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LAND EVALUATION FOR RAINFED FARMING

using global terrain information on a 1° longitude x 1° latitude grid

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INTERNATIONAL SOIL REFERENCE AND INFORMATION CENTRE

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CONTENTS

FOREWORD

Staff of ISRIC has prepared a number of small scale digital global data sets containing terrain information on soils, soil moisture regimes and agro ecological zones. The data sets were originally prepared to be used during the Conference "Soils and the Greenhouse Effect", which will be organized by ISRIC in August 1989.

These digital files have however wider, multiple use possibilities. They can be applied to estimate areal extents of soils and soil conditions and to relate this to the actual land cover.

The information present in the data sets is not new. However, since the data can be combined and manipulated in various ways with a computer, be shown on a video screen or plotted, the number of applications has grown in relation to the existing cartographic material.

In this Working Paper one application of the data sets is discussed. It is a land evaluation study, which relates actual land cover with land suitability. The study was carried out at the request of the Rijks Instituut voor Volksgezondheid en Milieuhygiëne (RIVM). The results will be used in the RIVM Integrated Model for the Assessment of the Greenhouse Effect (IMAGE).

Other applications are under consideration, and will be reported upon in the same series of Working Papers.

Dr. W.G. Sombroek
Director

INTRODUCTION

This study was carried out to analyse the suitability of world soils in relation to their land cover type. The first results presented in this Working Paper cover the developing nations of the world. The results will be used in a deforestation simulation model which is being developed at RIVM (The Netherlands) as part of the IMAGE model (Integrated Model for the Assessment of the Greenhouse Effect).

A number of global land evaluation studies have been carried out earlier, but so far no attempt has been made to correlate the lands's suitability to the natural vegetation or land use. The land evaluation method of this study essentially follows the procedure proposed in FAO (1978-1981) and FAO/IIASA/UNFPA (1983). However, since the scale of the basic data used here is smaller, a number of generalizations had to be made. The results were compared with the results of the larger scale studies, and where necessary, the basic assumptions adapted.

To achieve the aim of this land evaluation, i.e. to give estimates of the geographically referenced suitability of the major soils of the developing countries in relation to their land cover, a combination of a number of different digital data sets have been used.

With regard to the land cover, the vegetation and cultivation intensity data sets compiled by Matthews (1983-1985) were used. Matthews' vegetation classification is based on the classification system proposed by Unesco (1973) and its units can therefore be easily interchanged with other systems. Although the concepts are rather different, this data set is quite consistent with statistics such as Lanly (1982).

As for the soils and agro-ecological zones the FAO (1983) map and for soil moisture regimes USDA (1972) have been used in digitized form. The FAO legend of the Soil Map of the World (FAO/Unesco, 1971-1981), on which the FAO (1983) Resource Base map was based, is considered the best system for use at regional and global level.

Finally, a method for estimating soil degradation is proposed. This method considers soil types, crops and rainfall erosion rates.

It must be realized that the data used and the results produced are of a global character. They are based present on a 1^{o} x 1^{o} LON-LAT grid. Their reliability will increase as more detailed data are used for soils, climates and land cover.

MATERIALS USED

a. General

The geographic information on soils, land cover, climates and topography used and their source and original scale is presented in table 1. All data sets were organized in a digital form in a raster format, with each raster cell representing a 1^{o} x 1^{o} longitude-latitude element. The actual size of such a pixel is 111x111 km at the equator. The equation for the area of pixels away from the equator is 111 x 111 x [cos(latitude x pi/180)].

Table 1. Filenames, contents, sources and original scales of the terrain information used.

filename	contents	source	original scale
SOFA.GIS	soils	FAO (1983)	1:25,000,000
AEZ.GIS	agro ecol. zones	FAO (1983)	1:25,000,000*
CLIM.GIS	climates	???**	
SOMO.GIS	moisture regimes	USDA/SCS (1972)	1:50,000,000
		SMSS (1985)	± 1 x 1^{o} grid
		FAO (1978-1981)	1:40,000,000
TOPO.GIS	topography	Rand McNally (1977)	1:110,000,000
MATVEG.GIS	vegetation	Matthews (1983)	1 x 1 ^{o} grid***
MATINT.GIS	land use	Matthews (1983)	1 x 1 ^{o} grid***

* The Agro Ecological Zones on this map are for the developing nations only.

** At the moment of writing this Working Paper no climate classification was selected yet.

*** The Matthews Vegetation and Cultivation Intensity data sets were supplied by UNEP/GRID-Geneva. The files MATVEG.GIS and MATINT.GIS were combined in a file named LCOVER.GIS (see table 2). TOPO.GIS is not operational as yet.

Organization of the files

All (i , j) arrays are (360,180), 1 degree (lon,lat) resolution.
j = 1,180:j = 1: 1 degree band from 90 degrees South to 89 degrees South;
j = 180: 1 degree band from 89 degrees North to 90 degrees North;
i = 1,360:i = 1: 1 degree band from 180 to 179 degrees West;
i = 360: 1 degree band from 179 to 180 degrees east.

Array size

The total size of each data set is thus 180x360=64800 elements. The files in binary code are 64800 bytes in size. They can also be prepared as ASCII files or in any other format. For more details on the organization and contents of the files see the table 2.

Table 2. Description of the global 1 x 1 degree LON-LAT terrain data sets.

File name*	size	type	description of data
SOFA.GIS	360,180	I*2	soils: 1-18 ice : 19; water points : 0
SOMO.GIS	360,180	I*2	soil moisture regimes: 1-6 water points : 0
AEZ.GIS	360,180	I*2	agro-ecological zones: 1-13 water points : 0
LCOVER.GIS	360,180	I*4	natural vegetation : 1-30 ice : 31; water points : 0 100-130 /200-230 / 300-330 /400-430 : units and decades indicate vegetation types (1-30); hundreds:100=20% cultivated; 200= 50% cultivation, 300 and 400 are 75 and 100% cultivation, respectively.

* filenames are the names of the computer-files. For continents separate files were prepared. Each continent file has an additional letter code, e.g. SOFA_AF.GIS is the soil code file for Africa. Additional letter codes are: W= World; AF= Africa; ASI= Asia; AUS= Australia; SEA= Southeast Asia; LA= Latin America; SA= South America; NCA= North and Central America; EU= Europe)

Overlays of data sets and various combinations could be made using software written in Quickbasic Compiler 4.0[1] software; the maps can be visualized on a computer screen using simple GIS or graphics software.

