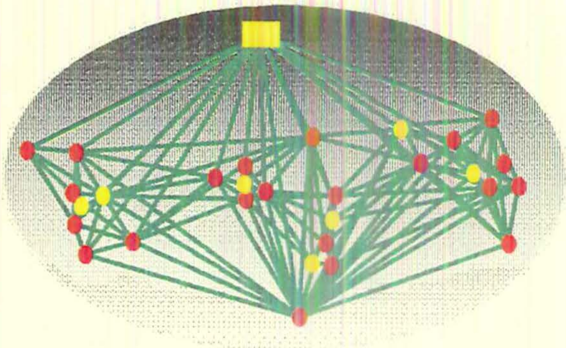

Workshop on

NATIONAL SOIL REFERENCE COLLECTIONS AND DATABASES (NASREC)

Wageningen, The Netherlands
November 6-17, 1995

Proceedings:
Volume 2 — Use of ISRIC's databases for the characterization of soils of major agroecological zones

Edited by
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GLOSSARY

Acronyms

CTA	Centre Technique de Coopération Agricole et Rurale
DGIS	Directorate General for International Cooperation
EC-STD	Science and Technology for Development Programme of the European Community
FAO	Food and Agriculture Organization of the United Nations
GLASOD	Global Assessment of Soil Degradation
IBSRAM	International Board for Soil Research Management
IIASA	International Institute of Applied Systems Analyses
ISIS	ISRIC Soil Information System
ISNAR	International Service for National Agricultural Research
ISRIC	International Soil Reference and Information Centre
SOTER	World Soils and Terrain Digital Database
STRESS	Land quality assessment program
SWEAP	Soil Water Erosion Assessment program
WISE	World Inventory of Soil Emissions Potentials

Abbreviations for major soil groupings

ACRI	Acrisols
AREN	Arenosols
CAMB	Cambisols
FERR	Ferralsols
LUVI	Luvisols
NITO	Nitosols
PHAE	Phaeozems
PLAN	Planosols
PODZ	Podzols
VERT	Vertisols

Other symbols

CEC	Cation Exchange Capacity
ETp	Potential Evapotranspiration (Penman)
LR	Leaching Rainfall
SOC	Soil Organic Carbon
$\bar{x}$	Arithmetic mean
s	Standard deviation
Pg	Petagram (10^{15} g)

PREFACE

During the last decade three soil databases have been developed at ISRIC, viz. ISIS (ISRIC Soil Information System), SOTER (Soil and Terrain Digital Database) and WISE (World Inventory of Soil Emission Potentials). On the occasion of the NASREC Workshop it was decided to present some initial applications of these three databases in the form of a background document to the workshop.

ISIS was developed in 1985 to store the information of ISRIC's soil reference collection, comprising field and analytical information on reference soils from all over the world, with special attention to those from the tropics and sub-tropics. The ISIS database has also been used by soil institutions establishing a National Soil Reference Collection (NASREC) in 15 countries in the period 1986 to 1994. Part I of this volume presents of a correlation study of 324 reference soils of the humid and seasonally dry (sub)tropics, based on ISIS data.

Comprehensive information on reference soils accompanied by good quality data — based on standard methodologies — is becoming increasingly important for modelling at the regional and global level, for instance in relation to climate change. Uniform and quality controlled datasets such as ISIS fulfil an essential role in the verification of heterogenous national soil datasets, in the development of pedotransfer functions as well as the testing and calibration of application programs. Global environmental research requires a larger number of soil profiles than is currently available in ISIS. Therefore the World Inventory of Soil Emissions Potentials (WISE) project was initiated by ISRIC, aiming at a geographic quantification of soil factors that control processes of global change. Part II is a characterization of Ferralsols based on the WISE database.

Although remaining the best available source on world soil resources, the 1:5 million scale FAO-Unesco Soil Map of the World is partly out-dated. Thus, in addition to FAO's own activities, a long-term effort to update the information on the world distribution of soils was initiated in 1986 by the International Society of Soil Science (ISSS): the World Soils and Terrain Digital Database (SOTER) project. SOTER is being implemented in a series of regional projects, executed by national soil institutions, with the support of ISRIC, UNEP and FAO. Part III introduces the SOTER methodology, with examples of applications for Kenya.

Sponsorship for the NASREC workshop was received from the Netherlands Directorate General for International Cooperation (DGIS), the International Service for National Agricultural Research (ISNAR), the Centre Technique de Coopération Agricole et Rurale (CTA), The European Community (EC), and the Food and Agriculture Organization of the United Nations (FAO).

