Working Paper 96/08

GLOBAL ASSESSMENT OF LAND VULNERABILITY TO WATER EROSION ON A ½° BY ½° GRID

N.H. Batjes

February 1996

IAL SOIL REFERENCE AND INFORMATION CENTRE

Accepted in *Land Degradation & Development* 1996, 7(4):353-365

Inquiries:
c/o Director, ISRIC
P.O. Box 353
6700 AJ Wageningen
The Netherlands

Telefax: +31-(0)317-471700
E-mail: SOIL@ISRIC.NL

TABLE OF CONTENTS

List of Tables

List of Figures

ABSTRACT

A simple methodology for assessing the risk of water erosion at the global level is presented. It uses a ½° latitude by ½° longitude soil database, developed at ISRIC, and auxiliary databases on climate and land cover with a similar spatial resolution. Area estimates are presented for (1) susceptible areas, as determined by rainfall erosivity, topography and soil erodibility, and for (2) vulnerable areas as further determined by the pressure of current land use. Model output for vulnerability is evaluated against observed data on severity of soil degradation by water as presented on the map of human-induced soil degradation (GLASOD). Cross-tabulation of the vulnerability and GLASOD subsets gave a significant Cramer's correlation coefficient of 0.72 ($P << 0.005$). Thus a fair geographic agreement was observed between the grid cells considered vulnerable to water erosion, under current conditions of land cover, and regions in which water erosion occurs currently.

The qualitative model can serve to raise awareness on issues of soil degradation by water at the global level by identifying regions at risk, where more detailed studies are needed. However, it does not provide any information on the actual rate of erosion at field scale nor on the associated decrease in crop productivity and biodiversity. The study of productivity changes associated with water-erosion, at different scales, is currently an important topic on ISRIC's research agenda.

KEY WORDS land degradation; vulnerability; water-induced soil erosion; global model; GIS; GLASOD

INTRODUCTION

Human-induced land degradation is one of the most destructive phenomena worldwide, and is fast becoming recognized as a key issue for world conservation as the twentyfirst century is approached (Barrow, 1991; EU, 1992; Van Lynden, 1995). Water erosion is by far the most important with 1094 million ha affected globally, followed by wind erosion (548 million ha). Other significant types of land degradation worldwide are chemical degradation (239 million ha) and physical degradation (83 million ha) (Oldeman, *et al.*, 1991). The on-site and off-site effects of land degradation on land resources, soil productivity and the environment are far reaching (e.g. De Boodt and Gabriels, 1980; El-Swaify, *et al.*, 1985; Rickson, 1994).

The assessment of water erosion hazard involves the determination of: (a) the vulnerability of land to erosion under specified conditions of management (i.e. social, economic and technological setting) and, (b) the resulting loss in productivity of the land affected. Water erosion includes detachment, transport and deposition of soil particles by the erosive forces of rainfall and surface flow of water. Of the $1094\text{x}10^6$ ha affected globally by water erosion, 43% is caused by deforestation and removal of natural vegetation, 29% by overgrazing, 24% by improper management of the agricultural land, and 4% as a result of over-exploitation of the natural vegetation (Oldeman, 1994).

An important direct consequence of soil erosion is a loss of productivity, causing reduced yields. On the short-term crop productivity and biodiversity decrease result from changes in the superficial horizon, namely loss of organic matter, loss of nutrient retention and fertility, decrease in water retention properties of the soil, poor tilth and reduced infiltration rate (e.g. Chengere and Lal, 1995; Biot and Lu, 1995). It is only in the first stages of degradation that these adverse effects can be offset readily by sound soil conservation and management practices. Long-term effects of water erosion are caused by reduction of topsoil and rootable depth, which may be considered an irreversible process on a human-life scale (Arnold, *et al.*, 1990). Off-site effects include pollution of surface water with sediment particles, possibly contaminated with agro-chemicals added to soil, and sedimentation in reservoirs and streams.

Erosion by water is variable in time and space; it can be intense in some years and negligible in others. Each soil type has a particular topography, a particular resilience to erosion under a given land use, and thus its own erosion type and intensity. In a ½° latitude by ½° longitude global inventory it will be possible to show general trends, over medium-term periods, using available databases and necessarily coarse assumptions.

This paper presents a simple model for assessing the susceptibility and vulnerability of soils to erosion by water at the global level, using readily available data. Model output is evaluated against data on field-observed status of human-induced soil degradation (Oldeman, *et al.*, 1991), and recommendations for future work are made. The study is a contribution to the United Nations Environment Programme's (UNEP) Pilot Global Environmental Outlook Project which focuses on the impact of land degradation on food production (UNEP/EAP, 1995).

MATERIALS AND METHODS

Water erosion model

The state of current knowledge of the factors and processes which determine soil loss, sediment delivery and their impact as well as models which employ these processes and factors for predicting erosion-impact have been reviewed by El-Swaify and Fownes (1992). A widely used approach to assess the intensity of sheet and rill erosion on a field basis is the Universal Soil Loss Equation or USLE (Wischmeier, *et al.*, 1971). The predicted soil loss (A), according to USLE, is:

$$A = R.K.LS.P.C \tag{1}$$

with:

- R, a rainfall erosivity factor;
- K, soil erodibility factor which is a function of soil properties such as texture, structure, organic matter content, and permeability;

LS, a factor for slope angle and length (topography);

P, a factor for management practices, including methods of cultivation and soil conservation; and,

C, a factor that takes into account vegetation density and structure.

