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AN ANALYSIS ON SOIL EROSION FACTORS AT THE GLOBAL SCALE

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Abstract

In assessing land use/development suitability for the sustainable use of terrestrial environmental resources such as agricultural development and reforestation, it is recognized that soil erosion possibility is one of key factors. In the statistical analysis using a global data set on spatial patterns of water/wind erosion severity ("GLASOD"; UNEP/GRID, 1990), important soil erosion factors including climate, topographic, soil, land cover and cultivation conditions are identified with statistical significance and relative weights of individual factors are estimated. "Possible" soil erosion by water or wind for a land unit when vegetative cover of the unit is removed for intensive cultivation can be estimated at the global scale by using the formulae obtained by the analysis. This is the first attempt to identify important factors of soil erosion at the global scale and to generate a global map of the possibility of soil erosion. Although there remain some problems for further studies such as low resolution of global data and resulting relatively low multiple correlation coefficient in the analysis, it is meaningful to estimate the erosion possibility at the global scale with a unified criteria. The global map will be very useful in the various aspects of discussion for better management strategies of terrestrial environmental resources.

KEYWORDS: *soil erosion possibility, soil degradation, GLASOD, environmental resources, land suitability analysis*

1. Introduction

Significance of better management of terrestrial environmental resources such as forest and soil are repeatedly stated for the sustainable use of the Earth to secure a sound basis of human habitation.

Soil erosion is one of the most serious threatening factors for the sustainable use of the Earth. Soil erosion causes reduction of crop productivity because of loss of nutrients and water holding capacity of soil. That also causes off-site problems such as water pollution. In addition, soil erosion is almost irreversible damage because soil forming is very slow. 200-1000 years are needed for forming 2.5 cm of topsoil under cropland conditions (Pimentel *et al.*, 1995).

As regards global data on soil degradation such as soil (water/wind) erosion, in 1990 ISRIC (International Soil Reference and Information Centre) and UNEP (United Nations Environmental Programme) compiled global database "GLASOD" (Global Assessment of Soil Degradation) for the global assessment of desertification and the production of the global atlas of

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desertification. GLASOD is based on the soil experts' answer to a questionnaire about soil degradation processes over the world (UNEP/ISRIC, 1991). Since GLASOD can be considered as the most reliable database on global soil degradation, the analysis on soil erosion factors are carried out with GLASOD in this paper.

The statistical analysis on spatial patterns of soil erosion are conducted with available global datasets corresponding to the factors after reviewing water/wind erosion factors. At last by using formulae which are obtained through the analysis, the possibility of water/wind erosion are estimated at the global scale.

There are many studies on soil erosion and it's impacts. Wicks *et al.* (1992) calibrated a soil erosion simulation model based on physical process with consideration of land cover difference. As introduced by Ponzi (1993), impacts of soil erosion have been discussed with respect to soil properties such as fertility, crop productivity so forth. Relations between soil erosion and productivity were reported by Larney (1995) and Nagasawa *et al.* (1995). Economic impacts of soil erosion was reported by Pimentel *et al.* (1995).

Generally they have focused on a specific region/soil type. Ponzi (1993) and Pimentel *et al.* (1995) referred some countries and climatic zones, but did not generate a global map. To explore sustainable use of terrestrial environmental resources at the global scale, a global map of the possibility of soil erosion is indispensable. This paper is the first attempt to identify important factors of soil erosion at the global scale and to generate a global map of soil erosion possibility with a unified evaluation criteria. The global map can provide basic information not only to estimate the potential impacts of land cover changes driven by agricultural development at each sites in terms of soil erosion, but also to identify regions risks with vulnerable basic of food production to meet pressing food demand by rapid local population growth.

2. Methodology

2.1 Factors of Water/Wind Erosion

USLE (Universal Soil Loss Equation) has been widely used as a formula to estimate the physical amount of soil loss caused by water erosion around the world. In USLE, the product of six coefficients affecting water erosion severity is used for the estimation as follows (Nagasawa *et al.*, 1993):

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

where, A; estimated physical amount of soil loss,
R; rainfall-runoff factor, K; soil erodibility factor,
L; slope length factor, S; slope gradient factor,
C; cover and management factor and P; support practice factor.

