio-economic and political forces that affect soil resilience.

Table 2. *Soil resilient classes*

class	resilience	description
0	highly resilient	rapid recovery, high buffering
1	resilient	recovery with improved management
2	moderately resilient	slow recovery with high input
3	slightly resilient	slow recovery even with change in land use
4	non-resilient	no recovery even with change in land use

and increases in biodiversity, including species' succession. Factors of soil resilience refer to the biophysical characteristics that govern the rate, path and pattern of recovery, and amplitude and malleability. Important factors include terrain characteristics, landscape position, soil quality, parent material, climate, water balance, vegetation and soil biodiversity. What causes soils to express resilience are the socio-economic and political forces that govern land use, land rights, institutional support, and income. Processes governing soil resilience depend on its intrinsic properties, but are driven by socio-economic and political forces (figure 4).

Extensive and subsistence agriculture can lead to degradation, because of inappropriate land use and soil mismanagement. Intensive agriculture, based on appropriate land use and scientific management, can lead to soil restoration through the exercise of resilience, although if badly managed, it can also lead to rapid degradation.

Soils can be grouped into different classes according to their degree of soil resilience (table 2). Highly resilient soils have high buffering capacities, high rates of recovery, and large amplitudes. Fragile soils are unstable, cannot recover to the initial state, and may have lost some or all of their specific functions in the new state. Soil functions are an important aspect of soil resilience. Soil is resilient if the new state can perform its functions efficiently and profitably. Non-resilient soils become dysfunctional following a perturbation.

Table 3. *Indicators of soil degradation and soil resilience*

degradative process	indicators of soil degradation	indicators of soil resilience
(i) erosion	(i) erosivity	(i) structural resilience
(ii) SOC depletion	(iI) topsoil loss	(ii) soil renewal rate
(iii) acidification	(iii) depletion constant	(iii) accretion constant
(iv) nutrient depletion	(iv) decline in pH	(iv) increase in base saturation
(v) compaction	(v) leaching	(v) buffering capacity
	(vi) decline in CEC	(vi) nutrient cycling
	(vii) decline in nutrient reserves	(vii) biological N fixation
	(viii) susceptibility to compaction	(viii) swell-shrink capacity
	(xi) crusting	(ix) self-mulching
		(x) soil biodiversity

There are different indicators of soil degradation and resilience (table 3). Indicators of degradation are used to evaluate relative susceptibility to degradative processes. In contrast, indicators of soil resilience can be used to assess the ease or rate of restoration. Specific indicators may differ among soils and land uses.

An example of soil resilience is available from the data for an Alfisol in western Nigeria. The watershed experiment conducted at IITA showed the resilient characteristics of Alfisols when put under a restorative natural fallow. The infiltration rate under traditional cropping declined from 156 cm h^{-1} under forest to 1.9 cm h^{-1} after four years of cultivation. When reverted back to natural fallow, regrowth was allowed to develop, the infiltration rate increased to 24.0 cm h^{-1}, 43.2 cm h^{-1}, 115.8 cm h^{-1} and 193.0 cm h^{-1} in one, two, three and four years of fallowing, respectively (Lal 1994*a*). Another experiment on the use of planted fallows and cover crops showed significant improvements in SOC content and soil structure. The rate of SOC sequestration in 0–10 cm depth was 1.5–2.6 Mt ha^{-1} yr^{-1} for grasses and 1.5–2.2 Mt ha^{-1} yr^{-1} for legumes (Lal *et al.* 1979). A high rate of SOC improvement was observed under *Melinis* (7.1 Mt ha^{-1} yr^{-1}) and *Glycine* (12.3 Mt ha^{-1} yr^{-1}) covers (Lal *et al.* 1978).

4. SOIL QUALITY AND SOIL RESILIENCE

Soil quality and soil resilience are interrelated but dissimilar attributes. Soil quality is related more to productivity and other functions than the ability of the soil to restore itself after a perturbation. Soil quality, productivity and environmental regulatory capacity, affect soil resilience. Resilient soils have high soil quality and vice versa. However, indicators of soil quality and resilience may be different for different functions (table 4), and may also differ between soils. In relation to soil productivity, indicators of soil quality are soil depth, and water and nutrient use efficiencies. Comparable indicators of soil resilience in relation to productivity are responses to input or management and rate of change of soil properties with restorative measures. Identification of indicators of resilience may be useful prior to adopting a land use that may have drastic effects on soil quality, e.g. land disposal of industrial or solid waste, brick making, growing turf for use in urban centres.

Soil quality can be assessed by developing pedotransfer functions relating crop yield to soil properties (equation (1)). Such pedotransfer functions are soil and crop specific (equation (9)):

$$y = f(\mathrm{SOC} \times S_c R_d e_d N_c B_d), \tag{9}$$

where y is biomass yield, SOC is soil organic and biomass carbon, S_c is an index of structural properties, R_d is effective rooting depth, e_d is charge density related to surface area, N_c is nutrient reserve, and B_d is a measure of soil biodiversity. Such functions are useful in planning soil and crop management strategies in relation to expected output. In comparison, knowledge of soil resilience and attributes affecting output is useful to manage stress or perturbation by providing an answer to the following questions: (i) can soil quality be restored to the antecedent state after perturbation? (ii) What is the rate of soil quality restoration? (iii) Can soil quality be restored following successive stresses? (iv) Can soil quality restoration be predicted through pedotransfer functions? (v) What is the cost of soil restoration? Analogous to equation (1), pedotransfer functions can be developed to predict soil restoration (equation (10)):

$$S_r = f(SOC \times {}' S'_c R'_d e'_d N'_c B'_d), \tag{10}$$

where S_r is soil resilience, SOC' is the rate of accretion or accumulation of total and biomass carbon, S'_c is the structural resilience index, R'_d is the change in rooting depth through soil renewal, e'_d is the change in charge properties, N'_c is the improvement in nutrient reserve, and B'_d is the rate of increase in soil biodiversity.

Variables listed in equations (1) and (2) may be different for different soils and functions. Further, combination of these variables to develop specific pedotransfer functions may also be done additively rather than multiplicatively, or by other relevant statistical or numerical analysis procedures.