PART I

SOILS OF THE HUMID AND SEASONALLY DRY (SUB)TROPICS

SOILS OF THE HUMID AND SEASONALLY DRY (SUB)TROPICS: A correlation of reference soil data and their assessment for agriculture using the ISIS database

J.H. Kauffman, S. Mantel and O.C. Spaargaren

ABSTRACT

Selected properties of 148 soil profiles of the humid tropics and 176 profiles of the seasonally dry (sub)tropics are analyzed. General environmental characteristics, physical, chemical and mineralogical soil data have been derived from ISIS, the ISRIC Soil Information System. The humid zone includes 6 dominant soil units: Acrisols, Arenosols, Cambisols, Ferralsols, Luvisols and Podzols. Podzols excluded, the seasonally dry (sub)tropics include 4 additional dominant soil units: Nitosols, Phaeozems, Planosols and Vertisols. For these soil units the arithmetic mean and standard deviation of selected key analytical properties, relevant for agronomic and ecological research, are presented for a standardized topsoil and subsoil. In addition, their major agronomic constraints were assessed. About 63 % of the humid tropics and 32 % of the seasonally dry (sub)tropics comprises Acrisols, Arenosols, Ferralsols and Podzols of low natural fertility, thus presenting various limitations when forests are cleared for (low input) arable farming. A low plant nutrient content, a low nutrient retention capacity and a high toxic exchangeable aluminium content are major constraints. The overall data presented in this paper show that Ferralsols and Acrisols, covering 57 % of the humid tropics, have rather similar key properties. The taxonomic separation is principally based on a relatively small increase in clay content, which will not determine the major vegetation type or crop productivity level. It is proposed that attention should be given to differentiating important chemical and physical properties. The study illustrates the usefulness of the ISIS database to correlate soil characteristics and to determine agronomic-ecological constraints of major soils groups.

1 INTRODUCTION

When the International Soil Reference and Information Centre (ISRIC) was established in 1966, its main task was to collect soil profiles, soil samples and associated information representative of the legend units of the FAO-Unesco Soil Map of the World (FAO, 1974). Suitable sites were selected with the national institutions concerned. The main selection criterion was the representativeness of a major soil type within any particular country. Furthermore, specific soil and land use features were taken into account such as sites with original vegetation

National Soil Reference Collections and Databases (NASREC — Vol. 2)
Edited by J.H. Kauffman

versus cleared land. At present, ISRIC's soil reference collection holds over 900 soils from 64 countries of which the data of about 600 soils have been stored in the ISIS database (ISRIC, 1993, 1995). Reference soils have a comprehensive set of soil and environmental data, which are stored in a relational database system, ISIS (Van Waveren and Bos, 1988). For a part of the reference soils these data have been published in a series of 'Country Reports', which are available for 13 countries (ISRIC, 1994, 1995). Additional information on these reference soils is provided in a series of 'Soil Briefs' which discuss the formation, characterisation and agricultural suitability of one or more related soils in their agro-ecological setting.

From the 600 reference profiles in ISIS, 324 are located in the humid tropics and the seasonally dry (sub)tropics. This number is considered sufficient to make a statistical analysis of major soil groups in these zones, of which the results are presented and discussed in this paper. The first results of the analysis of soils in the humid tropics were presented at the Third Conference on Forest Soils in Indonesia (Kauffman *et al.*, 1995). Similar studies will be made for the other major ecological zones (arid, the high mountain and the temperate zones) once the ISIS database for these regions has been completed. The results from this study should be seen as provisional, being a first exploration of the potential of the ISIS database for soil characterization.

2 MATERIALS AND METHODS

2.1 ISIS dataset, field and analytical methods

Data collected for ISRIC's soil reference collection are stored in the relational database management system ISIS (Van Waveren and Bos, 1988), which later formed the basis for developing the FAO-ISRIC Soil Database (FAO, 1989).

Version 4.0 of ISIS, which is written in dBase IV, permits handling and analysis of:

- Site data, which include about 60 mainly descriptive (coded) attributes on location, geology, landform, soil surface properties, hydrology, land use and vegetation.
- Quantitative synoptic climatic data from meteorological stations that are considered representative for the conditions prevailing at the profile site.
- Profile data, including:
  - soil profile descriptions based on FAO guidelines (FAO, 1977 and 1990).
  - soil classification according to the legend of the FAO-Unesco Soil Map of the World (FAO, 1974 and 1988), USDA Soil Taxonomy (Soil Survey Staff, 1992) and the national system.
  - physical, chemical and mineralogical attributes per soil horizon.