Since USLE was empirically developed based on experiments in United States (Nagasawa *et al.*, 1993), it is impossible to apply USLE for the analysis at global scale. From literatures of soil erosion and availability of global data, water erosion factors are extracted as Figure 1-a.

Among climatic factors, rainfall intensity is determined as a major influencing factor to water erosion. Many existing studies have reported that the soil loss are strongly correlated with peak rainfall intensity with short duration from thirty minute to one hour (Nagasawa *et al.*, 1993). But regarding as peak precipitation data, mean monthly data is only the data available at the global scale. Therefore maximum value of monthly precipitation is used as an index for the factor.

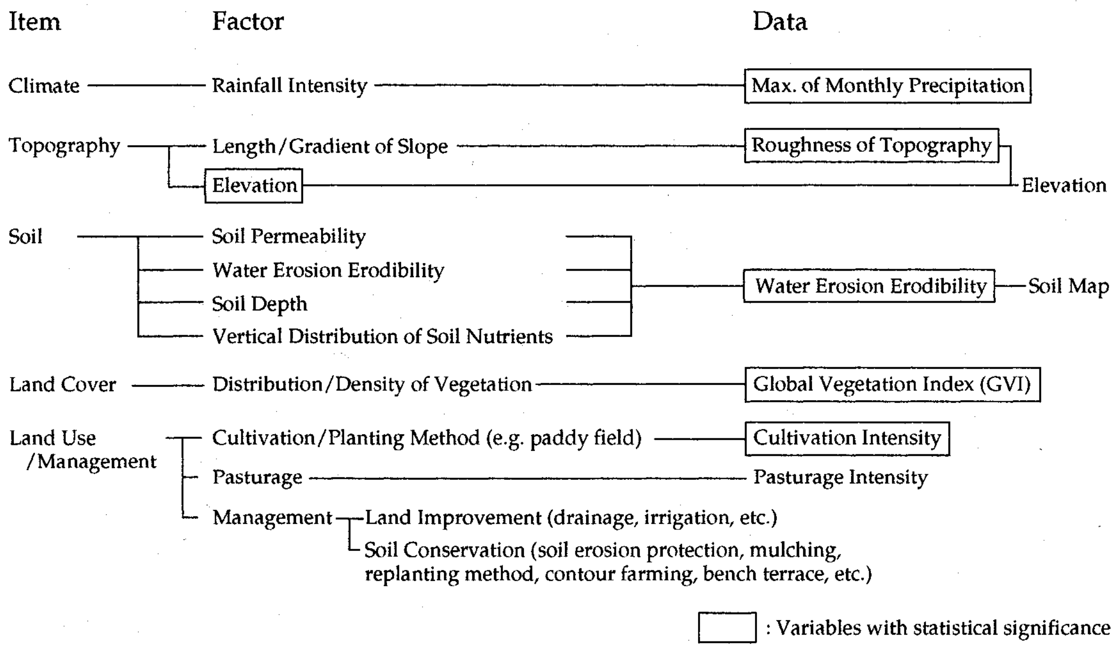


Figure 1-a. Factors and Data used in Water Erosion Analysis

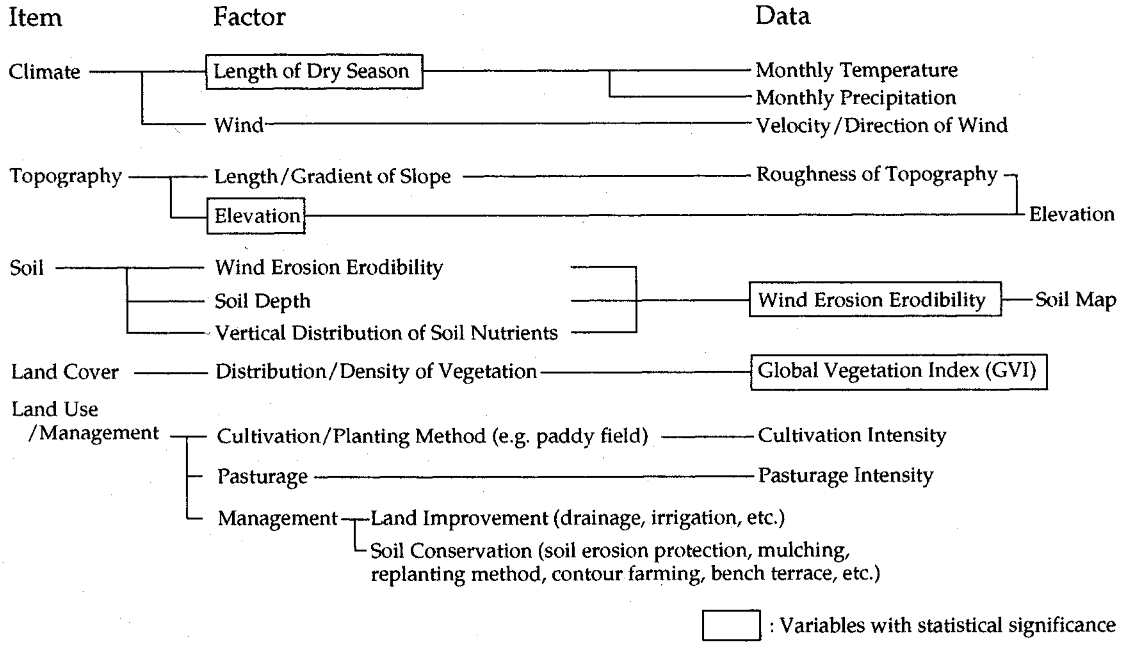


Figure 1-b. Factors and Data used in Wind Erosion Analysis

As for topography, length/gradient of slope should be considered as major water erosion factors as shown in formula 1, however global topographic data available now is only ETOPO-5 (Haxby *et al.*, 1983) which is a grid-based data set with five minute spacing. "Roughness" of topography is computed in a manner described in subsection 2.2 as an alternative index. Value of roughness of topography can be lower even in steep mountain areas due to relatively lower spatial resolution of ETOPO-5 data. Therefore elevation itself is also used to complement the roughness, assuming that actual slope gradient values tend to be larger in higher elevation areas.

As for soil, soil permeability, water erosion erodibility, soil depth and vertical distribution of soil nutrients are major water erosion factors (JSIDRE, 1983). Global soil data available is the world soil map (FAO/UNESCO, 1974). Water erosion erodibility is estimated based on the soil map to represent those factors.

For land cover characterization, distribution and density of vegetation is referred as major water erosion factors (Figure 1-a). In this analysis, global vegetation index (GVI , (Kidwell, 1990)), derived from NOAA AVHRR data, is used because GVI has strong correlation with distribution/density of vegetation on the quantitative basis.