Soil quality and resilience also differ in relation to critical limits and threshold values of key soil attributes. Soil quality, as measured by productivity, is affected by degradative processes which govern the net primary productivity (NPP) and the maximum sustainable yield. The latter is the quantity of biomass that can be harvested without jeopardizing soil quality. Soil quality may be regulated by controlling the yield, e.g. only 50% of the biomass produced may be harvested from some soils, compared with 70% in others. The quantity

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Table 4. *Indicators of soil quality and soil resilience*

soil function	indicators of soil quality	indicators of soil resilience
1. productivity	(i) soil depth	(i) response to input
2. environment regulation	(ii) water and nutrient use efficiencies	(ii) change in soil properties with restorative measures
3. urban use	(iii) soil erosivity	(iii) buffering capacity
4. industrial use	(iv) SOC content	(iv) SOC accretion rate, high surface area and charge density
	(v) swell–shrink capacity for strong foundation	(v) horizonation, uniformly deep profile with high productivity of subsoil, e.g. brick making, road construction
	(vi) texture to facilitate waste disposal	(vi) bioremediation, elemental transformations

Table 5. *Critical limit concept applied to soil degradation and resilience concepts*

process	soil degradation	soil resilience
1. erosion	(i) decline in soil structure SOC content and infiltration beyond which erosion rate is very serious	(i) threshold values of soil renewal and ameliorative rates in soil structure to let eroded soil recover
2. acidification	(ii) decline in soil pH and increase in concentration of Al to influence crop growth drastically	(ii) high buffering capacity to restore a soil pH which favourable to crop growth and soil chemistry quality
3. biological degradation	(iii) decline in SOC content to a level at which it adversely affects soil structure, and adversely affects the population and activity of soil	(iii) threshold value of total SOC content and turnover rate enables restoration of soil structure, improves biomass production, and increases the rate of SOC accumulation
4. fertility depletion	(iv) plant-available nutrients have reached the critical level to affect crop growth adversely	(iv) threshold level is above the 'exhaustion' limit and soil responds to input of fertilizers and organic amendments

of biomass produced may also be regulated through inputs in relation to soil properties. Critical limits refer to the range of soil properties that are necessary to maintain a desirable level of potential yield without jeopardizing productivity through soil degradation.

The critical limit concept also applies to soil resilience. What is the threshold level or range of key soil properties that can still be restored by appropriate measures? For example, what is the threshold SOC level which can maintain soil resilience, restore soil biodiversity, or enhance structural resilience (Kay *et al.* 1994).

There is, however, a subtle difference in critical limits with regard to the onset of degradative processes and threshold values for soil resilience, and these values are often not the same (table 5). These differences in critical limits may be due to hysteresis and malleability. They may also be due to differences in the elastic behaviour of soil resilience for specific functions.

5. SOIL EXHAUSTION AND SOIL RESILIENCE

Exhaustion refers to system fatigue due to overuse. Soil exhaustion implies decline in productivity, even with extra input or production effort (Dregne 1985). The soil reaches a critical point, determined by its quality, at which any further input fails to increase productivity or the capacity of the soil to denature pollutants.

Efforts to produce goods and services when a soil system attains a critical range may result in total loss in productivity or environmental regulatory capacity. However, soil is not necessarily irreversibly degraded. Change in land use or adoption of restorative measures may restore its functions. High quality soils are usually resilient and easily restored. In contrast, fragile soils are irreversibly degraded, are not resilient, and cannot be restored.

6. SOIL RESILIENCE AND LAND USE AND MANAGEMENT

Exogenous factors of land use and management have a drastic effect on soil resilience (Greenland & Szabolcs 1994). Appropriate land use and judicious soil and crop management have a favourable effect on soil resilience, and can restore functions of degraded soils. Some notable examples of soil restoration include soil fertility restoration in Kenya (Ford 1986) and ecosystem rehabilitation in Machakos in East Africa (Tiffen *et al.* 1994), soil erosion control in the USA (Brown 1991), highly productive agriculture in North America and Western Europe (Mengel 1990), maize (*Zea mays*) production in the savanna region of sub-Saharan Africa (Scherr & Yadav 1996), soybean production on Vertisols in Central India, dryland restoration in north-western India (Kolarkar *et al.* 1992), and recovery of saline/alkaline soils in north-western India (Gupta & Abrol 1990).