USLE is an empirical model that was developed for the eastern part of the USA to compute soil-loss by rainfall from agricultural land at field-scale. Thus some model parameters need adjustment when applied in other regions of the world and at a different scale (e.g. Bolline, 1985; Rickson, 1994; Van den Berg, 1992; EU, 1992). The general formula of USLE remains useful in global studies in that it lists the basic factors of soil erosion by water, but a number of simplifications will be necessary. The nature of these simplifications is largely dictated by the availability of data, their reliability and accuracy (Hudson, 1980), as well as the required spatial resolution. The current study uses ½° latitude by ½° longitude databases on biophysical factors, corresponding to a grid size of 55 x 55 km at the equator. This spatial resolution is commonly used in global assessments of crop production potentials, soil gaseous emissions, and in simulation of global land cover changes as affected by economic factors and climatic change (Prentice, *et al.* 1993; Zuidema, *et al.*, 1994).

The generalized model for assessing water-erosion hazard (E) at a global resolution of ½° x ½° is:

$$E = f(R, T, V) \qquad (2)$$

with:

R, a factor for rainfall erosivity;

T, a factor expressing terrain erodibility which considers slope and soil type;

V, a factor for land cover.

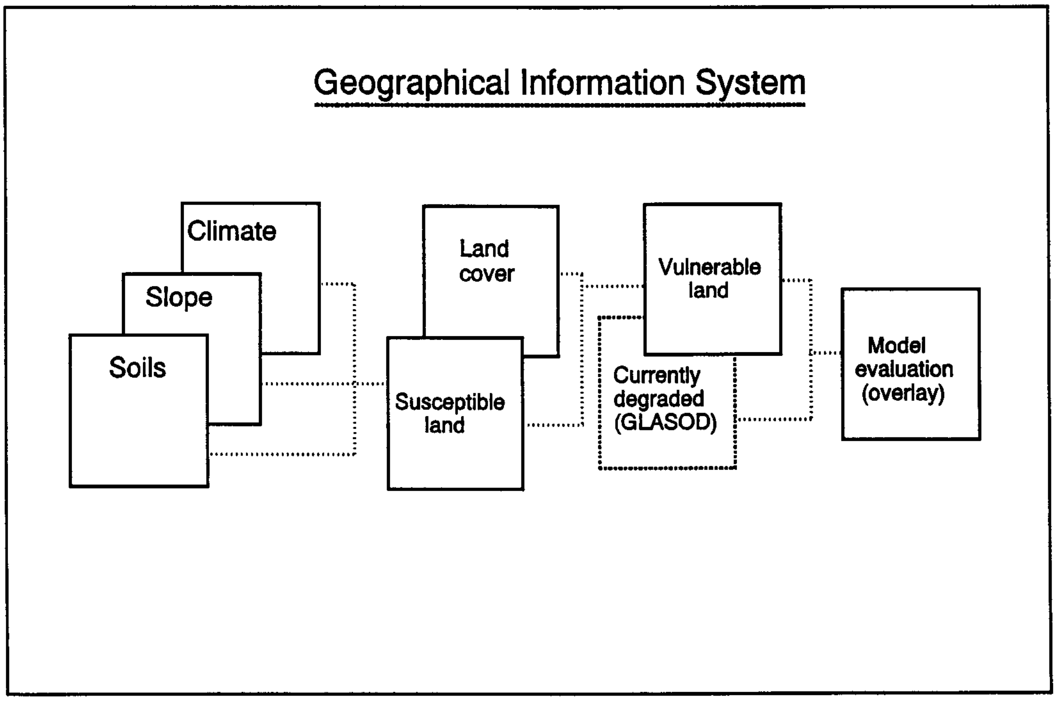

Figure 1. General methodology for assessing areas at risk from soil erosion by water

The indices for T, R and V are combined to estimate: (1) the intrinsic susceptibility of the system as determined by the relatively "stable" factors of rainfall erosivity and terrain erodibility; and, (2) the actual vulnerability which further takes into account the pressure of current land cover (Figure 1). The model is considered appropriate to differentiate between areas with contrasting risks of being eroded by water under current conditions of land cover. The effect of sound management practices in reducing soil erosion by water could not be considered explicitly in the present study. This also applies for the social and economic controls of soil conservation, which are essential in protecting the soil resources.

Soil and terrain erodibility

Soil erodibility refers to the intrinsic susceptibility of the soil to erosion by rainfall. Main determinants of soil erodibility are soil structural stability and the soil's ability to absorb rainfall. These properties in turn depend on a number of characteristics of the topsoil, such as texture, structure, organic matter content and salinity. Soil depth is of particular importance in that deeper soils have a higher water holding capacity and thus are able to absorb larger amounts of rainfall before overland flow begins. In addition, erosion of deep soils is considered less dramatic than for shallow soils over bedrock. Important terrain factors controlling overland flow by water are slope length and angle.

In the present assessment of soil erodibility by water three soil characteristics are considered: textural class of topsoil (0-30 cm); bulk density (as an indicator of soil structure/permeability); and soil depth. The basic soil data were derived from ISRIC's WISE database which holds 4,353 globally distributed profiles considered to be representative of the soil units shown on a ½° latitude by ½° longitude version of the corrected and digitized 1:5 M Soil Map of the World (FAO, 1991). Each grid cell in WISE is characterized by its main soil types (up to 10) and their relative extent (Batjes, *et al.*, 1995).

Soil factors were rated arbitrarily on a scale of 0 to 1, using expert-judgement. A value close to zero indicates soil conditions that are considered conducive to erosion in those areas where the erosive action of rainfall is high and the land is poorly protected by a vegetation cover. The rating scheme for textural class is shown in Table I.

Table I. Rating of textural classes (After: EU, 1992)

Index (I_t)	USDA textural class
1.0	C, SC, SiC
0.8	S, LS, SCL, CL, SiCL
0.6	L, SL, Si, SiL

Note: Codes are for textural classes of USDA (Soil Survey Staff, 1951). C stands for clay, Si for silt, S for sand, and L for loam (e.g. LS= loamy sand, SiL= silt loam). Peat soils are assigned an index of 1.0 by default.