In USLE (formula 1), C (cover and management factor) and P (support practice factor) are corresponding to land use/management item. No global data on current distribution of crops and on land conservation conditions are available, however, for solving this problem, cultivation intensity index is derived by combining global land use/cover data (Olson *et al.*, 1985) with 74 categories for the world and Matthews cultivation intensity data (Matthews, 1983) with five categories of the areal extent of cultivated land within one degree mesh. Other factors in land use/management item, such as pasturage and land improvement/soil conservation are also important. But corresponding global data on them are not available.

Wind erosion factors are also extracted in the same manner as water erosion, such as climate, topography, soil, land cover and land use/management variables as shown in Figure 1-b.

In climate item, aridity and wind condition are important. Global mean monthly data on temperature and precipitation are used to estimate length of dry season in a manner described in subsection 2.2. Velocity/direction of wind are needed, but wind factor are not included in the analysis because reliable global data with enough resolution are not available. The other variables are almost the same as those for water erosion factors.

2.2 Preparation of Global Data

(1) Global Assessment of Soil Degradation (GLASOD) Data (UNEP/ISRIC, 1991)

GLASOD have been compiled by UNEP and ISRIC. They are based on knowledge of more than 250 soil and environmental experts on soil degradation processes in their geographical regions. The definition of soil degradation in GLASOD is "human-induced phenomena which lower the current and/or future capacity of the soil to support human life." The degree of soil degradation has been estimated in terms of agricultural suitability, land productivity and soil biotic functions. Since GLASOD specifically focuses on human-induced soil degradation, natural degradation are excluded. GLASOD contains information on, types of soil degradation such as water/wind erosion, degree, areal extent, cause and so forth. They have been estimated and recorded by a "map unit" delineated by experts according to physical geographic criteria. In this paper, degradation severity index by each erosion types (a composite index taking degree