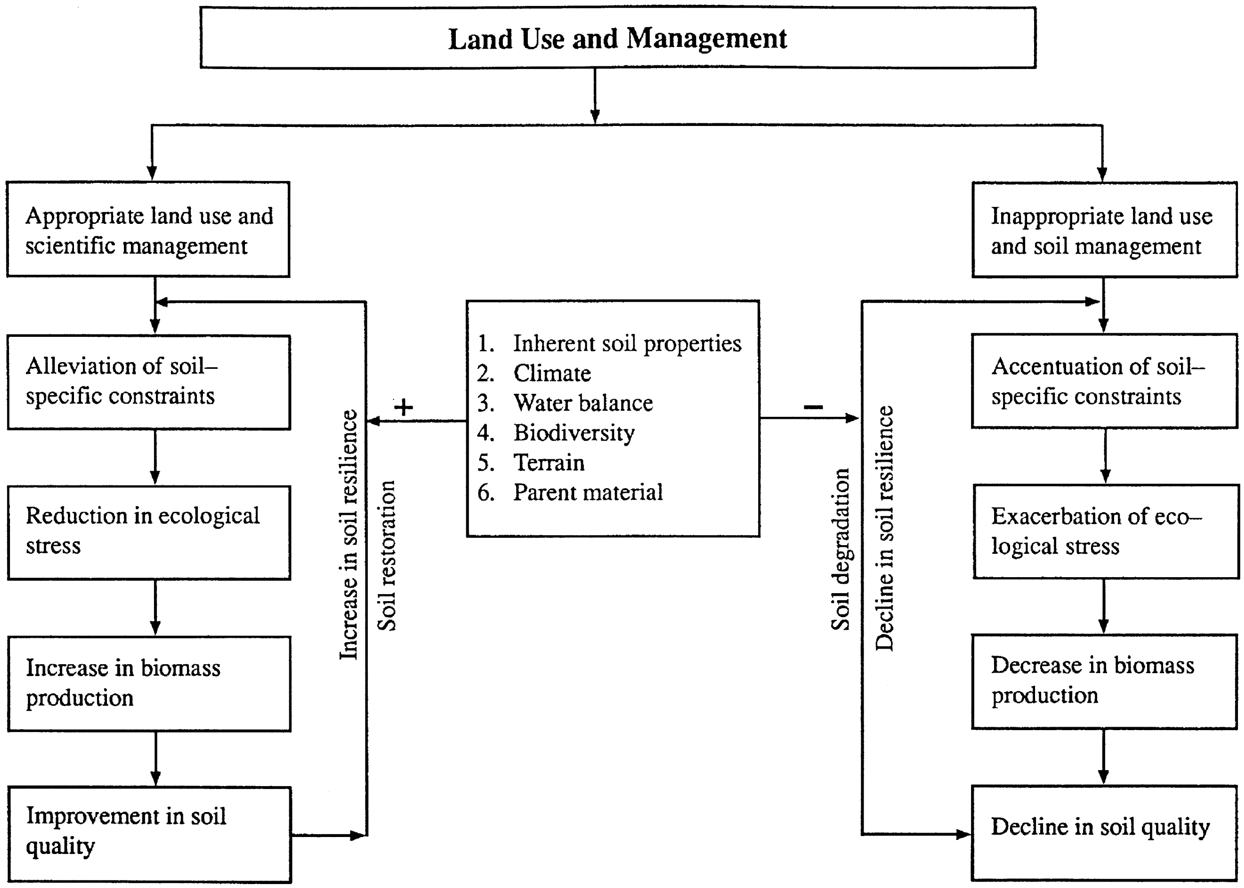

Figure 5. Land use management effects on soil resilience and degradation. Inherent soil properties and climate may have a positive effect on soil resilience with appropriate land use, and none or an adverse effect with inappropriate land use.

Restorative effects of appropriate land use and soil management are due to the improvements in: (i) soil structure, (ii) soil–water relations, (iii) erosion management, (iv) SOC content maintenance, (v) soil biodiversity regulation, and (vi) nutrient cycling. Using land according to its capability and managing soil resources to alleviate constraints enhances soil resilience through maintenance of the biological and ecological integrity of the soil and its economic functionality. Scientific management, based on 'how' rather than 'what', is important in the expression of soil resilience. The effect of land use on soil resilience is demonstrated by the data from drylands. Rozanov (1994) reported that the proportion of highly resilient soils in the world's dryland areas is about 28% in rangelands, 54% in rainfed crop lands, and 70% in irrigated crop lands. It is likely that either resilient soils were chosen initially for more intensive use, or that soil resilience in drylands is enhanced by (i) the intensive agricultural land use and intensity of technological input; and (ii) ecologically appropriate land use to alleviate ecological stresses.

Appropriate land use and judicious management, based on intensity of technological input, set in motion soil restorative processes that enhance soil resilience. With scientific input, there is a synergistic and positive effect on inherent soil properties, terrain and landscape and climatic factors (figure 5). Inappropriate land use and exploitative methods stimulate soil degradative processes that accentuate soil degradation and decrease soil resilience. Inappropriate land use exacerbates the adverse effects of poor parent material, different terrain, and harsh climate (figure 5).

7. ASSESSMENT OF SOIL RESILIENCE

To be functional and operational, it is important to develop methods of quantification of soil resilience. There are various approaches to quantifying soil resilience (figure 6).

(*a*) *Assessment of the rate of soil degradative process*

The rate of soil degradation under a specific ecological stress can be used to evaluate relative soil resilience. These stresses include the rate of soil erosion, SOC decline, changes in soil chemical and nutritional properties, clay and colloid content, and change in porosity.

Soil resilience can be computed from the rate of change of soil quality, as shown in equation (11). The positive value of the right-hand side of equation (3) refers to the rate of soil degradation.

$$S_r = -dS_q/dt, \tag{11}$$

where S_q is soil quality and t is time. The choice of temporal scale is extremely important and depends on several factors (Lal 1994*a*).

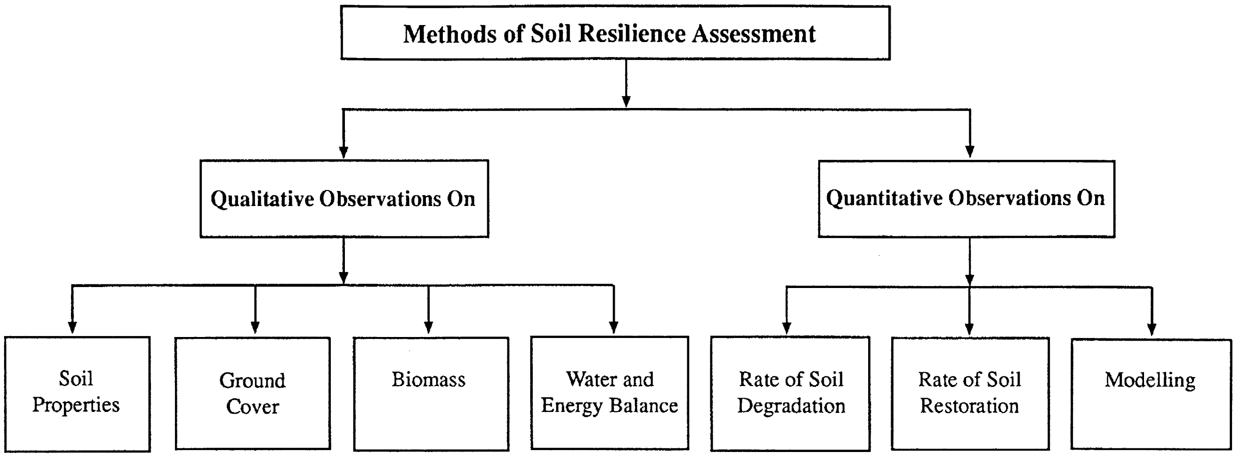

Figure 6. Methods of assessment of soil resilience.

(*b*) *Assessment of the rate of soil restoration*

In contrast to degradation, the rate of soil restoration can be used to assess soil resilience. Because of the strong hysteresis, there may be differences in degradative and restorative pathways. The rate of soil restoration can also be related to changes in soil quality, as shown in equation (12). The negative value on the right-hand side of equation (4) refers to the rate of soil degradation.

$$S_r = dS_q/dt. \tag{12}$$

Empirical development of time-dependent pedo-transfer functions is useful in assessing positive (resilience) or negative (degradation) changes in soil quality.

(*c*) *Modelling*

Temporal changes in soil quality and soil resilience can be modelled. Some suggested approaches include the following:

(i) *Soil renewal rate*

Soil properties and management affect soil renewal rate. Lal (1994*a*) proposed the following model:

$$S_r = S_a + \int_0^t (S_n - S_d + I_m)\, dt, \tag{13}$$

where S_a is the initial or antecedent condition, S_n is the rate of soil renewal, S_d is the rate of soil degradation, and I_m is the management input. Equation (5) is more easily applied to a specific soil property (SOC content, available water capacity, cation exchange capacity, porosity) than to the soil system as a whole. Individual soil properties can then be combined to evaluate soil resilience.