[1] Quickbasic is a trademark of Microsoft Corporation.

b. General characteristics of the major soils considered

The properties of the major Soil Groupings presented on the FAO (1983) map will be discussed below. Literature consulted is Buringh (1979), Young and Wright (1979), FAO/Unesco (1971-1981), USDA (1975) and Fitzpatrick (1983). In table 3 the areas of the 18 FAO Soil Groupings for 6 continents are listed. In table 7 the suitability ratings for two levels of management (inputs) are presented.

1. Acrisols (A)

Characteristics of Acrisols:
- strong acidity;
- high aluminium saturation, low base saturation;
- very low availability of nutrients;
- topsoil organic matter easily lost;
- weak physical structure, high susceptibility to rainfall erosion;
- water may stagnate on the argillic B-horizon, causing impeded internal drainage;
- low in trace elements.

Annual cultivation leads to rapid decomposition of the soil organic matter, and also to rapid structural deterioration, deficiencies of minor and major nutrients. Continued cultivation may lead to compaction and increased danger of water erosion. The required fallow periods are long under low management, with 1-2 years of cultivation followed by 20 or more years of rest. Under high management levels, shorter rest periods under grass or green manure crops are required.

2. Chernozems (C), Phaeozems (H) and Greyzems (M)

* Characteristics of Chernozems:
- inherent fertility good;
- excellent physical structure;
- high available water capacity;
- rich in organic matter;
- calcareous layer within 125 cm;
- moderate to high cation retention capacity.

Chernozems are developed almost exclusively in loess, but they also occur in other sediments. Chernozems are confined largely to continental conditions from Humid Continental to Mid-Latitude steppe. Annual cultivation of these soils leads to rapid loss of soil organic matter. Required fallow periods are short.

* Characteristics of Phaeozems:
- dark organic rich topsoil;
- good structure;
- high available water capacity;
- moderate to high cation retention capacity.

Phaeozems are developed under continental conditions with dry summers; evapotranspiration in summer exceeds precipitation. Therefore Phaeozems are susceptible to droughtiness.

* Greyzems are integrades between Chernozems and Luvisols (see No. 8 below). They are formed in warm continental areas under grassland cover. Topography in general is gently sloping.

3. Podzoluvisols (D) and albic Luvisols (La)

* Characteristics of Podzoluvisols:

- poor drianage;
- moderately acid soil reaction.

Podzoluvisols occur in cool humid continental regions. They are confined to flat or gently sloping areas where moisture can accumulate in the upper part of the soil.

* Characteristics of albic Luvisols

albic Luvisols are Luvisols (see 8 and 9) with a bleached horizon in between the humus rich topsoil and a heavier subsoil. This bleached horizon may exceed 20 cm in thickness. These soils occur in humid climates with a marked dry season. Albic Luvisols are moderately suitable to highly suitable for cropping, depending on the thickness of the above discussed bleached horizon. With high levels of management these soils are always good.

4. Ferralsols (F)

Characteristics of Ferralsols:

- strong acidity;
- very low availability of nutrients;
- high aluminium saturation and low base saturation;
- low cation retention;
- no reserves of weatherable minerals;
- organic matter predominantly in topsoil, is easily lost after cultivation;
- good physical structure and low inherent susceptibility to rainfall erosion.

Annual cultivation of Ferralsols leads to rapid loss of organic matter. Since organic matter is responsible for a great part of the cation retention, the latter will also decrease. Under a high level of management limited rest periods are required to control pests and diseases. Although inherent erodibility of Ferralsols is low, their usually sloping to rolling topography may induce high run off and soil loss rates.

5. Histosols (O) and Gleysols (G)

* Histosols are soils with an organic layer of at least 40 cm thickness. A more common name is peat soils. These soils frequently occur in association with Gleysols and usually have a flat topography. Drainage is a problem common to these soils.

* Gleysols (G) occur on level land, in many cases with a high water table. Their properties, such as texture, physical and chemical properties, vary widely. The Gleysols (and also Fluvisols) in the Amazon basin for example are formed in very poor material deposited by the rivers carrying material derived from very poor eroded Ferralsols, Acrisols and acid rocks. In other regions however, Gleysols and Fluvisols may be among the best soils available if their drainage is well managed. With intermediate and high input levels there is no need for rest periods.

6. Lithosols (I) (in new FAO legend: Leptosols)

The group of lithosols comprises all the soils which are shallow (less than 30 cm deep) independent of the parent rock.

7. Kastanozems (K)
Characteristics of Kastanozems:
- high organic matter content in the topsoil;
- good structure;
- high available water capacity;
- high inherent fertility, high cation retention capacity.

Kastanozems are found predominantly in the middle latitude steppe conditions. Grassland of medium height is their natural vegetation, their overall topography is gently sloping.

8. orthic Luvisols (L) and Cambisols (B)
* Characteristics of Luvisols:
- inherent fertility moderate;
- moderate to high cation retention capacity;
- organic matter content low to moderate;
- physical structure weak in the topsoils, moderate but unstable in the argillic B-horizon;
- moderate to high available water capacity.

They constitute one of the major soils for food production, particularly maize, sorghum, groundnuts, and other foodcrops. At a low input level, a fallow period of about 2 years in 3 is required to keep the soils in a good condition. At high levels of management, the required fallow period is shorter (Young and Wright, 1980).

* Characteristics of Cambisols:
This group of soils comprises a variety of soils in the tropics and temperate regions. The soils range from shallow to moderately shallow soils occurring in cool upland regions (South America) to deep soils in old alluvium in the Ganges flood plain. Generally the organic matter status is moderate to good. With high inputs almost continuous cultivation is possible.

9. Nitosols (N) and ferric Luvisols (L)
* Characteristics of Nitosols:
- moderate to high cation retention;
- nutrient availability high in eutric nitosols, low in dystric nitosols;
- dystric nitosols have a problem of acidity;
- moderately high reserves of weatherable minerals;
- generally higher organic matter levels than in other freely drained soils;
- high available water capacity;
- moderately high erosion hazard.