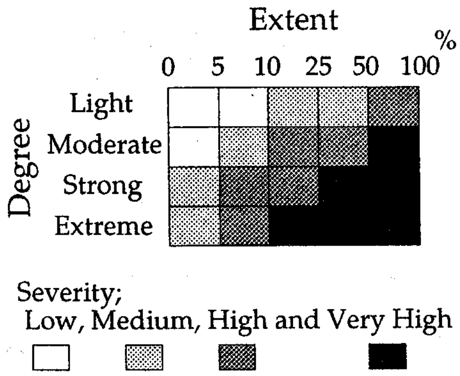


Figure 2. Evaluation of Severity from Degree and Extent of Soil Erosion

and spatial extent of erosion into account as shown in Figure 2) is used to represent erosion severity. In Figure 2, "degree" is a measure of how strongly the soil is affected by degradation, estimated in relation to changes in agricultural suitability, to declined productivity and to biotic functions of the soil, "extent" is the percentage of the area of the map unit that is actually affected by soil degradation. Figure 3-a, b are global maps of degradation severity.

(2) Climate Data

The maximum value of monthly precipitation is the maximum value among twelve mean monthly precipitation values by each grid.

After identifying "dry" months from temperature and precipitation data with the method in UNEP (1992), number of dry months are calculated to estimate dry season period. In UNEP (1992), months are "dry", if the monthly precipitation is less than 20% of monthly evapotranspiration estimated with the method by Thornthwaite and Mather (1955).

(3) Topographic Data

Roughness of topography with ten minute spacing is defined here to be the maximum value of slope gradients between four pairs of elevation points of ETOPO-5 within ten minute grid as shown in Figure 4.

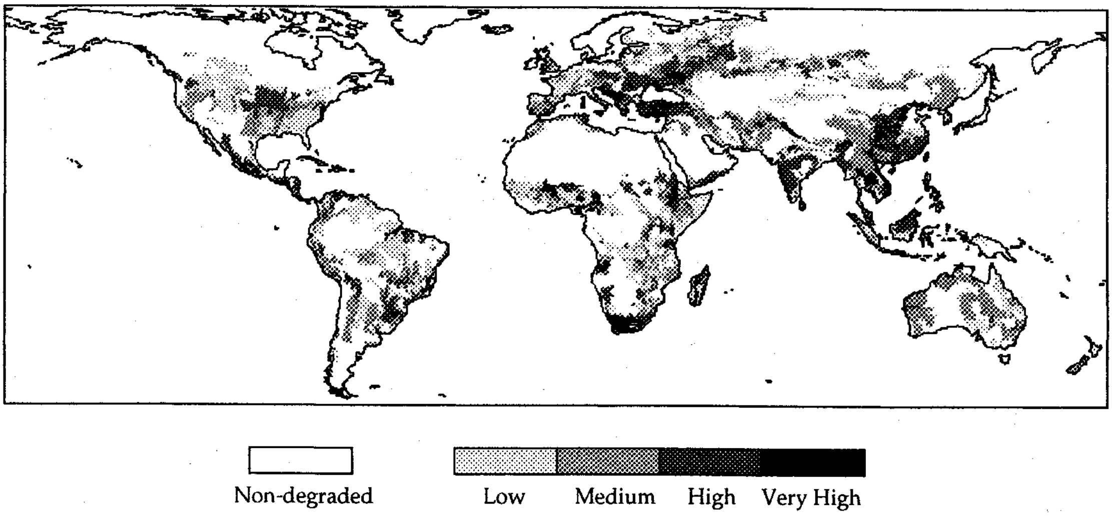
Global elevation data with ten minute spacing grid is generated by taking the median of four elevation values within ten minute grid.

(4) Soil Data

Soil erodibility for water/wind erosion are defined for each FAO soil unit with respect to soil features of vulnerability to erosion by the authors (Table 2).