(ii) *Physical analogue*

Rozanov (1994), by analogy with a common spring, proposed that the force responsible for resistance to change to return the spring could be equated with that required to restore the soil to its antecedent level (equation (14)).

$$dA/dx = -kx, \tag{14}$$

where A is the amount of work required for altering soil quality, x is the variable reflecting soil change, and k is the resilience coefficient, which differs among soils and may be altered with land use and management.

(iii) *Capacity to withstand stress*

Ellenberg (1972) suggested use of the concept of 'load or stress capacity' or vulnerability of a system (equation (15)):

$$\text{stress capacity } (S) = \frac{(100 - D \times L) \times R}{10}, \tag{15}$$

where D is disposition, or the ease with which an influence or perturbation reaches a system, L is susceptibility, and R is restoration or regeneration. All factors are estimated on a scale from one to ten. Applied to soils, soil resilience is the inverse of the stress capacity (equation 16):

$$S_r = (S)^{-1}. \tag{16}$$

(iv) *Characteristic return time*

The characteristic return time (T_r) is the time a system or a system component may take to return to equilibrium following a disturbance (May *et al.* 1974; Beddington *et al.* 1976).

$$T_r = 1/r, \tag{17}$$

$$dN/dt = rN(1-N/K). \tag{18}$$

N is a measure of a community or a population, t is time, and K and r are constants. The factor $(1-N/K)$ is called the 'regulatory capacity'.

8. CONCLUSIONS

Soil degradation is a severe problem, especially in the tropics and subtropics. Information on the economic impact of soil degradation is scanty, and needs to be collected at local, regional and global scales. What little information is available indicates severe economic and environmental impacts. The risks of soil degradation are higher with low inputs and subsistence agriculture than with science-based agricultural systems.

Soil resilience is important to food production and to other issues of global importance with regard to: (i) sources and sinks for C; (ii) environmental regulatory functions; (iii) sustainable development; and (iv) soil restoration. Some soils can restore themselves, if the disturbance/stress is alleviated. Although specific techniques depend on soil and site characteristics, ease of restoration depends on the resilience of the soil. Highly resilient soils are easily restored by appropriate management. Soil conditions may be improved in resilient soils by appropriate land use and judicious soil management. Agronomic productivity of non-resilient soils may fall quickly below the economic level, even with improved systems of soil and crop management. The quality of such soils declines rapidly, soon after the onset of degradative processes. In contrast, resilient soils are highly productive, do not undergo rapid degradative changes under stress or disturbance due to deforestation or tillage, and their quality is easily and rapidly restored. The productivity of such soils increases with improved management, designed to alleviate soil-related constraints to productivity. Management has its limits and cannot alleviate all the constraints. The identification of soil-specific properties that affect resilience is a very important management strategy.

For the understanding of soil degradation and resilience, there are several important researchable issues. These include: (i) refining basic concepts; (ii) developing methods of quantifying soil resilience; (iii) establishing critical limits and threshold values; (iv) developing practical methods of soil restoration; (v) evaluating the economic impact of soil degradation at regional and global scales; (vi) establishing links between social processes and soil resilience; and (vii) developing cause–effect relations between soil resilience and degradative processes.

REFERENCES

Barrow, C. J. 1991 *Land degradation: development and breakdown of terrestrial environments*. 295 pp. Cambridge University Press.

Beddington, J. R., Free, C. A. & Lawton, J. H. 1976 Concepts of stability and resilience in predator–prey models. *J. Anim. Ecol.* **45**, 791–816.

Blaikie, P. & Brookfield, H. 1987 *Land degradation and society*. London: Methuen.

Blum, W. E. H. 1990 Soil pollution by heavy metals: causes, processes, impacts, and need for future action information document. Sixth European Ministerial Conference on the Environment, Brussels, Belgium, 11–12 October, 1990, 42 pp.

Blum, W. E. H. 1994 General approaches and definition. XVth International Congress of Soil Science, Acapulco, Mexico, 10–16 July, 1994. Vol. **29**, 233–237.

Blum, W. E. H. & Agiular, S. 1994 A concept of sustainability and resilience based on soil functions: the role of ISSS in promoting sustainable land use. In *Soil resilience and sustainable land use* (ed. D. J. Greenland & I. Szabolcs), pp. 535–542. Wallingford, UK: CAB International.

Brown, L. 1991 The global competition for land. *J. Soil Water Cons.* **46**, 394–397.

Brown, L. R. 1995 *Who will feed China? Wake-up call for a small planet*. 166 pp. New York: Norton.

Changere, A. & Lal, R. 1995 Soil degradation by erosion of a Typic Hapludalf in central Ohio and its rehabilitation. *Land Degrad. Rehabilit.* **6**, 223–228.

Charreau, C. 1972 Problemes poses par l'utilisation agricole des sols tropicaux par des cultures annuelles. *Agron. Trop.* **27**, 905–929.

Colenbrander, H. J. 1973 The rational management of hydrological systems. In *The breakdown and restoration of ecosystems* (ed. M. W. Holdgate & M. J. Woodman) 1978, pp. 363–390. New York: Plenum Press.

Colenbrander, H. J. 1978 The rational management of hydrological systems. In *Amazonian rainforests: ecosystem disturbance and recovery* (ed. C. F. Jordan,), 1987, 363–390. New York: Springer-Verlag.

Crosson, P. 1995 Soil erosion and its on-farm consequences: what do we know? Discussion Paper 95–29, Resources for the Future, Washington, D.C.

Crosson, P. & Anderson, J. R. 1992 Resources and global food prospects: supply and demand for cereals to 2030. 122 pp. World Bank Technical Paper Number 184, Washington, D.C.

Dooge, J. C. I. 1973 The nature and components of hydrological cycle. Irrigation and Drainage Paper. Rome, Italy: FAO.

Doran, J. W. & Parkin, T. B. 1994 Defining and assessing soil quality. In *Defining soil quality for a sustainable environment* (ed. J. W. Doran, D. C. Coleman, D. F. Bezedicek & B. A. Stewart), SSSA Special Publication No. 35, Madison, WI, pp. 3–21.

Doran, J. W., Sarrantonio, M. & Liebig, M. A. 1996 Soil health and sustainability. In *Adv. Agron.* **56**, 1–54.