Bulk density is rated according to Table II. A high bulk density is considered indicative for a poor structure of the soil and poor infiltration characteristics, facilitating surface runoff.

Table II. Rating of bulk density

Index (I_b)	Bulk density (b in kg m^{-3})
1.0	$b \leq 1350$
0.8	$1350 < b \leq 1550$
0.6	$1550 < b$

Soil depth is defined as the median depth from the soil surface to the base of the regolith or unweathered parent material, and is rated according to Table III.

Table III. Rating of soil depth

Index (I_d)	Soil depth (d in cm)
1.0	$100 \leq d$
0.8	$50 \leq d < 100$
0.6	$d < 50$

Topography in the WISE database is indicated by an average regional slope angle by soil type, using the composition rules of FAO (1991). The criteria for defining slope classes are derived from the Soil Map of the World (FAO-Unesco, 1974). The rating system is shown in Table IV.

Table IV. Rating of topography

Index (I_a)	Slope angle (a in %)
1.0	$a < 8$
0.8	$8 \leq a < 30$
0.6	$30 \leq a$

The rating of terrain erodibility (T) involves two stages. Firstly, a subrating for erodibility (Z_j) is calculated for each soil type (j) in a grid cell (Table V), using the relevant indices for topsoil texture (I_t), bulk density (I_b), soil depth (I_d) and slope angle (I_a):

$$Zj = I_l \cdot I_o \tag{3}$$

with:

I_l, the most limiting (lowest) index (i.e. I_a, I_b, I_d or I_t), and

I_o, the average of the remaining 3 indices for the soil under consideration.

Table V. Rating of terrain erodibility by soil type

Z Rating	Terrain erodibility index[†]
1 - Low	$0.74 \leq Z_j$
2 - Moderate	$0.48 \leq Z_j < 0.74$
3 - High	$Z_j < 0.48$

[†] Ratings by constituent soil types in a grid cell (Z_j) are combined in a next stage to give the overall rating for terrain erodibility by grid cell (T, see text).

Secondly, the overall rating for terrain erodibility is determined on a grid cell basis. This is done by (1) calculating the total area of soils with a low (Z= 1), moderate (Z= 2) and high (Z= 3) erodibility rating (see Table V), and (2) by assigning each grid cell to one of three terrain erodibility classes (T), as follows:

Low (T= 1): The area of soils with a low erodibility rating is larger than the area having a moderate rating *or* the area with a low rating is larger than the area having a high rating, *and* the area with a moderate or high erodibility rating occupies less that 33 percent of the grid cell.

High (T= 3): Over 33 percent of the grid cell consists of soils with a high erodibility rating, *or* over 66 percent of the soils has a moderate or high erodibility rating.

Moderate (T= 2): all other areal combinations for Z.

Areas of "Oceans and inland waters" and "Glaciers" are flagged as separate units when they cover over 66 percent of a grid cell's area.

Rainfall erosivity

Rainfall erosivity depends primarily on rainfall intensity, amount and distribution. At the global scale it can be approximated from the Major Agro-Ecological Zones map (Fischer, *et al.*, 1996) and data from Bouwman (1989, p. 13 and 18), using GIS. Three classes for rainfall erosivity are used in the model (Table VI).

Table VI. Classification of rainfall erosivity

R class	Rainfall erosivity index
1 - Low	≤ 800
2 - Moderate	800 to 1250
3 - High	≥ 1250

Land-use/cover

Land-use and land-cover change play a pivotal role in global environmental change (Turner, *et al.*, 1995). It is one of the most crucial elements in model (2) in that it is the factor that is most readily altered by human intervention, thereby determining the actual vulnerability of the system to water erosion. Changes in land cover through management practices provide the main opportunity for erosion control (Stocking, 1994).

At the global level maps of land cover and land use are highly generalized and often not up to date (Leemans and Van den Born, 1995; Turner, *et al.*, 1995). Data on current land cover was derived from the Matthews database on cultivation density present on the Global Ecosystems Database (Kineman, 1992). Three classes are considered in the model (Table VII).

Table VII. Classification of land cover

V class	Cultivation density (%)
1 - Well protected	0 - 19
2 - Moderately protected	20 - 49
3 - Poorly protected	50 - 100

Rating of water erosion risk

The major difficulty in determining the areas at risk from water erosion is to rate and combine all factors in model (2) to arrive at a final estimate. The part of the erosion hazard that is due to the influence of the relatively "constant" factors of climate, relief and slope is often termed "potential" soil erosion (EU, 1992). In the current study the term susceptibility is preferred in that the corresponding rating refers to a hypothetical condition of having no vegetation cover at all. As such the current assessment of susceptibility is independent of land use and management practices, describing the erosion that can be expected when the terrain is not protected by vegetation/crops and conservation practices (worst-case scenario). The procedure for determining the susceptibility rating (Table VIII) thus only considers the ratings for terrain erodibility (*T*) and rainfall erosivity (*R*).

Table VIII. Rules for identifying areas susceptible to water erosion

Susceptibility rating (*SU*)	Terrain erodibility class (*T*)	Rainfall erosivity class (*R*)
1 - Low	1	1 or 2
2 - Moderate	Any other combination	Any other combination
3 - High	2 or 3	2 or 3

Vulnerability is defined as the (presumed) hazard of soil types, in a grid cell, being affected by water erosion under current conditions of vegetation and land use, the later reflecting the human-induced pressures on the land. Vulnerability thus is estimated by combining the ratings for terrain erodibility (*T*), rainfall erosivity (*R*) and vegetation cover (*V*), as shown in Table IX. At the considered resolution of ½° latitude by ½° longitude the possible effects of agricultural policy and land ownership on erosion control measures, and hence on regional land pressure, could not be considered explicitly.