Nitosols are among the most fertile tropical soils. At low input levels eutric nitosols may well be cultivated for at least 1 out of 2 years, while dystric nitosols need a longer rest period. Nitosols respond well to inputs and under high levels of management they can be continuously cropped.

* Characteristics of Ferric Luvisols: these soils are the tropical lateritic podzolic soils with high base saturation. They are widespread in the tropical savanna zone. They have an horizon with clay illuviation with a moderate but unstable structure. The physical structure is commonly weak in the topsoils. Organic matter content and inherent fertility are moderate.

10. Podzols (P)

Characteristics of Podzols:
- chemically poor;
- good drainage;
- acid soil reaction;
- low cation retention capacity;
- generally low available water capacity.

Podzols are usually formed in coarse to medium textured unconsolidated deposits, often containing a high proportion of boulders and stones. They generally occur in any topographic situation where aerobic conditions prevail and water is allowed to percolate freely through the soil profile. Under high levels of management these soils may be improved a lot. Tropical Podzols occur either in the cold tropics or in the lowland rainforest areas. The latter Podzols are formed in sands and their suitability for cultivation is probably low.

11. Arenosols (Q) and sandy Regosols (R)

Characteristics of both Arenosols and sandy Regosols:
- high sand content;
- low organic matter levels;
- low cation retention and nutrient availability;
- few or no reserves of weatherable minerals;
- rapid permeability, high susceptibility to leaching;
- low available water capacity.

Annual cultivation of these poor soils leads to rapid depletion of the organic matter content. This causes a rapid decline of the cation retention. In humid climates leaching is severe, in semi-arid and arid zones drought hazard is serious. Due to the rapid deterioration the period of sustainable cultivation is short and required fallow periods are long.

12. Chromic Luvisols (Lc) and Cambisols (B)

* Characteristics of chromic Luvisols:
- good physical structure;
- moderate organic matter content;
- moderate to high cation retention and inherent fertility;
- moderate to high available water capacity.

Chromic Luvisols are soils also known under the name Terra Rossa. They are usually soils found in areas with mediterranean conditions. Their potential for agriculture is moderate to high. Generally their susceptibilty to erosion is high. Topography is gently sloping to rolling.

* For a description of Cambisols see soil grouping No.8.

13. Solonchaks (Z) and Solonetz (S)

* Solonchaks are grouped because of their high salinity. They are soils with very little profile development. Due to their salinity they are not suitable for cultivation.

* Solonetz have a natric horizon in common, which is a subsoil with a clay illuviation from the topsoil, having a sodium (Na) saturation of over 15% at the cation exchange complex. The structure in the subsoil is columnar. These soils are considered virtually not suitable for cultivation.

14. Andosols (T)

Characteristics of Andosols:

- good physical structure;
- good drainage;
- high available water capacity;
- high cation retention;
- problems of phosphorous fixation.

Andosols are developed from volcanic ash. They are generally very good soils for cropping when they are well managed. In places Andosols may have fertility problems, usually due to phosphorous fixation. They frequently occur on steep slopes and this feature makes them highly susceptible to erosion. A further property is the phenomenon of thixothropy. Andosols occur in a wide variety of climates and under various vegetation types.

15. Vertisols (V)

Characteristics of Vertisols:

- high nutrient availability;
- relatively high organic matter content;
- high cation -retention;
- low water available capacity;
- slow permeability when wet, leading to low infiltration and high run off.
- soil is very hard when dry, causing problems of cultivation and seedbed preparation.

Vertisols in general have favourable chemical properties, but are problem soils in their physical qualities. Under high levels of management however, some of the physical problems can be overcome and high intensities of cultivation may become possible. Vertisols may be highly suitable for paddy rice cultivation, but lack of drainage may induce salinization.

16 Planosols (W)

Planosols have a slowly permeable subsoils, which may cause problems of drainage. Hydromorphic properties are general, and their topsoils may be of poor physical and chemical properties. Planosols with a leached topsoil are moderately suitable for cultivation, when their topsoil is richer, these soils are good.

17/18 Xerosols (X) and Yermosols (Y) and shifting sands

Xerosols and Yermosols are soils of semi arid (Xerosols) to arid (Yermosols) climatic conditions. Xerosols and Yermosols may be very fertile soils. Due to the lack of rainfall these soils are of little or no value for agriculture. Xerosols usually occur in areas with a growing period of less than 75 days. With irrigation these soils may be classified among the best soils.

19 Ice (non soil)

Table 3. Areas (in 10,000 ha) for the 18 FAO soil groupings and for 6 continents. The total land areas for continents in this table may be slightly different from the totals in table 6 due to discrepancies between the data sets. Ice is not included in this table. The soil codes presented in this table are the same as those in SOFA.GIS.

SOILS	North & Central America	South America	Europe	Africa	Asia (incl.Eur. part of USSR)	Australia & New Zealand	totals
1. Acrisols	13700	59950		5359	43856	3050	125915
2. Chernozems, Phaeozems and Greyzems	8759	4514	1675		22844		37792
3. Podzoluvisols and albic Luvisols	8995				27757		36752
4. Ferralsols		41187		55672	1652	242	98753
5. Histosols and Gleysols	47038	9039	2426	9983	66296	1629	136411
6. Lithosols	18185	13785	2978	27688	143404	4644	210684
7. Kastanozems	23913	5598			23611		53122
8. Orthic Luvisols and cambisols	33337	2283	21823	7484	30132	3756	98815
9. Nitosols and ferric Luvisols	1173			41813	8534		51520
10. Podzols	27571	1109	10431		8780		47891
11. Arenosols and sandy Regosols		7104		40534	4237	19445	71320
12. chromic Luvisols and Cambisols	6235	4800	8237	7532	7538	5465	39807
13. Solonchaks and Solonetz		3130		2002	12894	5241	23267
14. Andosols	3193	6130	1052	123	5558	294	16350
15. Vertisols	3090	2038		9114	8607	11014	33863
16. Planosols	470	4688	261	752	194	2183	8548
17. Xerosols	3539	5236		17546	14466	9614	50401
18. Yermosols and shifting sands	15586	10178		73475	58810	14209	172258
total land area:	214784	180769	48883	299077	489170	80786	1313469

c. Characteristics of the major climates

The FAO (1983) map of Physical Resources and the generalized maps in FAO (1978-1981) were used to compile the climate data set for the developing nations of the world. The major characteristics as well as the major crop groups which are suitable and relevant are in table 4. All data were taken and adapted from FAO/IIASA/UNFPA (1983). So far no climate data set covering the complete globe was selected.