Dregne, H. E. 1985 Aridity and land degradation: guarded optimism for future of arid lands. *Environment* **27**, 16–33.

Dregne, H. E. 1990 Erosion and soil productivity in Africa. *J. Soil Water Cons.* **45**, 431–436.

Dregne, H. E. 1992 Erosion and soil productivity in Asia. *J. Soil Water Cons.* **47**, 8–13.

Ellenberg, H. 1972 Belastung und belastbarkeit von okosystemen. *Tagber. Ges. Okologie Giessen* 1972 m K9–26.

Engelman, R. 1994 *Stabilizing the atmosphere: population, consumption and greenhouse gases*. 48pp. Washington, DC: Population Action International.

Engelman, R. & LeRoy, P. 1993 *Sustaining water: population and the future of renewable water supplies*. 56 pp. Washington, DC: Population Action International.

Engelman, R. & LeRoy, P. 1995 *Conserving land: population and sustainable food production*. 48 pp. Washington, DC: Population Action International.

Eriksson, J., Hakansson, I. & Danfors, B. 1974 The effect of soil compaction on soil structure and crop yields. Bulletin 354, Swedish Institute of Agricultural Engineering, Uppsala, Sweden.

Fahnestock, P., Lal, R. & Hall, G. F. 1995 Land use and erosional effects on two Ohio Alfisols. II. Crop yields. *J. Sust. Agric.* **7**, 85–100.

Ford, R. 1986 *Land, people and resources in Kenya*. R-15. Washington, DC: World Resources Institute.

Gantzer, C. J. & McCarty, T. R. 1987 Predicting corn yield on a claypan soil using a soil productivity index. *Trans. ASAE* **30**, 1347–1352.

Gardner, G. 1996 Shrinking fields: cropland loss in a world of 8 billion. 55 pp. Worldwatch Paper 131, Washington, DC.

Gill, W. R. 1971 *Economic assessment of soil compaction*. St Joseph, MI: ASAE Monograph.

Girt, J. 1986 The on-farm economics of sustainability and public intervention. *Can. Farm Econ.* **20**, 3–8.

Greenland, D. J. & Szabolcs, I. (eds) 1994 *Soil resilience and sustainable land use*. Wallingford, UK: CAB International.

Gupta, R. K. & Abrol, I. P. 1990 Salt-affected soils: their reclamation and management for crop production. *Adv. Soil Sci.* **11**, 223–287.

Hill, A. R. 1987 Ecosystem stability: some recent perspectives. *Prog. Phys. Geogr.* **11**(3), 315–333.

Himes, F. L. 1997 Nitrogen, sulfur and phosphorus and the sequestering of carbon. In *Management of carbon sequestration* (ed. R. Lal, J. Kimble, R. Follett & B. A. Stewart). Boca Raton, FL: CRC Publishers. (In the press.)

Holdgate, M. W. & Woodman, M. J. (eds) 1978 *The breakdown and restoration of ecosystems*. 496 pp. New York: Plenum Press.

Holling, C. C. 1973 Resilience and stability of ecological systems. *A. Rev. Ecol. Syst.* **4**, 1–23.

IPCC 1995 Technical summary. 44 pp. Geneva, Switzerland: Inter-Governmental Panel of Climate Change, WMO.

Johnson, D. & Lewis, L. 1995 *Land degradation: creation and destruction*. 335 pp. Oxford, UK: Blackwell Scientific Publishers.

Jordan, C. F. (ed.) 1987 *Amazonian rainforests: ecosystem disturbance and recovery*. 133 pp. New York: Springer-Verlag.

Kay, B. C., Rasiah, V. & Perfect, E. 1994 The structural aspect of soil resilience. In *Soil resilience and sustainable land use* (ed. D. J. Greenland & I. Szabolcs). Wallingford, UK: CAB International.

Kayombo, B. & Lal, R. 1994 Response of tropical crops to soil compaction. In *Soil compaction in crop production* (ed. B. D. Soane & C. Van Ouwerkerk), pp. 287–315. Amsterdam, Holland: Elsevier Science Publishers.

Klink, C. A., Moreira, A. G. & Solbrig, O. T. 1993 Ecological impact of agricultural development in the Brazilian cerrados. In *The world's savannas: economic driving forces, ecological contraints and policy options for sustainable land use* (ed. M. D. Young & O. T. Solbrig), 259–282. UNESCO, Paris: The Parthenon Publishing Group.

Kolarkar, A. S., Joshi, D. C. & Sharma, K. D. (eds) 1992 *Rehabilitation of degraded arid ecosystems*. 203 pp. Jodhpur, India: Scientific Publishers.

Lal, R. 1976*a* *Soil erosion problems on Alfisols in Western Nigeria and their control*. 208 pp. IITA Monograph 1. Ibadan, Nigeria: IITA.

Lal, R. 1976*b* No tillage effects on soil properties under different crops in Western Nigeria. *Soil Sci. Soc. Am. Proc.* **40**, 762–768.

Lal, R. 1984 Soil erosion from tropical arable lands and its control. *Adv. Agron.* **37**, 183–248.

Lal, R. 1987 Response of maize and cassava to removal of surface soil from an Alfisol in Nigeria. *Int. J. Trop. Agric.* **5,** 77–92.

Lal, R. 1989*a* Conservation tillage for sustainable agriculture. *Adv. Agron.* **42**, 85–197.

Lal, R. 1989*b* Agroforestry systems and soil surface management of a tropical Alfisol. II. Soil erosion and nutrient loss. *Agrofor. Syst.* **8**, 97–111.

Lal, R. 1989*c* Agroforestry systems and soil surface management of a tropical Alfisol. IV. Effects on soil physical and mechanical properties. *Agrofor. Syst.* **8**, 7–29.

Lal, R. 1989*d* Agroforestry systems and soil surface management of a tropical Alfisol. III. Soil chemical properties. *Agrofor. Syst.* **8**.

Lal, R. 1993 Tillage effects on soil degradation, soil resilience, soil quality and sustainability. *Soil Tillage Res.* **27**, 1–8.

Lal, R. 1994*a* Sustainable land use systems and soil resilience. In *Soil resilience and sustainable land use* (ed. D. J. Greenland & I. Szabolcs), pp. 41–67. Wallingford, UK: CAB International.

Lal, R. 1994*b* Land use and soil resilience. 15th International Congress Soil Science, Acapulco, Mexico, 10–16 July, **29**, 246–261.