Table IX. Rules for identifying areas vulnerable to water erosion

Vulnerability rating (*VU*)	Terrain erodibility class (*T*)	Rainfall erosivity class (*R*)	Vegetation cover class (*V*)
1 - Low	1	1	1
	1	≤3	1
	≤3	1	1
2 - Moderate	Any other comb.	Any other comb.	Any other comb.
3 - High	≥2	≥2	≥2
	1	3	3

Data analysis

All data sets were analyzed on a grid cell basis using a combination of dBASE IV and GIS operations. Firstly, erodibility ratings were determined for the component soils of each grid cell. Secondly, the area of potentially erodible soils (degree and relative extent) was calculated by grid cell. This information formed the basis for generating the GIS-layer for terrain erodibility. The databases on climate and land cover were reclassified into the categories described earlier, using GIS. Next the data files were analyzed jointly to determine the susceptibility (*S*) and vulnerability (*V*) ratings of each terrestrial grid with respect to water erosion. Finally, the output of the model was converted to GIS image files (IDRISI, 1993), which provided the basis for the model evaluation exercise.

A complicating factor in GIS studies dealing with compound map units (grid cells) is that the geographic distribution of the component soils, climate, and land under cultivation within the grid cell is not known explicitly. During the overlay procedure it was therefore necessary to assume that terrain erodibility, rainfall erosivity and vegetative cover are homogeneously distributed over the area of a grid cell. Although this is a common assumption in grid-based GIS studies (e.g. EU, 1992; Leemans and Van den Born, 1995), it creates some uncertainty in the results (Burrough, 1986 p. 103-135).

RESULTS

Extent of susceptible and vulnerable areas

The geographic distribution of regions considered susceptible and vulnerable to erosion by water is shown in Figure 2 and 3, respectively. While the area estimates for the highly susceptible and highly vulnerable classes in Table X are similar, the corresponding grid cells occur at different places of the world.

About 88 million km^2 of land, corresponding with about sixty percent of the world's terrestrial surface, is considered moderately to highly susceptible to erosion by water. The extent of moderately to highly vulnerable areas is estimated at about 52 million km^2, or about one third of the global land surface, reflecting the protective influence provided by present land cover. It is important to realize that only a part of each map unit (grid cell) is susceptible or vulnerable to water erosion. *This means* *that the actual extent of land at risk from water-erosion will be lower than the total shown for the vulnerable areas.*

Table X. Estimated global extent of land susceptible and vulnerable to water-erosion

Susceptible areas		Vulnerable areas	
Class	extent (x10^6 km^2)	Class	extent (x10^6 km^2)
Low susceptibility	41.5	Low vulnerability	78.2
Moderate susceptibility	63.8	Moderate vulnerability	27.3
High susceptibility	24.4	High vulnerability	24.2

Note: Classes for susceptibility and vulnerability are qualitative and, as such, do not depict the same kind of data. Data shown are for the region between latitude 70° N and 57° S, excluding oceans, inland waters, and land ice (≈ 323x10^6 km^2).

Model evaluation

Results of global models are difficult to evaluate. This is not only due to possible shortcomings in the assumptions underlying the model, but also to the uncertainty associated with the various global databases used (Leemans and Van den Born, 1995). The only known source available to evaluate results of the current modelling exercise is GLASOD. This 1:10 million scale map of the global status of human-induced soil degradation specifies the type, degree and relative extent of soil degradation by map unit (Oldeman, *et al.*, 1991). The units on the GLASOD map have been delineated and characterized by experts according to uniform criteria. Of particular interest for the current study are the data on "loss of topsoil by water erosion" (Wt). Information on the severity — degree of degradation and area affected within a map unit — was extracted from the GLASOD database for the evaluation exercise. The severity rating in GLASOD resembles the current vulnerability rating, which refers to the modelled seriousness of soil "deterioration" induced by water-erosion in a grid cell under present conditions of land use.

The GLASOD map was first rasterized at a ½° by ½° resolution to permit overlay with the vulnerability map. Since the GLASOD map only covers part of the world — from latitude 70° N to 57° S — similar geographical subsets were prepared for the susceptibility and vulnerability maps (about 130x10^6 km^2). The subset for vulnerability then formed the basis for model output evaluation.

A direct comparison of the area data for susceptibility, vulnerability and GLASOD water-erosion severity is difficult because the qualitative definitions for the classes are different. In view of these differences all three datasets were reclassified into three broad categories: 0 - areas of oceans, inland waters or glaciers; 1 - areas with a low susceptibility, vulnerability or GLASOD rating; 2 - areas with a moderate to high susceptibility, vulnerability or GLASOD severity rating.