The major Moisture Regimes were taken from the USDA/SCS (1972) moisture regimes map of the world. The main properties and corresponding FAO (1978-1981) definition of length of growing period are given in table 5.

Although the length of the growing period in FAO (1978-1981) and soil moisture regimes in USDA/SCS (1972) are quite different concepts, there is a good similarity between the two generalized maps. An advantage of using the USDA (1972) concepts is that it makes future correlation with the USDA (1975) soil classification system possible.

Table 4. Characteristics of the major climates and relevant crop groups. Adapted from FAO/IIASA/UNFPA (1983). The code given in the table is the same as in the Agro-Ecological Zone (AEZ.GIS) data sets.

No.	descriptive name	mean 24 h daily temperature during the growing period	suitable crop group*
01	tropics, warm	> 20	II,III
02	tropics, cool	5-20	I,IV
03	tropics, cold	< 5	I,IV
04	subtropics, warm, summer rains	> 20	II,III
05	subtropics, cool, summer rains	5-20	I
06	subtropics, cold, summer rains	< 5	I,IV
07	subtropics, cool, winter rains	5-20	I
08	subtropics, cold, winter rains	< 5	I,IV
09	temperate, cool	5-20	I
10	temperate, cold	< 5	I,IV
11	temperate, very cold (permafrost)		none
12	subtropics,summer rains,warm/cool var. combinations		I,II,III
13	temperate, cool/cold in various combinations		I

*crop group I (C3 photosynthesis pathway): spring wheat, winter wheat, highland phaseolus bean, white potato, winter barley.
crop group II (C3 photosynthesis pathway): paddy rice, lowland phaseolus bean, soybean, sweet potato, cassava, upland rice, groundnut, banana/plantain, oil palm.
crop group III (C4 photosynthesis pathway): pearl millet, lowland sorghum, lowland maize, sugar cana.
crop group IV (C4 photosynthesis pathway): highland sorghum, highland maize.

table 5. Soil moisture regimes and corresponding lengths of growing period. The codes given in this table are the same as those used in SOMO.GIS.

Type*	Length of growing period**	Main characteristics[1]
01 wet	> 270	never dry
02 moist	> 270	intermediate between udic and wet
03 udic	210-270	in most years not dry for as long as 90 cumulative days
04 ustic	150-210	dry for 90 or more cumulative days in most years; moist for more than 180 cumulative days or continuously moist for more than 90 consecutive days
05 xeric	90-150	intermediate between ustic and aridic
06 aridic	< 90	dry in all parts more than half of the time; never moist in some or all parts for as long as 90 days

* USDA/SCS (1972); USDA (1975)
** FAO (1978-1981)

d. Vegetation Types

The vegetation data set used in this study is the scheme prepared by Matthews (1983). The vegetation classification basic to Matthews (1983) is the physiognomic vegetation classification by Unesco (1973). Matthews (1983) further prepared a separate data set of the cultivation index. In this study both data sets were combined. The cultivation intensity (given as a class) was separated per pixel into areas of pure cultivation and areas of "natural" or "original" vegetation. The combined data set is present on the LCOVER.GIS file. In table 6 the classes used in LCOVER.GIS are presented for 6 continents separately.

Table 6. Land Cover classification used in LCOVER.GIS. The codes are the same as those present on the computer files except for No. 32 (cultivated area). In this table areas of pure cultivation and "natural" vegetation were separated per pixel using the cultivation intensity figure. In LCOVER.GIS cultivated area is indicated using a coding system as explained in table 2.

Matthews vegetation types	North & Central America	South America	Europe	Africa	Asia (incl.Eur. part of USSR)	Australia & New Zealand	totals
1. tropical evergreen rainforest	2156	68578		20772	29216	1973	122695
2. trop./subtrop.evergr.seas.broadleaved forest	5107	2577		7027	17867	834	33412
3. subtrop. evergr. rainforest		1663				219	1882
4. temperate/subpolar evergreen rainforest		2807				1119	3926
5. temp.evergr.seas. broadleaved forest (summer rain)					7062	1020	8082
6. evergr.broadl. sclerophyll.forest (winter rain)	607		874	314	1059	1845	4699
7. trop./subtrop. evergr.needleleaved forest	359				4493		4852
8. temp./subpolar evergr. needleleaved forest	39080		9068		42904		91052
9. tropical/subtropical drought decid. forest	850	14866	438	779	12305		29238
10. cold deciduous forest with evergreens	14862	742	10190		25248		51042
11. cold deciduous forest without evergreens	4248		2957		32083		39288
12. xeromorphic forest/woodland	3792	21297		1226	764		27079
13. evergreen broadleaved sclerophyllous woodland	324		2102	2039	1984	10552	17001
14. evergreen needleleaved woodland	22582		43		2088		24713
15. trop./subtrop. drought deciduous woodland	767	116	21	32816	3095	238	37053
16. cold deciduous woodland	132				24289		24421
17. evergr.broadleaved shrubland/thicket	811			4863	5639	1709	13022
18. evergr.needleleaved shrubland/thicket	2252		92	207	3726	313	6590
19. drought deciduous shrubland/thicket	5149			1747	1472		8368
20. cold deciduous subalpine/subpolar shrubland	316		945		3294		4555
21. xeromorphic shrubland/dwarf shrubland	8901	14947		18165	29383	16950	88346
22. arctic/alpine tundra and mossy bog	42119		2781		27346		72246
23. grassland(10-40% woody tree cover)	966	19196	22	24876	17388	1775	64223
24. grassland(<10% woody tree or plant cover)	583	9146		13591	3409	8833	35862
25. grassland with shrub cover	5897	3418	455	42663	33155	7426	93014
26. tall grassland	67	3209		4601	123	121	8121
27. medium grassland	2682			2883	706	1620	7891
28. short grassland	6213	11750	296	3277	31445	7432	60413
29. forb formations	2598			123			2721
30. desert	3221	242		81946	57082	12284	154775
31. ice (Not given for individual continents)							163247
32. cultivated area	38907	4317	18601	35276	70547	5083	172731
total land area:	215848	178871	48685	299191	489172	81346	1476560

LAND EVALUATION PROCEDURE

The data sets of soils, climates, moisture regimes are overlayed first to extract the land's final agro-ecological suitability classification. Areas in each suitability class are calculated per land cover type in the last step. The procedure discussed below is followed for each individual pixel.