In the field, soil horizons were described and sampled in pits of about 2 m depth. Deeper layers were sampled using a soil auger to a maximum depth of 6 m in some cases. The effective, or 'rootable', soil depth was observed in the soil pits. It is > 2.0 m for 90 % of the upland sites studied, while for the other soils it ranges between 0.5 and 2.0 m. Rootable depth is limited by physical root barriers such as hard rock, hard pans, high permanent water table, or by chemical hindrance such as low content of one or more macro or micro nutrients, or toxic levels of exchangeable aluminium.

Chemical, physical and mineralogical data of ISRIC's soil collection were determined by ISRIC's laboratory, using standardized analytical and quality assurance procedures (Van Reeuwijk, 1993). The following 'key soil properties', frequently used in agricultural land use assessment and soil vegetation/bio-diversity research, were selected from ISIS for statistical analysis:

Chemical properties
- Soil reaction (pH-H_2O in 1:2.5 soil-water solution, and pH-KCl in 1 *M* KCl solution)
- Organic carbon (%, Walkley Black procedure)
- Organic nitrogen (micro Kjehldahl procedure)
- Sum of exchangeable bases (percolation with 1 *M* ammonium acetate buffered at pH 7)
- Exchangeable aluminium (extraction with 1 *M* KCl)
- Cation Exchange Capacity (CEC, 1 *M* ammonium acetate buffered at pH 7)
- Base saturation percentage

Physical properties
- Particle size distribution. Sand fractions (2000-1000, 1000-500, 500-250, 250-100, 100-50 μm) were determined by sieving. The silt fractions (50-20 and 20-2 μm) and clay fraction (<2 μm) were determined by pipetting from a sedimentation cylinder.
- pF or soil moisture retention data were obtained from undisturbed core-samples equilibrated with water at various tensions or pF values. The following parameters were derived: a) bulk density; b) Potential Rootable Pore Volume, calculated as pF 0 - pF 2.0, in volume percent; and c) Potential Plant Available Moisture, calculated as pF 2.0 - pF 4.2, in volume percent.

In this paper most analytical results are presented for a standardized topsoil and subsoil; if no specific depth ranges are given in the text the topsoil refers to the depth range from 0 to 20 cm while for the subsoil it is from 70 to 100 cm. Statistical analyses were made with a commercially available software package (Statistix, 1994).

2.2 Ecological zones

The use of major climatic and soil-ecological zones for correlation of agricultural research is being promoted by several international agencies, such as the Food and Agriculture Organisation of the United Nations (FAO, 1978-1981), the Consultative Group of International Agricultural Research (CGIAR, 1992), and the International Board for Soil Research and Management (IBSRAM) (Greenland *et al.*, 1994). ISRIC applies the concept of major ecological zones in projects such as NASREC and SOTER.

Altitude, Length of Growing Period (LGP according to FAO, 1978 - 1981) and average monthly temperature are the criteria used for the definition of the ecological zones; this coincides broadly with Köppen's climate classes (Table 1).

Table 1 Definition of major ecological zones

Zones	LGP[1)]	Altitude (m)	Köppen
Humid Tropics	270 - 365 d P[2)] > 1500 mm yr^{-1}	0 - 1000	Af and Am
Seasonally dry (sub)tropics	120 - 270 d	0 - 2000	Aw and Cw [3)]

1) LGP = Length of Growing Period
2) P is precipitation
3) The Köppen C-climates subdivision into Sub-tropics and Temperate zones is based on 8 - 12 months with an average temperature of more than 18 °C (according to Trewartha, 1968)

FAO, in cooperation with IIASA and ISRIC, is preparing a series of up-dated small-scale world climatic maps based on the IIASA climate database (Leemans and Cramer, 1991) and Length-of-Growing-Period concept (de Pauw *et al.*, 1996). Provisional results, presented on a 30 minute global terrestrial grid, include maps of Length of Growing Period, the annual precipitation, the annual evapotranspiration and the thermal regimes of the world (see maps 1 to 4).