Lal, R. 1994*c* Tillage effects on soil degradation, soil resilience, soil quality and sustainability. *Soil Tillage Res.* **27**, 1–8.

Lal, R. 1995 Erosion–crop productivity relationships for soils of Africa. *Soil Sci. Soc. Am. J.* **59**, 661–667.

Lal, R. 1996*a* Axle load and tillage effects on crop yields on a Mollic Ochraqualf in northwest Ohio. *Soil Tillage Res.* **37**, 143–160.

Lal, R. 1996*b* Deforestation and land use effects on soil degradation and rehabilitation in Western Nigeria. I. Soil physical and hydrological properties. *Land Degrad. Dev.* **7**, 19–45.

Lal, R. 1996*c* Deforestation and land use effects on soil degradation and rehabilitation in Western Nigeria. II. Soil chemical properties. *Land Degrad. Dev.* **7**, 87–98.

Lal, R. 1996*d* Deforestation and land use effects on soil degradation and rehabilitation in Western Nigeria. III. Runoff, soil erosion and nutrient loss. *Land Degrad. Dev.* **7**, 99–119.

Lal, R. 1997*a* Long-term tillage and maize monoculture effects on a tropical Alfisol in Western Nigeria. I. Crop yield and soil physical properties. *Soil Tillage Res.* (In the press.)

Lal, R. 1997*b* Long-term tillage and maize monoculture effects on a tropical Alfisol in Western Nigeria. II. Soil chemical properties. *Soil Tillage Res.* (In the press.)

Lal, R., Wilson, G. F. & Okigbo, B. N. 1978 No-till farming after various grasses and leguminous cover crops in tropical Alfisol. I. Crop performance. *Field Crops Res.* **1**, 71–84.

Lal, R., Wilson, G. F. & Okigbo, B. N. 1979 Changes in properties of an Alfisol produced by various crop covers. *Soil Sci.* **127**, 377–382.

Lal, R., De Vleeschauwer, D. & Nganje, R. M. 1980 Changes in properties of a newly cleared tropical Alfisol as affected by mulching. *Soil Sci. Soc. Am. J.* **44**, 827–833.

Lvovitch, M. I. 1971 *The water balance of the continents of the world and method of studying it*. Moscow: International Association of Scientific Hydrology.

May, R. M. 1976 *Theoretical ecology: principles and applications*. Oxford, UK: Blackwell Scientific Publishers.

May, R. M. 1978 Factors controlling the stability and breakdown of ecosystems. In *Amazonian rainforests: ecosystem disturbance and recovery* (ed. C. F. Jordan), pp. 11–25. New York: Springer-Verlag.

May, R. M., Conway, G. R., Hassell, M. P. & Southbound T. R. E. 1974 Time delays, density dependence, and single species oscillations. *J. Anim. Ecol.* **43**, 747–770.

Mbagwu, J. S. C., Lal, R. & Scott, T. W. 1984 Effects of desurfacing of Alfisols and Ultisols in southern Nigeria. I. Crop performance. *Soil Sci. Soc. Am. J.* **48**, 828–833.

Mengel, K. 1990 Impacts of intensive plant nutrient management on crop production and environment. *Fourteenth Congress of the ISSS, 12–18 August 1990, Kyoto, Japan*. Plenary Papers, 42–52.

Mitchell, B. 1979 *Geography and resource analysis*. London: Longman.

Mokma, D. L. & Sietz, M. A. 1992 Effects of soil erosion on corn yields on Marlette soils in south-central Michigan. *J. Soil Water Cons.* **47**, 325–327.

Mortimore, M. J. 1988 Desertification and resilience in semi-arid West Africa. *Geography* **73**, 61–64.

Mortimore, M. J. 1989 *Adapting to drought: farmers, famines and desertification in West Africa*. Cambridge University Press.

Nye, P. H. & Greenland, D. J. 1960 *Soils under shifting cultivation*. Commonwealth Technical Bulletin no. 51. Harpenden, UK: Commonwealth Agricultural Bureau.

Oldeman, L. R. 1994 The global extent of soil degradation. In *Soil resilience and sustainable land use* (ed. D. J. Greenland & I. Szabolcs), pp. 99–118. Wallingford, UK: CAB International.

Olson, K. R. & Nizeyimana, E. 1988 Effects of soil erosion on corn yields of seven Illinois soils. *J. Prod. Agric.* **1**, 13–19.

Patten, B. C. 1974 The zero state and ecosystem stability. Proc. 1st Int. Congress on Ecology. The Hague, Wageningen: Pudoc.

Peters, R. H. 1991 *A critique for ecology*. Cambridge University Press.

Pimentel, D. C., Harvey, P., Resosudarmo, K. *et al.* 1995 Environmental and economic costs of soil erosion and conservation benefits. *Science* **267**, 1117–1120.

Pimm, S. L. 1984 The complexity and stability of ecosystems. *Nature* **307**, 321–326.

Postel, S. 1992 *Last oasis: facing water scarcity*. New York: Norton.

Postel, S. L., Gretchen, C. D. & Ehrlich, P. R. 1996 Human appropriation of renewable fresh water. *Science* **271**, 785–788.

Raghavan, G. S. V., McKyes, E., Gendron, G., Borglum, B. & Le, H. H. 1978 Effects of soil compaction on development and yield of corn. *Can. J. Plant Sci.* **58**, 435–443.

Raghavan, G. S. V., Alvo, P. & McKyes, E. 1990 Soil compaction in agriculture: a view toward managing the problem. In *Soil degradation* (ed. R. Lal & B. A. Stewart), *Adv. Soil Sci.* **11**, 1–35.

Reining, L. 1992 *Erosion in Andean hillside farming*. Hohenheim Tropical Agricultural Series 1, 219 pp. Weikersheim, Germany: Verlag Josef Margaraf.

Richards, J. F. 1990 Land transformation. In *The Earth as transformed by human action* (ed. B. L. Turner, W. C. Clark, R. W. Kates, J. F. Richards, J. T. Mathews & W. E. Meyer), pp. 163–178. Cambridge University Press.

Rozanov, B. G. 1994 Stressed soil systems and soil resilience in drylands. 15th Int. Congress of Soil Science, Acapulco, Mexico, 10–16 July, 1994, V**29**, 238–245.

Ruppenthal, M. 1995 Soil conservation in Andean cropping systems: soil erosion and crop productivity in traditional and forage-legume based cassava cropping systems in the South Colombian Andes. 110 pp. Hohenheim Tropical Agricultural Series 3, Weikersheim, Gemany: Verlag Josef Margaraf.