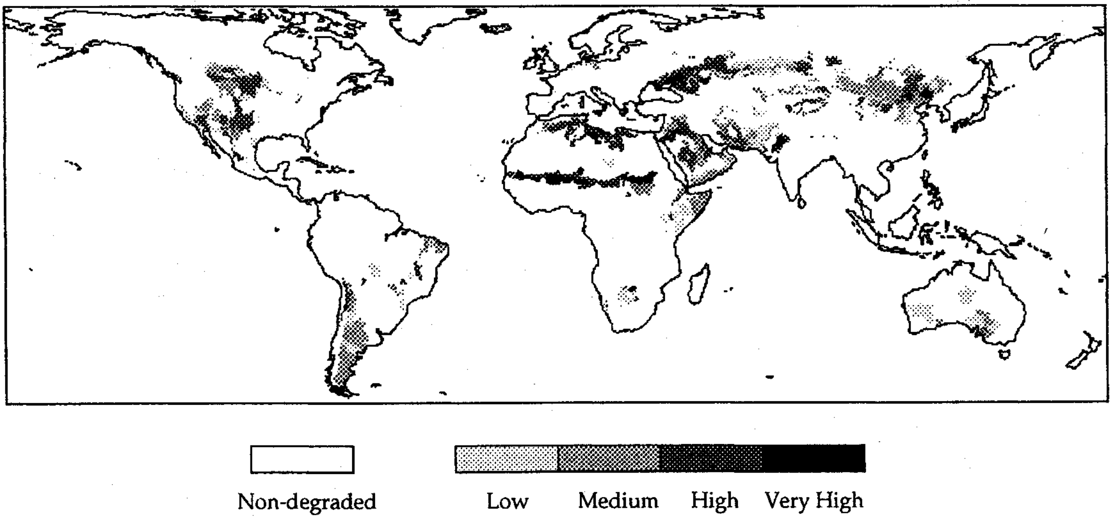
(5) Land Cover Data

As described in previous subsection 2.1, for land cover characterization, mean annual GVI data from 1985 to 1989, which are recognized as normal years, are used in the analysis.



Source: GLASOD (UNEP/GRID)

Figure 3-a. Water Erosion Severity



Source: GLASOD (UNEP/GRID)

Figure 3-b. Wind Erosion Severity

Table 1. Data used in the Analysis and Their Sources

Data	Source Dataset	Original Resolution	Creater of Dataset
Monthly Precipitation	IIASA Mean Monthly Precipitation	30 minute	Leemans and Cramer (1990)
Monthly Temperature	IIASA Mean Monthly Temperature	30 minute	Leemans and Cramer (1990)
Elevation	ETOPO-5	5 minute	NGDC (Haxby, 1983)
Soil Map	FAO Soil Map	1 : 5,000,000	FAO/UNESCO (1974)
Annual GVI	Global Vegetation Index	16 km	USDC/NOAA (Kidwell, 1990)
Cultivation Intensity	Matthews Cultivation Intensity Olson World Ecosystem Classes	1 degree 10 minute	Matthews (1983) Olson et al. (1985)

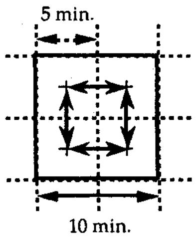


Figure 4. Computation of Roughness of Topography (10min. resolution) from ETOPO-5 (elevation data with 5min. resolution)

Table 2. Soil Erodibility of Each Soil Class

No.	Soil Unit	Water Erosion	Wind Erosion
1	ACRISOLS	3	1
2	CAMBISOLS	4	2
3	CHERNOZEMS	4	3
4	PODZOLUVISOLS	2	1
5	RENDZINAS	3	1
6	FERRALSOLS	1	1
7	GLEYSOLS	3	1
8	PHAEOZEMS	4	1
9	LITHOSOLS	3	3
10	FLUVISOLS	2	2
11	KASTANOZEMS	2	3
12	LUVISOLS	2	1
13	GREYZEMS	4	4
14	NITOSOLS	4	2
15	HISTOSOLS	1	2
16	PODZOLS	1	1
17	ARENOSOLS	1	4
18	REGOSOLS	1	2
19	SOLONETZ	1	2
20	ANDOSOLS	3	4
21	RANKERS	3	1
22	VERTISOLS	3	2
23	PLANOSOLS	3	1
24	XEROSOLS	3	2
25	YERMOSOLS	2	2
26	SOLONCHAKS	2	2