2.3 Distribution of ISIS soil reference profiles over the ecological zones

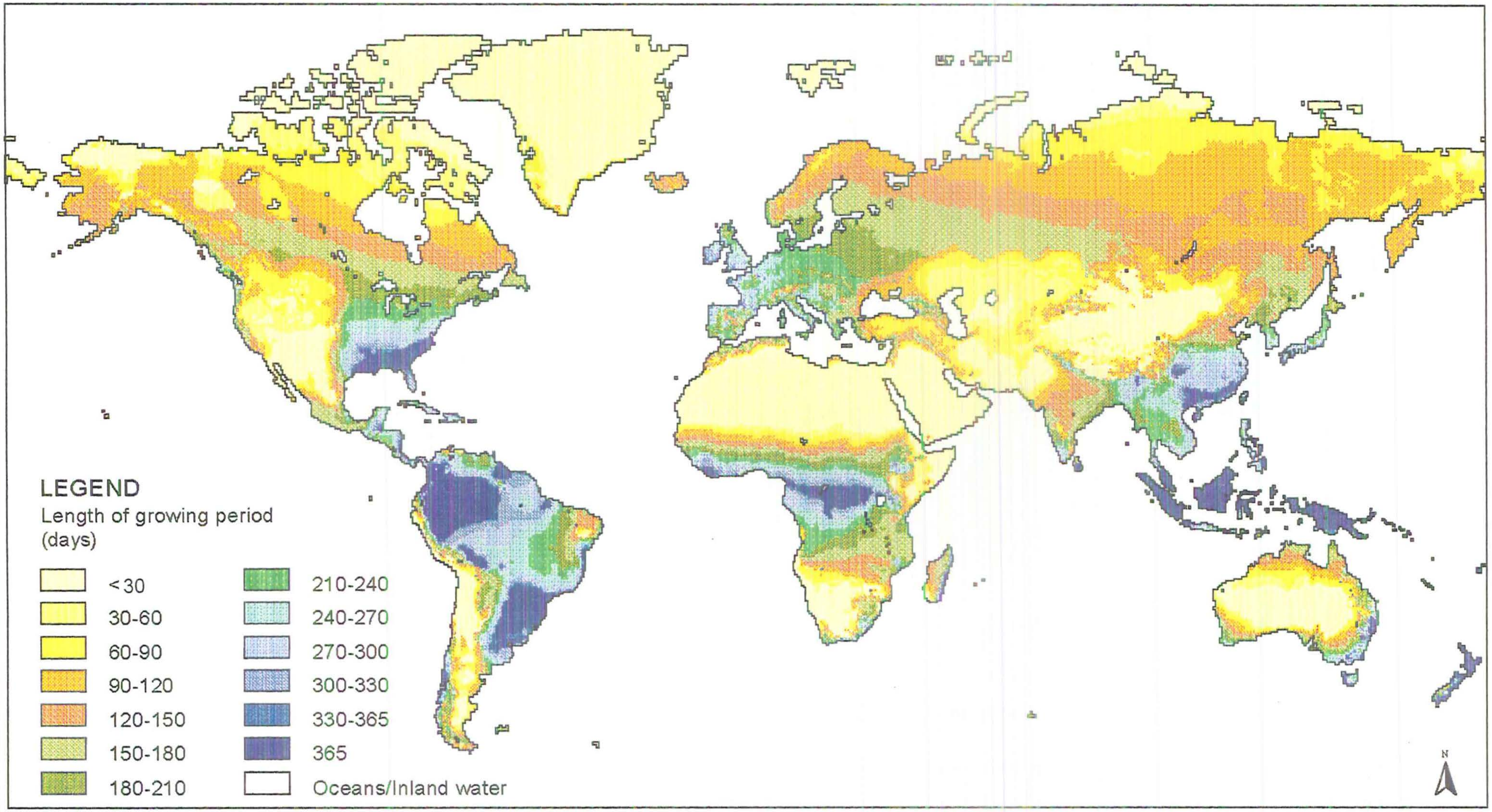
Map 5 shows the distribution of profiles held in the soil reference collection of ISRIC, for which data are available in ISIS. The distribution of these soils over the two major ecological zones, per country, is summarized below

Humid tropics

Based on the criteria of the humid tropics in Table 1, 148 reference profiles were selected. They originate from 20 countries: Brazil (7), China (3), Colombia (14), Costa Rica (10), Côte d'Ivoire (7), Cuba (5), Ecuador (4), Gabon (6), India (1), Indonesia (29), Jamaica (4), Malaysia (18), Nicaragua (4), Nigeria (10), Peru (11), Philippines (6), Samoa (3), Sri Lanka (1), Thailand (3) and Zaire (2). The profiles are well distributed throughout the humid tropics, but soils from Brazil and Zaire are under-represented.