1. From the agro ecological zone (AEZ.GIS) the suitable crop group is selected.

2. Secondly, the soil group is read from SOFA.GIS. The suitability ratings for the soil groups for two levels of management are presented in table 7. If 2 figures are given for a soil and input level, the most favourable figure is used. If two crop groups are suited, the crop best suited to the climatic conditions and soil (see table 7) is considered in the following steps. In case of climate regions 12 or 13, consisting of various combinations of other climates, the area is divided in 50% suitable for the crop best suited for one climate type and 50% suited for the other climate. It must be stressed here that the ratings in table 7 need further testing and checking.

3. Subsequently, the soil suitability is compared with the moisture regime (SOMO.GIS). A factor for the soil moisture regime is added to the soil rating according to the scheme presented in table 8. Results higher than 4 are reduced to 4. Results for both high and low management levels are determined (see table 7). The resulting figures (2 per pixel) are the agro-ecological suitability classes of the land at two levels of input. They are written to a temporary file to be used in another module which overlays the agro-ecological suitability and the land cover types.

4. Calculation by Land Cover Type. The above results from the temporary file of agro-ecological suitability ratings and the file LCOVER.GIS are overlayed to calculate the agro-ecological suitability per land cover type.

The areas calculated thus for Africa, Latin America (= South + Central America), South America, Southeast Asia, and India- Bangladesh- Nepal-Buthan are presented in the Appendices 1-5, respectively.

Table 7. FAO Major soil groupings (FAO, 1983), and their suitability rating for 2 levels of mangement for the crop groups as defined in FAO/IIASA/UNFPA (1983). Ratings are adapted from FAO (1978-1981). For crop groups see also table 1. l=high management level, l= low management level. The codes for Soil Groupings are the same as those used in SOFA.GIS.

FAO Soil Grouping	Crop Group I		II		III		IV	
	l	h	l	h	l	h	l	h
1 Acrisols	2	1/2	2/3	1/2	2	1/2	3/2	1/2
2 Chernozems-Phaeozems-Greyzems	1	1	1	1	1	1	1	1
3 Podzoluvisols-albic Luvisols	3	2	2	2	2	1	2	2
4 Ferralsols	3	2	2/3	2	2	1	2	1
5 Histosols-Gleysols	2	1	3	3	3	3	3	3
6 Lithosols	3	3	3	3	3	3	3	3
7 Kastanozems	1	1	1	1	1	1	1/2	1/2
8 Orthic Luvisols-Cambisols	1	1	1	1	1	1	1	1
9 Nitosols-Ferric Luvisols	1/2	1	1	1	1	1	1	1
10 Podzols	3	2	2	2	2	1	2	2
11 Arenosols-sandy Regosols	3	3	2/3	2/3	2	1	3	2
12 Chromic Luvisols-Cambisols	1	1	1	1	1	1	1	1
13 Solonchaks-Solonetz	3	3	3	3	3	3	3	3
14 Andosols	1	1	1	1	1	1	1	1
15 Vertisols	2	2	2/3	1/2	2/3	2	2/3	1
16 Planosols	3	2	2	2	2	2	2/3	1/2
17 Xerosols	2	2	1/2	1/2	1	1	1/3	1/3
18 Yermosols-shifting sand	3	3	3	3	3	3	3	3

Table 8. Correction factor for determination of the agro-ecological suitability of land for the 6 soil moisture regimes used.

moisture regime*	management level low				high			
	crop group 1	2	3	4	1	2	3	4
1	3	3	3	3	2	2	2	2
2	0	0	0	0	1	1	0	0
3	1	1	0	0	0	0	0	0
4	2	2	1	1	1	1	0	0
5	3	3	2	2	2	2	2	2
6	3	3	3	3	3	3	3	3

* see table 5.

LAND DEGRADATION

Many soils cannot be continuously cultivated with annual crops without undergoing decline in productivity. As was reported in some of the descriptions of the soil units, cultivation causes a loss of soil organic matter. Cultivation brings about more favourable conditions for microorganisms which decompose the organic matter. Loss of soil organic matter also causes reduction of cation retention capacity. A reduced nutrient retention will increase the danger of leaching of nutrients. Nutrients will also be lost due to soil erosion by wind or by water. Moreover, cultivation in many cases causes soil structure to deteriorate. Young & Wright (1979) give an indication of possible rest period requirements for the 10 major soils of the world.

Here rainfall erosion is considered to determine the long term land suitability. The rate of soil loss is greatly influenced by climate, land use and the soil conditions. The erosion model proposed here is a simplified version of the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978):

$$A = R \times K \times S \times L \times C \times P \quad (1)$$
$$K = 2.73 \times t^{1.14} (10^{-6}) \quad (2)$$
$$t = (\%\ silt) \times (100 - \%\ clay); \quad (3)$$
$$S = (0.65s^2 + 0.454s + 6.5) \times (10^{-2}) \text{ for } s < 20\% \quad (4)$$
$$S = (s/9)^{1.35} \text{ for } s > 20\% \quad (5)$$
$$L = (l/22.2)^{0.5} \quad (6)$$

where:
- A = soil loss ($0.1\ kg\ m^{-2} = T\ ha^{-1}$);
- R = Rainfall erosivity (index);
- K = soil erodibility ($0.1\ kg\ m^{-2}$);
- S = slope factor (no dimension);
- L = slope length factor (no dimension);
- C = crop factor (no dimension);
- P = soil conservation factor (no dimension);
- l = slope length (m);
- s = slope gradient (%);

USLE uses parameters for rainfall erosivity, soil erodibility, topography, land use and soil conservation. The proposed values for the rainfall erosivity in relation to the Soil Moisture Regime are presented in table 9. The soil erodibility depends on the topsoil characterisitics and the soil's permeability. Slopes can be derived from the original soil maps (FAO, 1971-1981). Slope lengths may be assumed to have a constant value of 100 m everywhere. The proposed values of the conservation factor and the crop factor for the 4 crop groups in dependance of the input level are shown in table 10. With the above method the annual soil loss can be estimated for the 1 x 1° LON-LAT pixels. The relationship between soil loss and long term suitability is given in table 11.