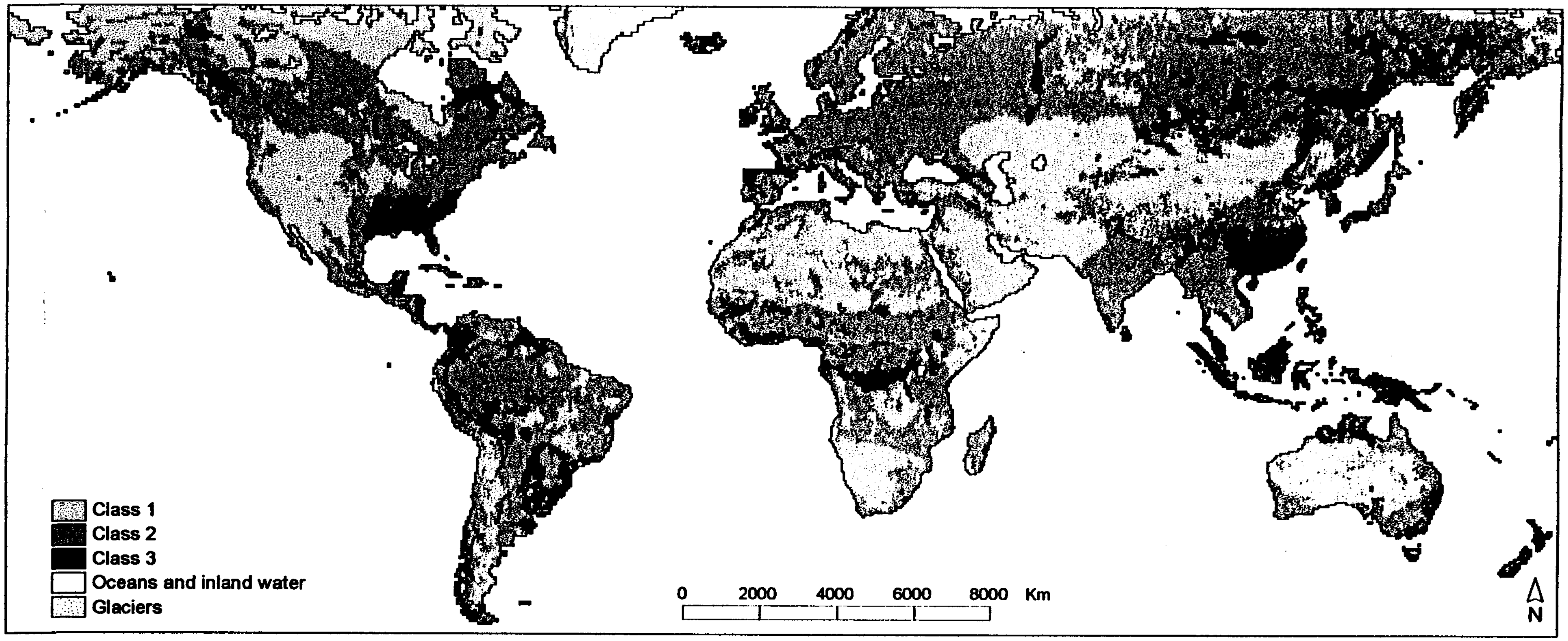

Figure 2. Regions susceptible to water-induced erosion (<u>Legend</u>: Susceptibility classes: 1= low ; 2= moderate; 3= high)

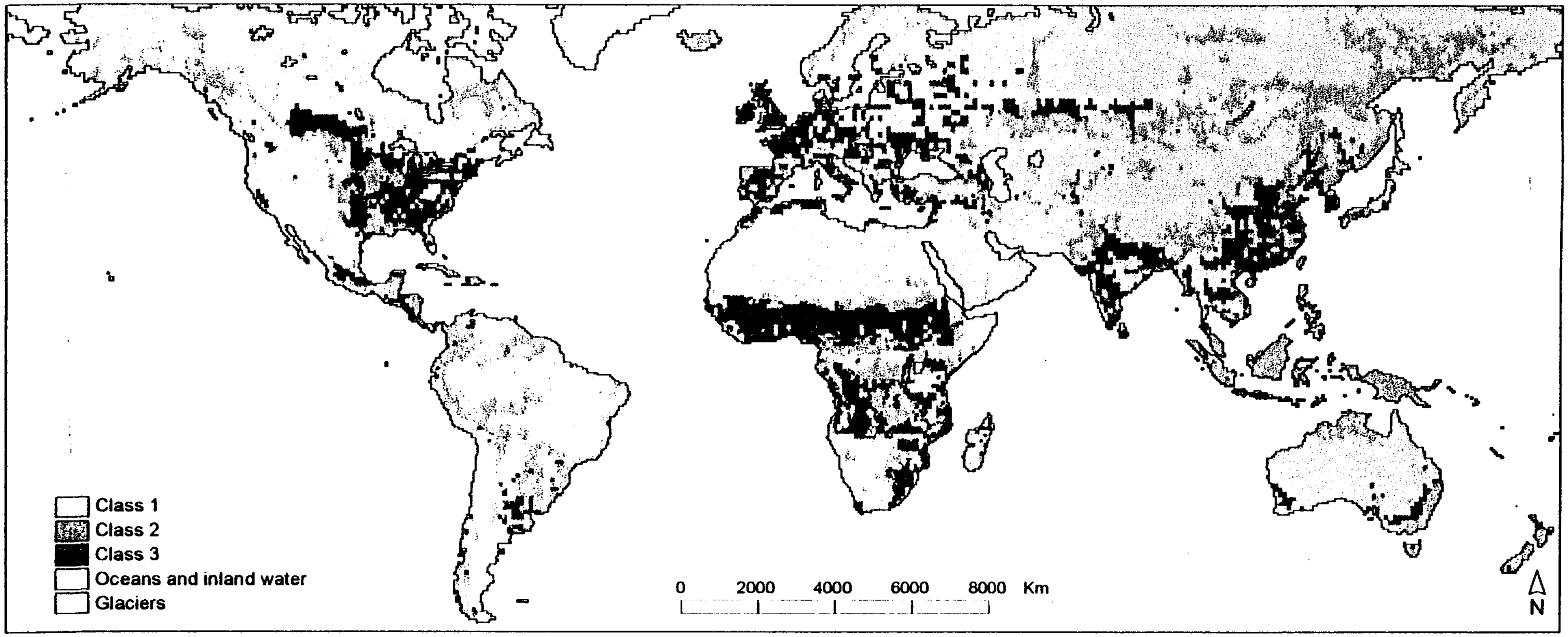

Figure 3. Regions vulnerable to water-induced erosion (Legend: Vulnerability classes: 1= low ; 2= moderate; 3= high)