Scherr, S. J. & Yadav, S. 1996 Land degradation in the developing world: implications for food, agriculture, and the environment to 2020. IFPRI Discussion Paper No. 14, Washington, DC. 36 pp.

Schlesinger, W. H. 1990 Evidence from chronosequence studies for a low carbon storage potential of soils. *Nature* **348**, 232–234.

Schumacher, T. E., Lindstrom, M. J., Mokma, D. L. & Nelson, W. W. 1994 Corn yield: erosion relationships of representative loess and till soils in the North Central United States. *J. Soil Water Cons.* **49**, 77–81.

Scott, G. A. G. 1987 Shifting cultivation where land is limited. In *Amazonian rainforests: ecosystem disturbance and recovery* (ed. C. F. Jordan), pp. 34–45. New York: Springer-Verlag.

Soane, B. D. & Van Ouwerkerk, C. 1994 Compaction problems in world agriculture. In *Soil compaction in crop production* (ed. B. D. Soane & C. Van Ouwerkerk), 1–21. Amsterdam, Holland: Elsevier Science Publishers.

Stocking, M. 1986 The cost of soil erosion in Zimbabwe in terms of the loss of three major nutrients. Consultant's Working Paper No. 3, Soil Conservation Program, Land and Water Division. Rome: Food and Agriculture Organization of the United Nations.

Stoorvogel, J. J., Smaling E. M. A. & Janssen, B. J. 1993 Calculating soil nutrient balances in Africa at different scales. I. Supra-national scale. *Fert. Res.* **35**, 227–235.

Szabolcs, I. 1994*a* Concepts of soil resilience. In *Soil resilience and sustainable land use* (ed. D. J. Greenland & I. Szabolcs). Wallingford, UK: CAB International.

Szabolcs, I. 1994*b* Introduction to the symposium on stressed ecosystem and soil resilience. Fifth International Congress on Soil Science., Acapulco, Mexico, 10–16 July 1994, V**29**, 218–220.

Tiffen, M., Mortimore, M. & Gichuki, F. 1994 *More people, less erosion: environmental recovery in Kenya*. 311 pp. Chichester, UK: John Wiley & Sons.

Tolba, M. K. & El-Kholy, O. A. (eds) 1992 *The world environment 1972–1992*. London: Chapman & Hall/UNEP.

UNEP 1991 *Status of desertification and implementation of the United Nations Plan of Action to combat desertification*. III/3. Nairobi, Kenya: UNEP/GCSS.

UNEP 1992 *World atlas of desertification*. London: Edward Arnold.

UNEP 1994 Land degradation in south Asia: its severity, causes and effects upon the people. UNDP/UNEP/FAO World Soil Resources Reports 78. 100 pp. Rome: FAO.

Westman, W. E. 1978 Measuring the inertic and resilience of ecosystems. *BioScience* **28**, 705–710.

Whitaker, R. H. 1975. *Communities and ecosystems*. 2nd edn. New York: Macmillan.

Discussion

Mr A. Wagner (*London*). Food is a privilege not a right.

R. Lal. Those involved in conducting agricultural research have a mission to enhance food production and professional commitment, to develop technologies to produce enough food for meeting the basic dietary needs of all inhabitants of the Earth. However, the food production technologies must also maintain the natural resource base and environmental quality by minimizing risks of land degradation and environmental pollution.

D. J. Greenland (*University of Reading, UK*). (1) Deposition of eroded soil in rice lands in Asia causes less increase in yield than would be obtained if the soil remained *in situ*. (2) Experiments on erosion control conducted in NSW, Australia, showed yield losses between 17 and 27% even after adopting erosion control measures for 17 years. These methods of assessment of erosion which caused decline in productivity are highly objective.

R. Lal. (1) Yes, slight increase in yield at depositional sites is not enough to compensate the drastic reduction in yield on eroded soils. Further, sediments transported in reservoirs and lakes lead to eutrophication of water and damage to civil structures. (2) Productivity of severely eroded soils, with a root-restrictive layer at shallow depths or with edaphologically inferior subsoil, cannot be restored by erosion-control measures. Some soils are prone to irreversible soil degradation. Because of low resilience, soil quality cannot be restored even with improved management.

There is a need for developing objective methods of assessment of erosion impact on productivity. The assessment of productivity loss must include both direct and indirect costs, and on-site and off-site damages.

T. Quine (*Department of Geography, University of Exeter, UK*). Implementation of a policy for soil restoration raises three important issues. (1) There is a need for quantitative definition of degraded soil and its potential to be restored. Using soil erosion rate to define degradation is not satisfactory because of the large variation in the impact of soil loss on different soils. A better criterion would be the assessment of soil quality and its change due to degradation. (2) There is a need to identify those soils which may be recoverable. To what extent does current understanding of soil processes allow this identification? (3) In order to implement rehabilitation strategies at farm level, it is necessary to consider the existence of variation in soil degradation and the processes which lead to the development of those patterns. The research done at Exeter has shown large variations on erosion and aggregation rates within agricultural fields, and this variation may be due to tillage erosion. Improvement of understanding of all processes which lead to within field variation in soil degradation and development of simple models which account for such processes would make a valuable contribution to the future implementation of rehabilitation strategies.

R. Lal. These are excellent comments, and extremely relevant to improving the existing database on land degradation and developing restoration strategies. (1) Yes, there is a strong need for a quantitative definition of soil degradation. The criterion should be related to soil functions. If the soil function is agricultural productivity, then the magnitude of loss in productivity must be quantified for different levels of input. In addition to productivity, there are numerous other soil functions of importance to humans, e.g. engineering uses, regulating environments, repository of gene pool, etc. Therefore, there is an equally strong need to develop quantitative definition of soil degradation with regard to each function. The currently available information on soil degradation is weak and subjective because it is not based on standardized and quantitative criteria or indices. It is difficult to develop a technology or strategy of soil restoration without knowing the severity of soil degradation in quantitative terms.

Soil quality is an appropriate approach to assess soil degradation, providing that there exists a quantitative and an objective definition or index for its assessment. Some progress has been made in developing quantitative methods of assessment of soil quality, but additional research is needed to develop generic and soil-specific standards of soil quality assessment.