The method described here is only a proposal. It was not applied as yet. In future it may be chained to the IMAGE deforestation model in a dynamic way, so as to simulate decline in productivity in different scenarios for different regions.

Table 9. Rainfall erosivity (R) in relation to the major Soil Moisture Regimes defined in table 5.

code	R
01	1500
02	1250
03	1000
04	900
05	800
06	700

Table 10. Crop factors (C) and soil conservation factors (P) in relation to the input level and crop group.

		C			
input level	P	crop group(see table 4) 1	2	3	4
low	1	0.6	0.7	0.6	0.6
high	0.5	0.2	0.4	0.4	0.3

Table 11. Long term relation between soil loss and decrease of land's suitability for cultivation.

rate of soil loss (0.1 kg $m^{-2}y^{-1}$)	change in suitability
<12	no change
12 - 50	50% downgrades by 1 class; 50% remains unchanged
50 - 100	100% downgrades by 1 class
100- 200	50% downgrades to class 4 (not suitable); 50% downgrades by 1 class
>200	100% downgrades to class 4 (not suitable)

Source: FAO/IIASA/UNFPA (1983).

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Appendix 1 Results for Africa

very Small Scale Land Evaluation Model
Output for Africa
01-27-1989
land suitability per land cover type
All figures are presented in 10,000 ha
A.F. Bouwman (1989). Working Paper and Preprint 89/1 , ISRIC, Wageningen

Land suitability classes:
1 = high suitablility
2 = moderate suitability
3 = low suitability
4 = very low suitability (marginal land)

vegetation type	suitability class for relevant crops low input level 1	2	3	4	high input level 1	2	3	4	total
1 tropical evergreen rainforest	0	2383	13793	4400	2873	14959	122	2622	20576
2 trop./subtrop.evergr.seas.broadleaved forest	86	1093	5111	733	2551	3739	516	216	7023
3 subtrop. evergr. rainforest	0	0	0	0	0	0	0	0	0
4 temperate/subpolar evergreen rainforest	0	0	0	0	0	0	0	0	0
5 temp.evergr.seas. broadleaved forest (summer	0	0	0	0	0	0	0	0	0
6 evergr.broadl. sclerophyll.forest (winter ra	0	0	0	82	0	0	82	0	82
7 trop./subtrop. evergr.needleleaved forest	0	0	0	0	0	0	0	0	0
8 temp./subpolar evergr. needleleaved forest	0	0	0	0	0	0	0	0	0
9 tropical/subtropical drought decid. forest	0	187	181	406	187	587	0	0	775
10 cold deciduous forest with evergreens	0	0	0	0	0	0	0	0	0
11 cold deciduous forest without evergreens	0	0	0	0	0	0	0	0	0
12 xeromorphic forest/woodland	0	218	0	1010	218	0	97	913	1229
13 evergreen broadleaved sclerophyllous woodlan	0	587	572	657	939	316	192	369	1816
14 evergreen needleleaved woodland	0	0	0	0	0	0	0	0	0
15 trop./subtrop. drought deciduous woodland	0	8906	11371	12480	9707	16675	1753	4623	32757
16 cold deciduous woodland	0	0	0	0	0	0	0	0	0
17 evergr.broadleaved shrubland/thicket	0	509	120	3928	509	120	332	3597	4557
18 evergr.needleleaved shrubland/thicket	0	0	0	104	0	0	0	104	104
19 drought deciduous shrubland/thicket	0	615	122	1004	615	122	0	1004	1742
20 cold deciduous subalpine/subpolar shrubland	0	0	0	0	0	0	0	0	0
21 xeromorphic shrubland/dwarf shrubland	89	1997	809	15023	3311	1421	993	12194	17919
22 arctic/alpine tundra and mossy bog	0	0	0	0	0	0	0	0	0
23 grassland(10-40% woody tree cover)	0	6261	10195	8212	7139	13799	1005	2725	24668
24 grassland(<10% woody tree or plant cover)	0	6044	6342	885	6335	6146	136	653	13271
25 grassland with shrub cover	797	7169	2171	32032	9820	6370	1005	24974	42169
26 tall grassland	0	356	1381	2872	990	1596	1735	288	4608
27 medium grassland	27	1716	0	1133	1743	0	0	1133	2876
28 short grassland	0	574	913	1793	574	972	170	1565	3280
29 forb formations	0	0	0	123	0	0	0	123	123
30 desert	0	120	0	82075	310	0	0	81835	82195
31 ice	0	0	0	0	0	0	0	0	0
32 cultivated area	214	9649	11393	12775	12872	13705	2369	5085	34031

total area: 295800

Appendix 2 Results for Latin America

very Small Scale Land Evaluation Model
Output for Latin America
01-27-1989
land suitability per land cover type
All figures are presented in 10,000 ha
A.F. Bouwman (1989). Working Paper and Preprint 89/1 , ISRIC, Wageningen

Land suitability classes:
1 = high suitablility
2 = moderate suitability
3 = low suitability
4 = very low suitability (marginal land)