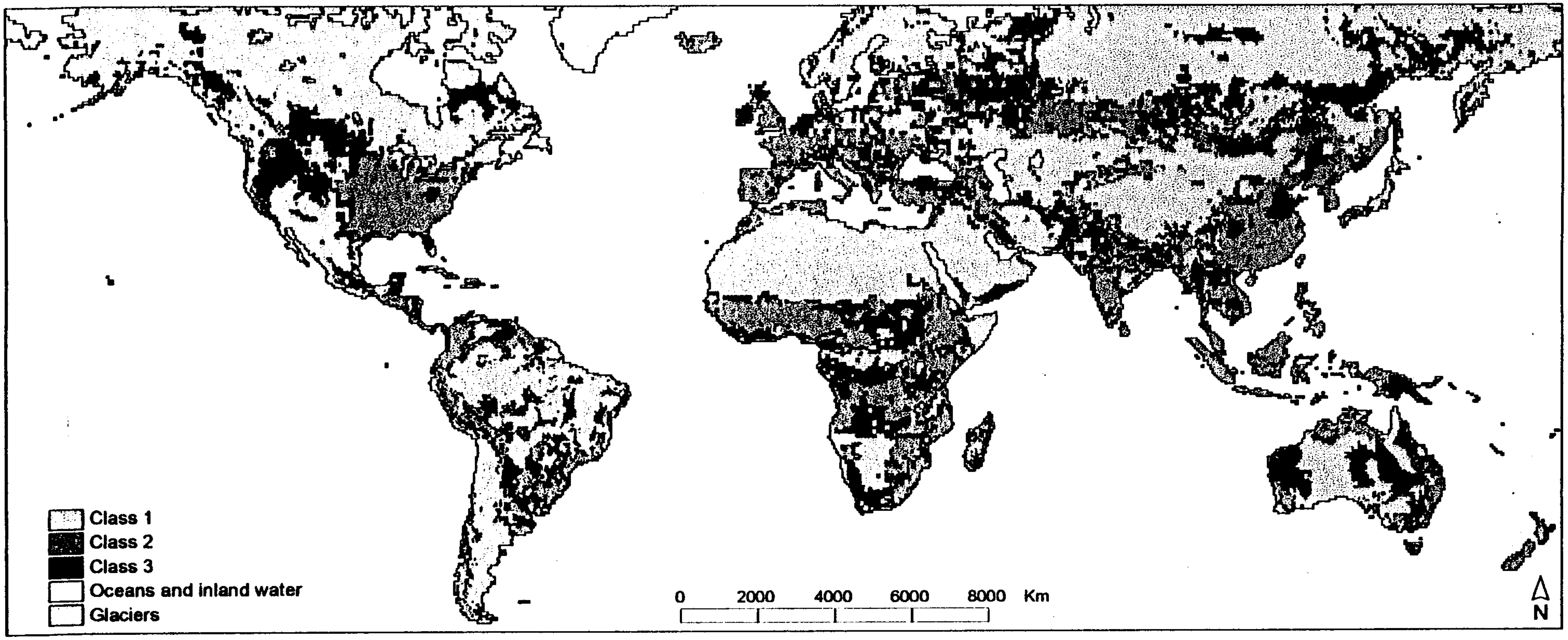

Figure 4. GIS overlay of regions vulnerable to and currently degraded by water-erosion (Legend: Class 1: full overlap of low vulnerability (V1) and low degradation severity (D1) category (see Table XI); Class 2: full overlap of mod. to high vulnerability (V2) and mod. to high degradation severity (D2) category; Class 3: categories V1 and D2, or V1 and D2 overlapping); Class 4: Glaciers and land ice; Class 5: Oceans and inland waters).

The values in Table XI relate to the total area of regions in which "problems" of water-induced soil degradation may occur. They do not provide any information on the actual extent of the area that is at risk or affected within these regions. Thus values in Table XI *should not* be compared with statistics on "extent" of water-erosion (Wt) presented in the GLASOD report (Deichmann and Eklundh, 1991). The latter figures are estimates of the area currently degraded by water erosion (10.9×10^6 km^2, see Oldeman, *et al.*, 1991), whereas severity in the current study relates to the total land area (grid cells) in which water erosion was observed.

Table XI. Extent of land susceptible, vulnerable, and currently degraded (GLASOD) by water-erosion

Susceptible area		Vulnerable area		Degraded area	
Class	extent ($\times 10^6$ km^2)	Class	extent ($\times 10^6$ km^2)	Class	extent ($\times 10^6$ km^2)
S0 Oceans/glacier	323.0	V0 Ocean/glaciers	323.0	D0 Ocean/glaciers	325.0
S1 Low	41.5	V1 Low	78.2	D1 Low	84.2
S2 Mod. to High.	88.2	V2 Mod. to high	51.5	D2 Mod. to high	43.4

Note: The numbers above refer to the *total* area of grid cells in a class, not to the *actual* area (possibly) affected within the grid cells. Data shown are for the region between latitude 70° N and 57° S. Small differences in total land areas are due to differences in map rasterization.

A cross-tabulation of the vulnerability and GLASOD maps was made using GIS (Table XII). About 50% of the terrestrial grid cells have a low rating for both vulnerability and severity (Class 1 in Figure 4), 17% have a moderate-high rating for both vulnerability and severity (Class 2), while 33% have either a low rating for vulnerability and moderate-high rating for severity *or* a moderate-high rating for vulnerability and a low rating for severity (Class 3). Cramer's V-coefficient — an indicator of Goodness-of-Fit (see IDRISI, 1993 p. 43-44) — for the cross-tabulation was 0.72 ($P \ll 0.005$). This means that despite the differences in class definitions, and fuzziness/noise associated with the modelling and gridding procedures, a fairly good agreement was observed between the regions (grid cells) considered vulnerable to water-erosion and regions currently affected by water erosion as shown on the GLASOD map.