(2) True, it is important to identify the extent and severity of degradation and also soil attributes or properties which respond to management and those that can be restored. Similarly to the extent of soil degradation, this information is also not available. There is a need to identify key soil properties and 'critical limits' or threshold values of soil properties and processes beyond which soil undergoes severe degradation. Key soil properties and their critical limits differ among soils and functions, and need to be identified. Quantitative indices of soil quality must be based on critical limits. It is difficult to identify soils that can be restored without knowing their antecedent soil quality, and critical limits of key soil properties in relation to specific soil functions or uses.

(3) Soil variability is a practical reality even in soils which have not been degraded. Soil degradation may accentuate variability in some soils more than in others. Patterns of variability are influenced by management, especially soil surface management. Tillage erosion is an important process affecting soil degradation and spatial variability patterns in a farm field. Activity of soil fauna is another factor, e.g. termite activity in soils of the tropics. The concept of 'precision farming' or 'farming by soil' is based on the recognition of soil variability at the farm level. Restoration strategy based on the use of soil amendments can also be adopted using the principles of precision farming, applying input or chemicals at a rate commensurate with the laboratory soil-test data for specific mapping unit within the farm. Identifying the cause–effect relationships responsible for variation in soil degradation within a soilscape or landscape unit, and adopting the strategy of precision farming would be an economic and environmentally compatible strategy.

D. W. Billing (*Haynes*, *Bedfordshire*, *UK*). The substantial loss of primary agricultural land to urbanization and expansion of agriculture to marginal lands must be recognized. These shifts in land use may jeopardize any agronomic and genetic gains made by the research, especially in rapidly urbanizing South East Asia. Some regions which were net food exporters are now importers of rice due to this shift in land use.

R. Lal. Prime agricultural soil resources of the world are finite, essentially non-renewable, unequally distributed, and prone to degradation by misuse and mismanagement. Change of land use from agriculture to industrial and urban uses is a major problem in densely populated countries with rapidly expanding urban populations, e.g. China, India. The process, in fact, is a 'double jeopardy', (1) due to loss of prime land, and (2) because agricultural activities are pushed into marginal lands and ecologically sensitive ecoregions. In addition to population control, which is a slow process with a long response time, it is important to intensify agriculture on all available prime agricultural land. There is a need to develop 'soil use policy' at regional, national, and global scales. Such policies should be carefully identified and rigorously imposed, especially with regards to the use of marginal lands. Land capability assessment of marginal lands is crucial to their judicious use. The 'World Soil Policy' developed by FAO/UNEP has not been effective. To be effective, such a policy must be developed and implemented at the national level. The 'Farm Bill' and 'Conservation Reserve Programs' in the USA are examples of successful identification and implementation of such policies.

R. Evans (*Cambridge*, *UK*). Professor Lal opened his paper by referring to Pimentel *et al.* (1995), and quoted the rates of water erosion given in that paper. I want to urge caution in using that data because it is based on plot experiments and not from measuring amounts eroded in farmers' fields. It has yet to be shown that results gathered from 22 m long plots relate well to erosion in the field. Indeed, what evidence there is (Evans 1995) suggests that rates of erosion measured in farmers' fields are much less than those recorded on plots. Also, mapping erosion in the field puts it into perspective, because it does not happen everywhere. In some places, erosion will be severe, but over much of the landscape there will be no erosion at all. Pimentel's information implies that erosion occurs all across a landscape—it does not. If Pimentel *et al.*'s estimates of erosion are too high, the costs of the impacts of erosion are also likely to be too high.

References

Evans, R. 1995 Some methods of directly assessing water erosion of cultivated land—a comparison of measurements made on plots and in fields. *Prog. Physical Geogr.* **19**, 115–129.

Pimentel, D., Harvey, C., Resosudarmo, P. *et al.* 1995 Environmental and economic costs of soil erosion and conservation benefits. *Science* **267**, 1117–1123.

R. Lal. The value of data presented by Pimentel *et al.* lies more in creating awareness about the economic costs of soil erosion than in the accuracy and reliability of the statistics presented. Like numerous other reports on soil erosion and degradation, the statistics presented by Pimentel *et al*. are questionable.

Soil erosion rates and productivity losses measured on field plots provide only the 'relative' information. As was also pointed out by Professor Greenland, there is a need to develop and standardize methodology for assessment of soil erosion rate and its impact on productivity. The scale at which such measurements are made is important. The scale should preferably be the 'watershed' of 'landscape unit'. An example of measuring the erosion–productivity relationship under on-farm conditions is that being followed by a regional research group in USA. The North Central Regional Committee (NC-174), comprising ten states in the USA, is evaluating erosion–productivity effects under on-farm conditions. Crop yields are measured under farmer management, and related to the remaining depth of the A horizon in erosion phases and increases in thickness of the A horizon in depositional phases. The rate of past erosion is also monitored by using $^{137}C_s$ technique.

The lack of progress in obtaining reliable statistics on soil erosion rates and its impact at the global level is due to the problem of (i) scaling or lack of appropriate methodologies on extrapolating data from field plots to landscape and watershed level; (ii) lack of information on delivery ratio; and (iii) the lack of knowledge and uncertainties regarding the impact of deposition of sediment on yield and soil quality.

K. Giller (*Wye College*, *University of London*). In your discussion of increasing soil C contents in relation to both building-up soil organic matter to enable better crop growth, and to increase C sequestration, you did not mention the importance of tillage in determining the 'storage capacity' of soils for carbon. We cannot expect the storage capacity of tilled soils to approximate to that of the natural forest or savanna vegetation as tillage increases the rates of turnover or organic matter (and losses of fuel to erosion), and thus reduce the potential 'storage capacity' of the soil. What role do you see for conservation tillage in this discussion?

R. Lal. Conservation tillage is indeed an important strategy to enhance soil quality, decrease soil erosion risks, and sequester C in soil to mitigate the 'greenhouse effect'. Judicious use of crop residue and farm waste can lead to improvement in soil quality and reduction in risks of environmental degradation. The rate of crop residue production in the world is about 3.5 Pg yr^{-1} ($1 Pg = 10^{15} g$). If 20% of the C contained in the residue can be converted into a stable humus fraction, it can be a substantial input of C into soil. In 1995, conservation tillage was practised on about 40 million ha or 30% of crop land in the USA. By the year 2020, conservation tillage may be adopted on 140 million ha or 75% of crop land. Conversion of conventional to conservation tillage may lead to global C sequestration in soil by the year 2020 at a rate of about 1.5 Pg C yr^{-1}. Realization of the C sequestration potential of conservation tillage also requires identification and implementation of national soil policy.