vegetation type	suitability class for relevant crops								
	low input level				high input level				
	1	2	3	4	1	2	3	4	total
1 tropical evergreen rainforest	0	2899	54543	12248	39569	18851	6793	4477	69690
2 trop./subtrop.evergr.seas.broadleaved forest	0	2408	2186	1374	4826	442	466	234	5968
3 subtrop. evergr. rainforest	0	556	128	961	556	778	108	204	1646
4 temperate/subpolar evergreen rainforest	0	1148	0	1324	1148	0	1324	0	2472
5 temp.evergr.seas. broadleaved forest (summer	0	0	0	0	0	0	0	0	0
6 evergr.broadl. sclerophyll.forest (winter ra	0	0	0	0	0	0	0	0	0
7 trop./subtrop. evergr.needleleaved forest	0	60	0	0	60	0	0	0	60
8 temp./subpolar evergr. needleleaved forest	0	0	0	0	0	0	0	0	0
9 tropical/subtropical drought decid. forest	0	864	6635	7454	4429	8703	490	1330	14953
10 cold deciduous forest with evergreens	0	357	0	370	357	0	370	0	728
11 cold deciduous forest without evergreens	0	0	0	0	0	0	0	0	0
12 xeromorphic forest/woodland	0	8408	6469	8402	10471	6617	1085	5106	23279
13 evergreen broadleaved sclerophyllous woodlan	0	0	0	106	0	0	0	106	106
14 evergreen needleleaved woodland	0	1862	0	557	1978	0	0	441	2419
15 trop./subtrop. drought deciduous woodland	0	331	0	558	331	0	113	445	889
16 cold deciduous woodland	0	0	0	0	0	0	0	0	0
17 evergr.broadleaved shrubland/thicket	0	0	0	317	0	0	0	317	317
18 evergr.needleleaved shrubland/thicket	0	0	0	0	0	0	0	0	0
19 drought deciduous shrubland/thicket	0	573	113	213	573	113	0	213	899
20 cold deciduous subalpine/subpolar shrubland	0	0	0	0	0	0	0	0	0
21 xeromorphic shrubland/dwarf shrubland	0	2992	240	16826	2992	0	1568	15497	20057
22 arctic/alpine tundra and mossy bog	0	0	0	0	0	0	0	0	0
23 grassland(10-40% woody tree cover)	0	219	11817	7180	2151	14237	470	2359	19217
24 grassland(<10% woody tree or plant cover)	0	985	5146	3040	5032	2316	973	851	9172
25 grassland with shrub cover	0	1033	793	1769	1462	1922	0	211	3595
26 tall grassland	0	1289	480	1411	1523	613	917	126	3180
27 medium grassland	0	114	0	0	114	0	0	0	114
28 short grassland	594	2329	955	8880	3045	0	3422	6289	12757
29 forb formations	0	0	0	0	0	0	0	0	0
30 desert	0	0	0	237	0	0	237	0	237
31 ice	0	0	0	0	0	0	0	0	0
32 cultivated area	0	4307	775	1851	4652	1075	662	544	6933

total area: 198687

Appendix 3 Results for South America

very Small Scale Land Evaluation Model
Output for South America
01-27-1989
land suitability per land cover type
All figures are presented in 10,000 ha
A.F. Bouwman (1989). Working Paper and Preprint 89/1 , ISRIC, Wageningen

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Land suitability classes:
1 = high suitablility
2 = moderate suitability
3 = low suitability
4 = very low suitability (marginal land)

vegetation type	suitability class for relevant crops								
	low input level				high input level				
	1	2	3	4	1	2	3	4	total
1 tropical evergreen rainforest	0	1333	54309	12248	38004	18617	6793	4477	67890
2 trop./subtrop.evergr.seas.broadleaved forest	0	0	1588	793	1588	442	117	234	2381
3 subtrop. evergr. rainforest	0	556	128	961	556	778	108	204	1646
4 temperate/subpolar evergreen rainforest	0	1148	0	1324	1148	0	1324	0	2472
5 temp.evergr.seas. broadleaved forest (summer	0	0	0	0	0	0	0	0	0
6 evergr.broadl. sclerophyll.forest (winter ra	0	0	0	0	0	0	0	0	0
7 trop./subtrop. evergr.needleleaved forest	0	0	0	0	0	0	0	0	0
8 temp./subpolar evergr. needleleaved forest	0	0	0	0	0	0	0	0	0
9 tropical/subtropical drought decid. forest	0	718	6401	7454	4283	8469	490	1330	14573
10 cold deciduous forest with evergreens	0	357	0	370	357	0	370	0	728
11 cold deciduous forest without evergreens	0	0	0	0	0	0	0	0	0
12 xeromorphic forest/woodland	0	7275	6355	6772	9086	6502	830	3984	20402
13 evergreen broadleaved sclerophyllous woodlan	0	0	0	0	0	0	0	0	0
14 evergreen needleleaved woodland	0	0	0	0	0	0	0	0	0
15 trop./subtrop. drought deciduous woodland	0	0	0	116	0	0	0	116	116
16 cold deciduous woodland	0	0	0	0	0	0	0	0	0
17 evergr.broadleaved shrubland/thicket	0	0	0	0	0	0	0	0	0
18 evergr.needleleaved shrubland/thicket	0	0	0	0	0	0	0	0	0
19 drought deciduous shrubland/thicket	0	0	0	0	0	0	0	0	0
20 cold deciduous subalpine/subpolar shrubland	0	0	0	0	0	0	0	0	0
21 xeromorphic shrubland/dwarf shrubland	0	2673	240	11153	2673	0	1347	10046	14066
22 arctic/alpine tundra and mossy bog	0	0	0	0	0	0	0	0	0
23 grassland(10-40% woody tree cover)	0	219	11817	7073	2151	14237	470	2251	19109
24 grassland(<10% woody tree or plant cover)	0	956	5146	3040	5003	2316	973	851	9143
25 grassland with shrub cover	0	1033	793	1558	1462	1922	0	0	3384
26 tall grassland	0	1289	480	1411	1523	613	917	126	3180
27 medium grassland	0	0	0	0	0	0	0	0	0
28 short grassland	594	1789	955	8206	2506	0	3287	5751	11544
29 forb formations	0	0	0	0	0	0	0	0	0
30 desert	0	0	0	237	0	0	237	0	237
31 ice	0	0	0	0	0	0	0	0	0
32 cultivated area	0	1928	775	1510	2190	1075	489	460	4214

total area: 175083

Appendix 4 Results for Southeast Asia

very Small Scale Land Evaluation Model
Output for
South and Southeast Asia (Bangladesh-Bhutab-Birma-India-Indonesia-Kampuchea-Laos-Malaysia-Nepal-Papua New Guinea-Phillipines-Singapore-Sri Lanka-Thailand-Vietnam)
06-19-1989
land suitability per land cover type
All figures are presented in 10,000 ha
A.F. Bouwman (1989). Working Paper and Preprint 89/1 , ISRIC, Wageningen