Table XII. Proportional cross-tabulation of vulnerability classes and GLASOD severity classes (in percent)

	V0	V1	V2	Total
D0	69.15	0.18	0.45	69.78
D1	0.14	15.06	5.71	20.91
D2	0.02	4.06	5.22	9.31
Total	69.31	19.30	11.39	100.00

Note: See table XI for definitions of vulnerability (V) and severity (S) classes.

DISCUSSION AND CONCLUSIONS

This paper presents a methodology to map regions considered at risk from water erosion on a ½° by ½° global grid. The databases available for this study were of variable quality and resolution (see Leemans and Van den Born, 1995), thereby determining to a large extent the reliability of the model output and level of detail of conclusions (Hudson, 1980; Burrough, 1986).

Model output was evaluated against the GLASOD map, showing a fair geographic agreement between regions considered vulnerable to water erosion (model) and regions in which water erosion (GLASOD) occurs currently. Thus the approach can be used to raise awareness on issues of soil degradation by water at the international level. The structure of the model seems useful to estimate future scenarios of land erosion by rainfall, for example upon predicted climatic change or following changes in land cover/use, at the global scale. The growth of the world population and associated demand for increased food production, either through land-productivity increases or area-expansion, may increasingly become an important driving force of land degradation (Biswas, 1994), requiring a holistic approach to sustainable land use (Cattizone and Muchena, 1994).

The type of approach described in this paper may also be useful for a first assessment of areas considered vulnerable to chemical pollution on a ½° by ½° grid, pending more detailed studies at the regional or continental level (see Batjes, *et al.*, 1993).

Although the current model can identify areas considered prone to water-erosion at the global level, it cannot provide any information on the rate of erosion nor on the associated decrease in crop productivity and biodiversity. Recent reviews identify the study of productivity changes due to erosion as a prime research area (Pierce and Lal, 1994; Van Lynden, 1995; Young, 1994; Sanders, *et al.*, 1995). Staff at ISRIC are currently developing and testing a quantitative approach, using the recently completed 1:1 M SOTER databases for Kenya, Uruguay and Argentina (see Oldeman and Van Engelen, 1993), in the framework of UNEP's Global Environmental Outlook programme (Mantel, *personal communication, 1996*). In order for such erosion-productivity impact models to become most useful they should be presented in a form that can be linked directly to socio-economic models (e.g. El-Swaify and Fownes, 1992; Dyke and Heady, 1985; Young, 1994; Sanders, *et al.*, 1995). Once fully integrated, such pressure-state-response models will provide a powerful tool to guide the planning of soil conservation at the regional level, using scenario analyses.

ACKNOWLEDGEMENTS

This study was prepared in the framework of a UNEP-sponsored collaborative activity between the National Institute of Public Health and Environmental Protection (RIVM), Bilthoven, and the International Soil Reference and Information Centre (ISRIC), Wageningen. I thank Ms. J.W. Resink for preparing the final GIS figures.

REFERENCES

Arnold, R.W., Szabolcs, I. and Targulian, V.O. 1990. *Global soil change.* Report of an IIASA-ISSS-UNEP task force on the role of soil in global change. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Barrow, C.J. 1991. *Land Degradation — Development and Breakdown of Terrestrial Environments,* Cambridge University Press, Cambridge.

Batjes, N.H., Bridges, E.M. and Nachtergaele,F.O. 1995. World Inventory of Soil Emission Potentials (WISE): Development of a global soil database of process controlling factors, pp. 102-115 *in* S. Peng, et al. (eds) *Climate Change and Rice*, Springer Verlag, Heidelberg.

Batjes, N.H., van Engelen, V.W.P. and Oldeman, L.R. 1993. 'Proposed Assessment of the Vulnerability of European Soils to Pollution Using a SOTER-shell Approach', *Land Degradation & Rehabilitation*, **4**, 223-231.

Biot, Y. and Lu, X.X. 1995. 'Loss of yield caused by soil erosion on sandy soils in the UK', *Soil Use and Management* **11**, 157-162.

Biswas, M.R. 1994. Agriculture and environment: a review, 1972-1992. *Ambio* **23**, 192-197.

Bolline, A. 1985. Adjusting the Universal Soil Loss Equation for use in western Europe, pp. 206-213 *in* S.A. El Swaify and W.C. Moldenhauer and A. Lo (eds) *Soil Erosion and Conservation,* Soil Conservation Society of America, Ankeny, Iowa.

Bouwman, A.F. 1989. Land evaluation for rainfed farming using global terrain information on a 1° longitude by 1° latitude grid. Working Paper and Preprint 89/01, ISRIC, Wageningen.

Burrough, P.A. 1986. *Principles of Geographical Information Systems for Land Resources Assessment.* Monographs on Soil and Resources Survey No. 12, Oxford University Press, Oxford.

Catizzone, M. and Muchena, S.C. 1994. *A Holistic Approach to Sustainable Soil Use in SADC Countries.* Office for Official Publications of the European Communities, Luxembourg, 22 pp.

Chengere, A. and Lal, R. 1995. 'Soil degradation by erosion of a Typic Hapludalf in Central Ohio and its rehabilitation', *Land Degradation & Rehabilitation*, **6**, 223-238.

De Boodt, M. and Gabriels, D. (eds) 1980. *Assessment of Erosion*, John Wiley & Sons, Chichester.

Deichmann, U. and Eklundh, L. 1991. Global digital datasets for land degradation studies: a GIS approach. GRID Case Study Series No. 4, Global Environmental Monitoring System (GEMS), United Nations Environment Programme, Nairobi.

Dyke, P.T. and Heady, E.O. 1985. Assessment of soil erosion and crop productivity with economic models, pp. 105-117 *in* R.F. Follet and B.A. Stewart (eds) *Soil Erosion and Productivity,* American Society of Agronomy, Madison, Wisconsin.