Soil Erodibility	Low ↑ ↓ High	1 ↑ ↓ 4

Table 3. Categorizing Method of Cultivation Intensity

Cultivation Intensity in this study [10min. × 10min./pixel]		Olson World Ecosystem Classes Ver. 1.4D [10min. × 10min./pixel]	
		Non-cultivated Land	Cultivated Land
Matthews Cultivation Intensity (the areal extent of cultivated land) [1deg. × 1deg./pixel]	0-50%	1	2
	50-100%	1	3

(6) Cultivation Intensity Data

Cultivation intensity is an index which is generated by combining land cover classification (Olson *et al.*, 1985) and cultivation intensity (Matthews, 1983) in a manner as shown in Table 3. The former data have 74 categories about land use/cover while the latter data have five categories; 0, 20, 50, 75, 100 (%), the areal percentage of cultivated land within in one degree grid.

To take into consideration the effects of different management schemes of cultivated land among nations, the class of cultivation intensity are set to be unit value in the nations with GNP per capita more than US$5,000 in 1990.

2.3 Method of the Analysis

By using available global datasets, the statistical analysis on spatial patterns of water/wind erosion are conducted.

The method of the analysis called as Quantification Theory I (Taura, 1985, for description), a multiple regression analysis which can handle categorical variables is applied to estimate relative weights (category score; x_{ij}) of categorical variables (δ^k_{ij}) (formula 2). Larger positive value of category score shows the category have higher positive correlation with the objective variable, and vice versa.

$$y_k = \sum_{i=1}^{n} \sum_{j=1}^{n_j} x_{ij}\, \delta^k_{i\,j} \tag{2}$$

x_{ij} (category score) are determined to minimize the total amount of square error $(\sum_{k=1}^{m}(f_k - y_k)^2)$.

where, f_k; observed erosion severity at grid k, y_k; estimated erosion severity at grid k, x_{ij}; category score, δ; explanatory categorical variable,

$$\delta^k_{ij} = \begin{cases} 1 & \text{(when item-i of grid } k \text{ corresponds to category-j)} \\ 0 & \text{(the other cases)} \end{cases}$$

m; number of samples, n; number of items, n_i; number of categories for each item.

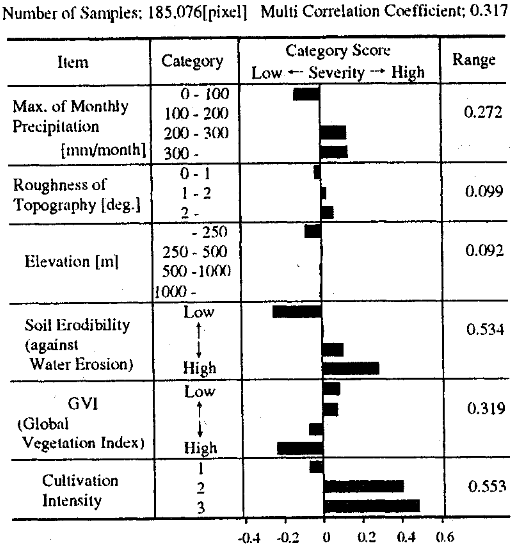
In this paper, erosion severity of water/wind erosion described in the subsection 2.2 are used as objective variables. The erosion severity is handled as a continuous variable, though it is an ordinal variable. Explanatory variables with statistical significance are shown in Figure 1-a, b.

3. Results of Analysis on Water/Wind Erosion Factors

3.1 Water Erosion

The analysis has been carried out for grid data with ten minute spacing, covering from 72 degree north to 57 degree south, the same area as that of GLASOD data.

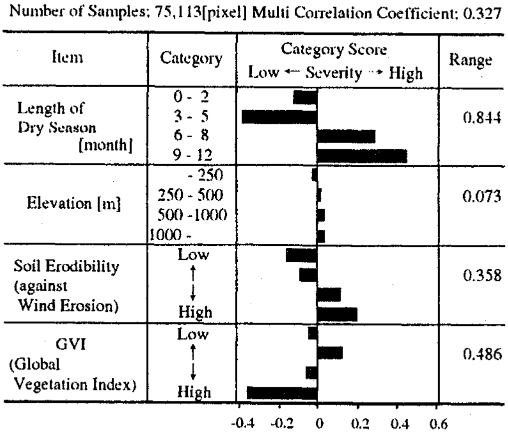
Figure 5-a shows the results of the analysis on water erosion factors. In figure 5-a relative values of category scores standardized within an item are denoted by bar charts. Categories with higher positive score value tend to make more positive contribution to increasing severity and vice versa. The right colomn, "range" shows the difference between maximum and minimum category score for each item. The item with wider range is more influential to the severity.