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Land suitability classes:
1 = high suitablility
2 = moderate suitability
3 = low suitability
4 = very low suitability (marginal land)

vegetation type	suitability class for relevant crops								
	low input level				high input level				
	1	2	3	4	1	2	3	4	total
1 tropical evergreen rainforest	965	5444	15760	4047	18936	3232	2149	1898	26216
2 trop./subtrop.evergr.seas.broadleaved forest	0	2522	7351	2638	9900	58	2188	366	12511
3 subtrop. evergr. rainforest	0	0	0	0	0	0	0	0	0
4 temperate/subpolar evergreen rainforest	0	0	0	0	0	0	0	0	0
5 temp.evergr.seas. broadleaved forest (summer	0	0	0	0	0	0	0	0	0
6 evergr.broadl. sclerophyll.forest (winter ra	0	0	0	0	0	0	0	0	0
7 trop./subtrop. evergr.needleleaved forest	0	318	0	315	318	0	213	103	634
8 temp./subpolar evergr. needleleaved forest	0	0	0	104	0	0	0	104	104
9 tropical/subtropical drought decid. forest	0	6065	1363	4635	9749	582	1318	415	12063
10 cold deciduous forest with evergreens	0	0	0	0	0	0	0	0	0
11 cold deciduous forest without evergreens	0	0	0	0	0	0	0	0	0
12 xeromorphic forest/woodland	0	554	0	200	728	0	26	0	754
13 evergreen broadleaved sclerophyllous woodlan	0	0	0	120	0	0	120	0	120
14 evergreen needleleaved woodland	0	0	0	0	0	0	0	0	0
15 trop./subtrop. drought deciduous woodland	0	193	1944	601	1524	893	0	322	2739
16 cold deciduous woodland	0	0	0	0	0	0	0	0	0
17 evergr.broadleaved shrubland/thicket	0	0	296	119	296	0	0	119	414
18 evergr.needleleaved shrubland/thicket	0	0	0	0	0	0	0	0	0
19 drought deciduous shrubland/thicket	0	27	0	424	27	0	157	267	451
20 cold deciduous subalpine/subpolar shrubland	0	0	0	0	0	0	0	0	0
21 xeromorphic shrubland/dwarf shrubland	0	0	0	247	0	27	0	219	247
22 arctic/alpine tundra and mossy bog	0	0	0	0	0	0	0	0	0
23 grassland(10-40% woody tree cover)	0	204	225	0	429	0	0	0	429
24 grassland(<10% woody tree or plant cover)	0	0	0	0	0	0	0	0	0
25 grassland with shrub cover	0	0	59	59	59	0	0	59	119
26 tall grassland	0	0	0	120	0	0	120	0	120
27 medium grassland	0	0	0	111	0	0	0	111	111
28 short grassland	0	107	0	1361	107	0	629	731	1467
29 forb formations	0	0	0	0	0	0	0	0	0
30 desert	0	0	0	1049	0	107	0	942	1049
31 ice	0	0	0	0	0	0	0	0	0
32 cultivated area	0	8981	3378	9079	14195	1477	2113	3652	21437

total area: 80984

Appendix 5 Results for India, Sri Lanka, Bangladesh, Nepal and Bhutan.

very Small Scale Land Evaluation Model
Output for India-Bangladesh-Bhutan-Nepal-Sri Lanka
06-19-1989
land suitability per land cover type
All figures are presented in 10,000 ha
A.F. Bouwman (1989). Working Paper and Preprint 89/1 , ISRIC, Wageningen

Land suitability classes:
1 = high suitablility
2 = moderate suitability
3 = low suitability
4 = very low suitability (marginal land)

vegetation type	suitability class for relevant crops								
	low input level				high input level				
	1	2	3	4	1	2	3	4	total
1 tropical evergreen rainforest	0	0	96	0	96	0	0	0	96
2 trop./subtrop.evergr.seas.broadleaved forest	0	1671	751	2016	2507	0	1576	355	4439
3 subtrop. evergr. rainforest	0	0	0	0	0	0	0	0	0
4 temperate/subpolar evergreen rainforest	0	0	0	0	0	0	0	0	0
5 temp.evergr.seas. broadleaved forest (summer	0	0	0	0	0	0	0	0	0
6 evergr.broadl. sclerophyll.forest (winter ra	0	0	0	0	0	0	0	0	0
7 trop./subtrop. evergr.needleleaved forest	0	318	0	421	318	0	213	208	739
8 temp./subpolar evergr. needleleaved forest	0	0	0	104	0	0	0	104	104
9 tropical/subtropical drought decid. forest	0	4889	0	4127	7791	0	868	357	9016
10 cold deciduous forest with evergreens	0	0	0	0	0	0	0	0	0
11 cold deciduous forest without evergreens	0	0	0	0	0	0	0	0	0
12 xeromorphic forest/woodland	0	554	0	200	728	0	26	0	754
13 evergreen broadleaved sclerophyllous woodlan	0	0	0	0	0	0	0	0	0
14 evergreen needleleaved woodland	0	0	0	0	0	0	0	0	0
15 trop./subtrop. drought deciduous woodland	0	193	0	391	472	0	0	111	583
16 cold deciduous woodland	0	0	0	0	0	0	0	0	0
17 evergr.broadleaved shrubland/thicket	0	0	0	0	0	0	0	0	0
18 evergr.needleleaved shrubland/thicket	0	0	0	0	0	0	0	0	0
19 drought deciduous shrubland/thicket	0	27	0	424	27	0	157	267	451
20 cold deciduous subalpine/subpolar shrubland	0	0	0	0	0	0	0	0	0
21 xeromorphic shrubland/dwarf shrubland	0	0	0	247	0	27	0	219	247
22 arctic/alpine tundra and mossy bog	0	0	0	0	0	0	0	0	0
23 grassland(10-40% woody tree cover)	0	0	0	0	0	0	0	0	0
24 grassland(<10% woody tree or plant cover)	0	0	0	0	0	0	0	0	0
25 grassland with shrub cover	0	0	0	0	0	0	0	0	0
26 tall grassland	0	0	0	0	0	0	0	0	0
27 medium grassland	0	0	0	111	0	0	0	111	111
28 short grassland	0	107	0	1466	107	0	629	837	1573
29 forb formations	0	0	0	0	0	0	0	0	0
30 desert	0	0	0	1049	0	107	0	942	1049
31 ice	0	0	0	0	0	0	0	0	0
32 cultivated area	0	6767	390	7867	10047	425	2008	2545	15024

total area: 34187