El-Swaify, S.A. and Fownes, J.H. 1992. Erosion processes and models: Applications in the tropics, pp. 135-149 *in* H. Hurni and K. Tato (eds) *Erosion, Conservation, and Small-Scale Farming,* Geographica Bernensia/International Soil Conservation Organisation/World Association of Soil and Water Conservation, Walsworth Publ. Co., Marceline, Missouri.

El Swaify, S.A., Moldenhauer, W.C. and Lo, A. (eds) 1985. *Soil Erosion and Conservation*, Soil Conservation Society of America, Ankeny, Iowa.

EU, 1992. *CORINE Soil Erosion Risk and Important Land Resources in the Southern Regions of the European Community: An Assessment to Evaluate and Map the Distribution of Land Quality and Soil Erosion Risk.* Report EUR 13233 EN, Office for Official Publications of the European Communities, Luxembourg.

FAO, 1991. *The Digitized Soil Map of the World. Notes: Volume - Africa.* World Soil Resources Report 67/1 (Release 1.0), FAO, Rome.

FAO-Unesco, 1974. *Soil Map of the World (1:5,000,000)*, Volume 1: Legend. Unesco, Paris.

Fischer, G., De Pauw, E., van Velthuizen, H., Nachtergaele, F.O. and Antoine, J. 1996. A provisional world climatic resource inventory based on the length-of-growing period concept *in* Batjes, N.H., J.H. Kauffman and O. Spaargaren (eds) *Proceedings NASREC workshop (November 6-17, 1995, Wageningen)*, International Soil Reference and Information Centre, Wageningen [in press].

Hudson, N.W. 1980. Erosion prediction with insufficient data, pp. 279-284 *in* De Boodt, M. and D. Gabriels (eds) *Assessment of Erosion*, John Wiley & Sons, Chichester.

IDRISI, 1993. *IDRISI User Guide (Version 4.0)* Clark University, Worcester.

Kineman, J.J. 1992. *Global Ecosystems Database (Version 1.0).* United States Department of Commerce, National Oceanic and Atmospheric Administration, National Geophysical Data Centre and World Data Centre-A for Solid Earth Geophysics, Boulder.

Leemans, R. and Van den Born, G.J. 1995. 'Determining the potential distribution of vegetation, crops and agricultural productivity', *Water, Air, and Soil Pollution,* **76**, 133-161.

Oldeman, L.R., 1994. The global extent of soil degradation, pp. 99-118 *in* D.J. Greenland and I. Szabolcs (eds) *Soil Resilience and Sustainable Land Use*, CAB International, Wallingford.

Oldeman, L.R. and Van Engelen, V.W.P. 1993. 'A World Soils and Terrain Digital Database (SOTER) — An improved assessment of land resources', *Geoderma*, **60**, 309-325.

Oldeman, L.R., Hakkeling, R.T.A. and Sombroek, W.G. 1991. *World Map of the Status of Human-induced Land Degradation: An Explanatory Note (2nd revised edition).* ISRIC, Wageningen & UNEP, Nairobi.

Pierce, F.J. and Lal, R. 1994. Monitoring the impact of soil erosion on crop productivity, pp. 236-263 *in* R. R. Lal (ed.) *Soil Erosion Research — Research Methods (2nd ed.),* Soil and Water Conservation Society, Ankeny, USA.

Prentice, I.C., Sykes, M.T. and Cramer, W. 1993. 'A simulation model for the transient effects of climate change on forest landscapes', *Ecological Modelling*, **65**, 512-70.

Rickson, R.J. (ed.) 1994. *Conserving Soil Resources: European Perspectives.* CAB, Wallingford.

Sanders, J.H., Southgate, D.D. and Lee, J.G. 1995. *The economics of soil degradation: technological change and policy alternatives.* SMSS Technical Monograph No. 22, U.S. Department of Agriculture, Washington DC.

Soil Survey Staff, 1951. *Soil Survey Manual.* U.S. Dep. Agr. Handb. 18, U.S. Govt. Printing Office, Washington, D.C.

Stocking, M.A. 1994. Assessing vegetative cover and management effects, pp. 211-252 *in* R. Lal (ed.), *Soil Erosion Research — Research Methods (2nd ed.)*, Soil and Water Conservation Society, Ankeny, USA.

Turner II, B.L., Skole, D., Sanderson, S., Fischer, G., Fresco, L. and Leemans, R. 1995. *Land-Use and Land-Cover Change: Science/Research Plan.* IGBP Report No. 35 / HDP Report No. 7, Stockholm.

UNEP/EAP, 1995. *Report on the UNEP/RIVM workshop on UNEP's Pilot Global Environmental Outlook Project Focusing on Land Degradation and Food Production.* UNEP/EAP/MR.95-4, Environment Assessment Programme & United Nations Environment Programme, Nairobi.

Van den Berg, M. 1992. *SWEAP: A Computer Program for Water Erosion Assessment Using SOTER.* SOTER Report 7, UNEP/ISRIC, Wageningen.

Van Lynden, G.W.J. 1995. 'European soil resources: current status of soil degradation, causes, impacts and needs for action', *Nature and Environment*, **71**, Council of Europe, Strasbourg.

Wischmeier, W.H. and Smith, M.D. 1978. *Predicting Rainfall Erosion Losses — A Guide to Conservation Planning,* Agricultural Handbook No. 537, United States Department of Agriculture, Washington DC.

Young, A. 1994. Modelling changes in soil properties, pp. 423-447 *in* D.J. Greenland and I. Szabolcs (eds) *Soil Resilience and Sustainable Land Use*, CAB International, Wallingford.

Zuidema, G., van den Born, G.J., Alcamo, J. and Kreileman, G.J.J., 1994. 'Simulation of global land cover changes as affected by economic factors and climate', *Water, Air and Soil Pollution*, 76, 163-198.