PROVISIONAL

LENGTH OF GROWING PERIOD



FAO, IIASA, ISRIC; Global Agro-Ecological Zones
Projection Miller - October 1995

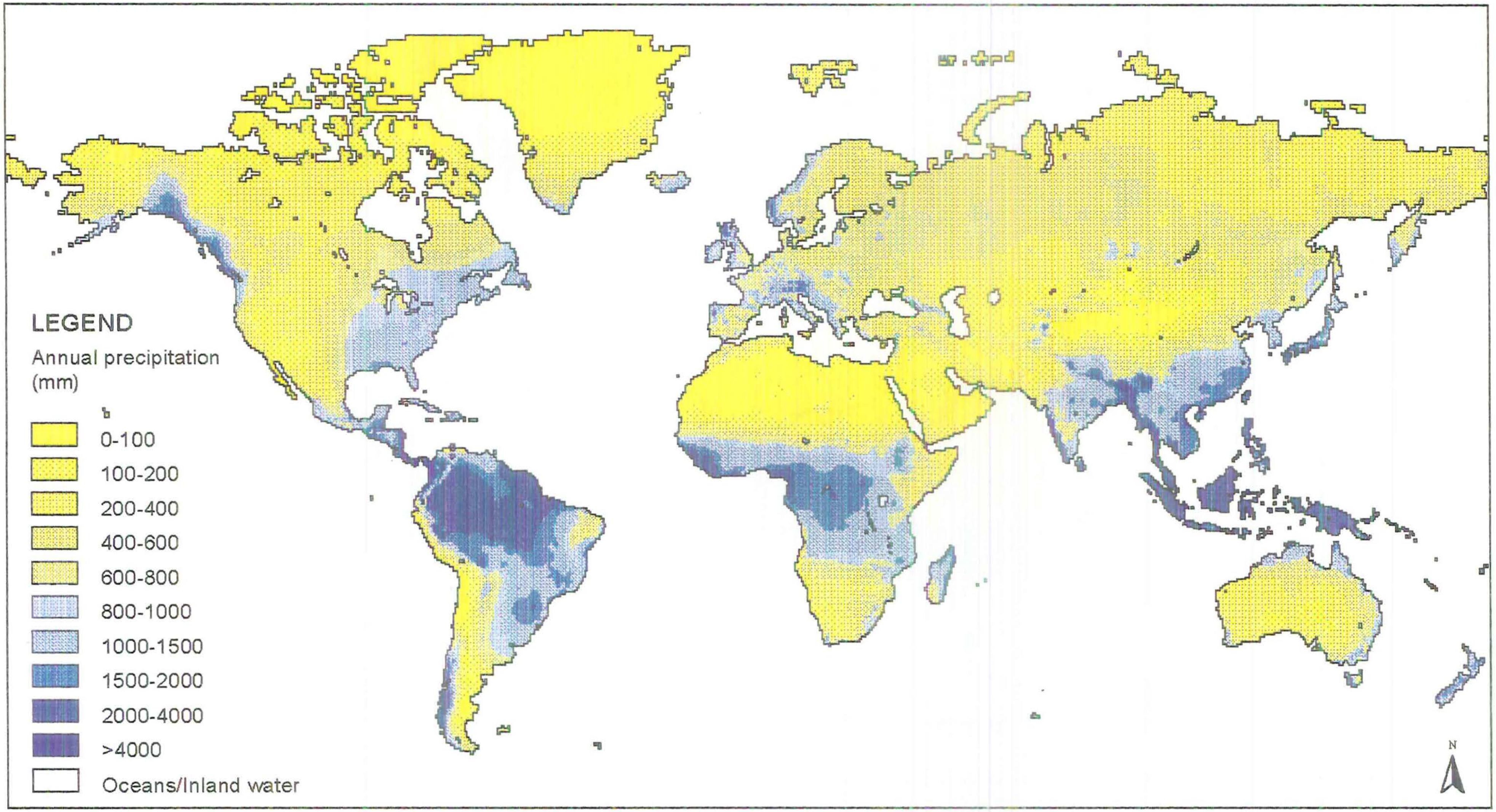
0 2000 4000 6000 8000 Kilometers

Based on Leemans, R. and W. Cramer (1991)
Derived from 30' Global Terrestrial Grid