Number of Samples; 185,076[pixel] Multi Correlation Coefficient; 0.317

Item	Category	Category Score Low ← Severity → High	Range
Max. of Monthly Precipitation [mm/month]	0 - 100 100 - 200 200 - 300 300 -		0.272
Roughness of Topography [deg.]	0 - 1 1 - 2 2 -		0.099
Elevation [m]	- 250 250 - 500 500 -1000 1000 -		0.092
Soil Erodibility (against Water Erosion)	Low ↑ ↓ High		0.534
GVI (Global Vegetation Index)	Low ↑ ↓ High		0.319
Cultivation Intensity	1 2 3		0.553

Figure 5-a. The Results of an Analysis on Water Erosion Factors



Number of Samples; 75,113[pixel] Multi Correlation Coefficient; 0.327

Item	Category	Category Score Low ← Severity → High	Range
Length of Dry Season [month]	0 - 2 3 - 5 6 - 8 9 - 12		0.844
Elevation [m]	- 250 250 - 500 500 -1000 1000 -		0.073
Soil Erodibility (against Wind Erosion)	Low ↑ ↓ High		0.358
GVI (Global Vegetation Index)	Low ↑ ↓ High		0.486

Figure 5-b. The Results of an Analysis on Wind Erosion Factors

Cultivation intensity, soil erodibility and GVI have wider range than others. Concerning cultivation intensity, the item with the widest range, category 1 (non-cultivated land) has the least or the most negative contribution to water erosion severity. More intensive cultivation made more contribution to severity. For soil erodibility against water erosion, the item with the second widest range, soil with higher erodibility, highly vulnerable soil against water erosion, have more contribution to severity and vice versa. As for GVI, the item with third widest range, because lower GVI value which means lower density of vegetation, lower GVI value have more contribution to higher severity and vice versa.

Concerning other items, the maximum value of monthly precipitation and roughness of topography show reasonable tendency: higher values have higher contribution to severity. Area lower than 250 meter elevation have lower contribution to severity and more than 250 meter elevation have relatively high contribution. It is because relatively low areas tend to have lower slope gradient.

3.2 Wind Erosion

Figure 5-b shows the results of the analysis on wind erosion factors.

The length of dry season, GVI and soil erodibility have wider range than others. Concerning the length of dry season which has the widest range, longer length have more contribution to wind erosion severity. GVI and soil erodibility against wind erosion have also reasonable relations with wind erosion severity.

Roughness of topography and cultivation intensity have been excluded for the analysis on wind erosion, because they do not have enough statistical significance.

3.3 Discussions

As the results of the analysis on water/wind erosion factors, reasonable relations and statistical significance have been found between water/wind erosion severity and the affecting factors examined in this study.

However, values of the multiple correlation coefficient; 0.317 for water erosion and 0.327 for wind erosion, are rather low.

At first, the characteristics of severity as an objective variable have to be discussed. Severity is an index spatially averaged or aggregated over a map unit which is usually much larger than ten minute grid. That means that a certain, averaged level of severity can be recorded in a map unit where area with severe erosion are so much concentrated, while all other areas are almost erosion free. To improve the reliability of analysis, it is necessary to consider the spatial distribution of erosion extent within map unit. But at present, there is no global data with finer resolution than GLASOD.

Topography data also pose some limitation. According to Figure 5-a tendencies of categorical weights for roughness of topography and elevation are reasonable, but ranges of them are relatively small. Also in Figure 5-b, tendency of categorical weights for elevation is reasonable, but range is relatively small. In addition, roughness of topography does not have enough statistical significance in wind erosion analysis. It is considered that lower significance of topography may come from the fact low spatial resolution of ETOPO-5 is not enough to represent actual distribution of slope gradient. But, the resolution will be improved in future by the generation of high resolution (1km grid) data. Low resolution of the other data such as cultivation intensity seems to be one of major reasons for low correlation coefficient.