Map 1

PROVISIONAL

ANNUAL PRECIPITATION



ISRIC

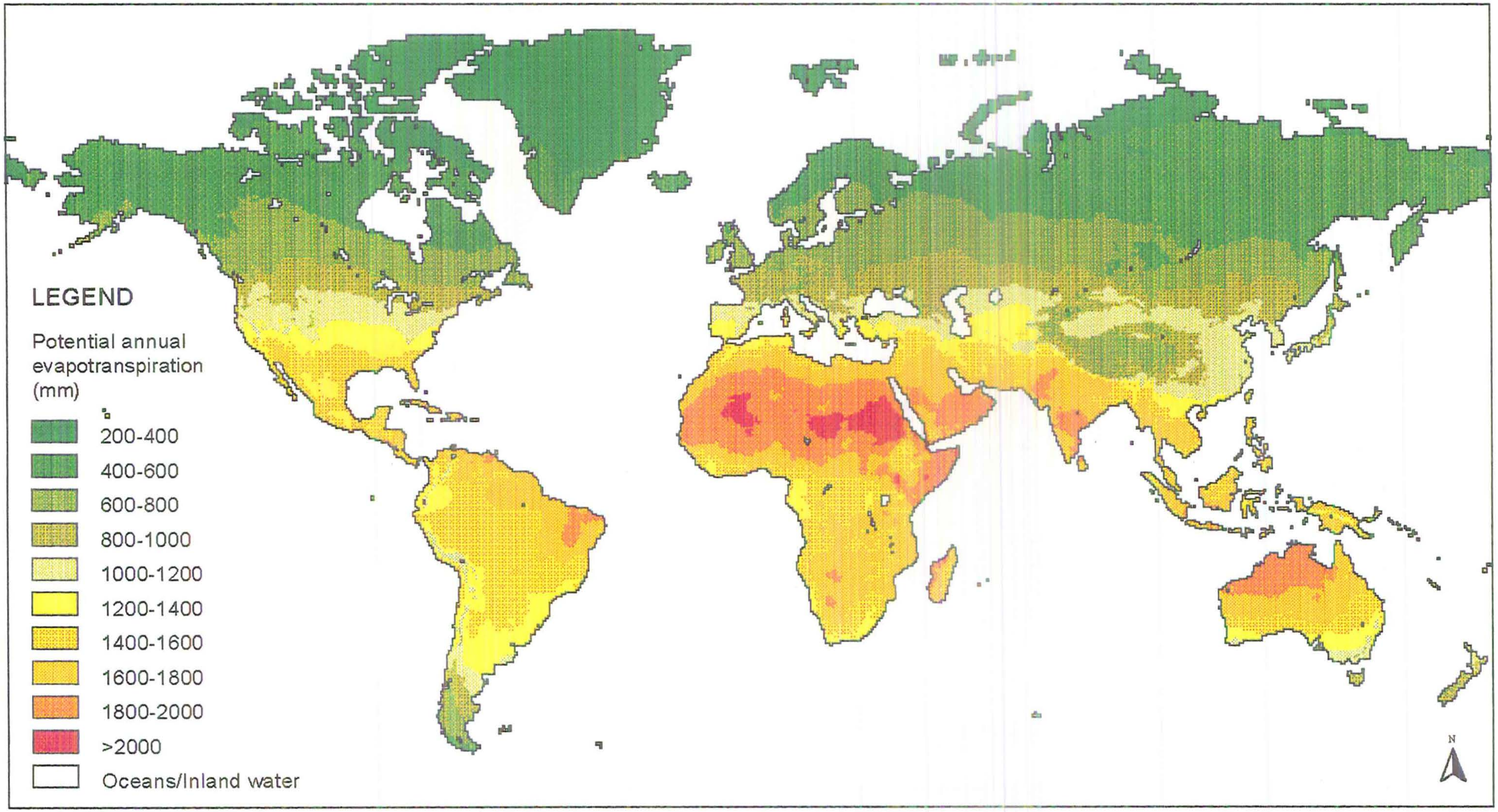
FAO, IIASA, ISRIC; Global Agro-Ecological Zones
Projection Miller - October 1995

Based on Leemans, R. and W. Cramer (1991)
Derived from 30' Global Terrestrial Grid