As described by Hiraga (1994), land abandonment due to decrease of productivity by over cultivation/pasturage is one of major causes of human induced desertification in arid areas. However cultivation intensity used in the analysis represents only current status (i.e. no cultivation) and does not reflect any history of cultivation/pasturage of a land unit. This may also be one of reasons why cultivation intensity has no significant correlation with wind erosion severity. For water erosion, there is no consideration in the analysis on the protective effect of paddy fields against water erosion, frequently observed in East/South East Asia. This is again due to the lack of appropriate global data on agricultural land use.

Although there remain some problems left for further study, the results of the analysis reveal reasonable relations between water/wind erosion severity and the factors extracted in this study. Utilization of the formulae (Figure 5-a and 5-b) explaining soil erosion severity will be discussed in section 4.

4. Estimation of Soil Erosion Possibility

In order to estimate environmental impacts due to land cover and land use changes such as deforestation and intensive cultivation etc., it is very useful to know "possible" soil erosion, the severest erosion which may occur at a land unit. The "possible" water/wind erosion can be estimated by substituting the lowest GVI value and the highest cultivation intensity value to the formulae which have been obtained through the analysis, because it can be assumed that deforestation and/or agricultural development may realize the lowest GVI value and the highest cultivation intensity value. Figure 6 shows estimated soil erosion possibility, showing the larger severity of water or wind erosion. Although the estimated severity may not be very accurate at each land unit due to the limited accuracy of the soil erosion formulae, global patterns of erosion possibilities can be described under a unified framework.

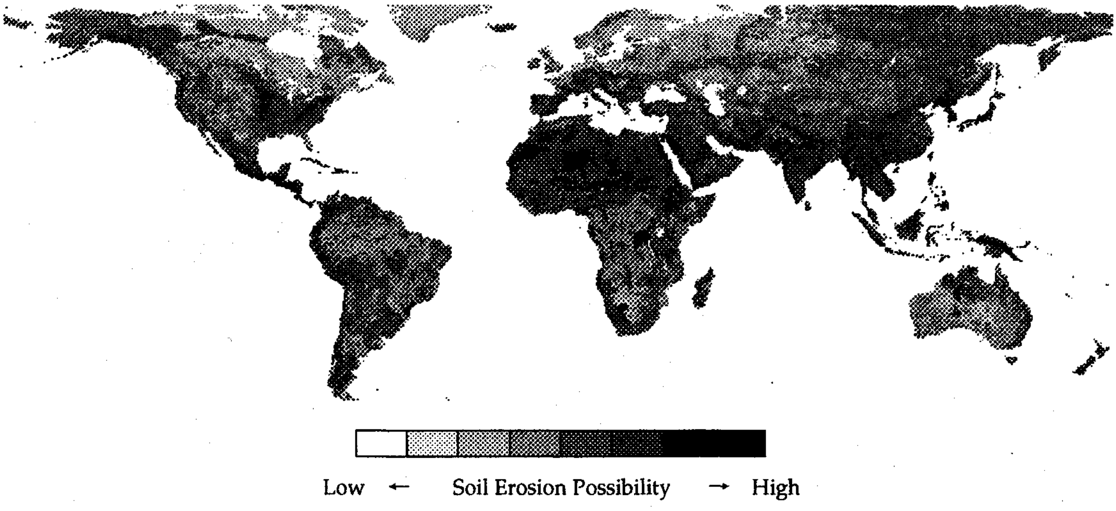


Figure 6. A Global Map of Estimated Soil (Water/Wind) Erosion Possibility

5. Conclusions and Future Prospects

As the results of the analysis on water/wind erosion factors, reasonable relations and statistical significance are revealed between water/wind erosion severity and the climatic, topographic factors and so forth. The possible water/wind erosion are estimated by using formulae obtained through the analysis.

It is considered that the soil erosion possibility can be a useful index in estimating impacts of deforestation, natural factors affecting reforestation cost, farm land conservation cost, cost of agricultural land development, environmental impacts due to land development and so forth. Therefore, by taking into consideration estimated soil erosion possibility, possibility of suitability assessment of forest and agricultural land for the sustainable use can be investigated at the global scale. Shibasaki *et al.* (1995) is an example of the efforts toward this direction. The results of this analysis can provide basic information for better management strategies of terrestrial environmental resources.

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