Map 2

PROVISIONAL

POTENTIAL EVAPOTRANSPIRATION



ISRIC

FAO, IIASA, ISRIC; Global Agro-Ecological Zones
Projection Miller - October 1995

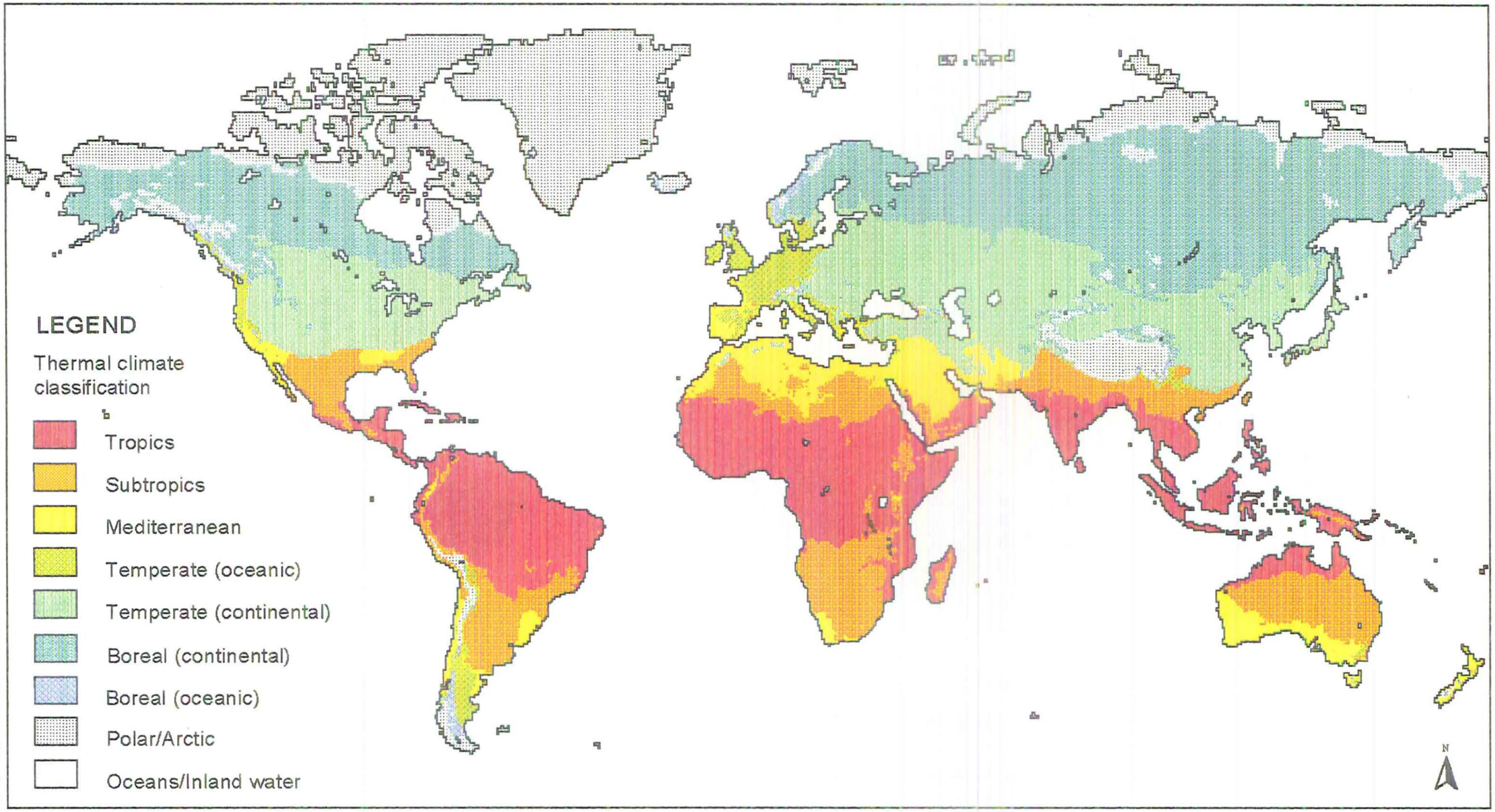
0 2000 4000 6000 8000 Kilometers

Based on Leemans, R. and W. Cramer (1991)
Derived from 30' Global Terrestrial Grid

Map 3

PROVISIONAL

THERMAL CLIMATE CLASSIFICATION



ISRIC

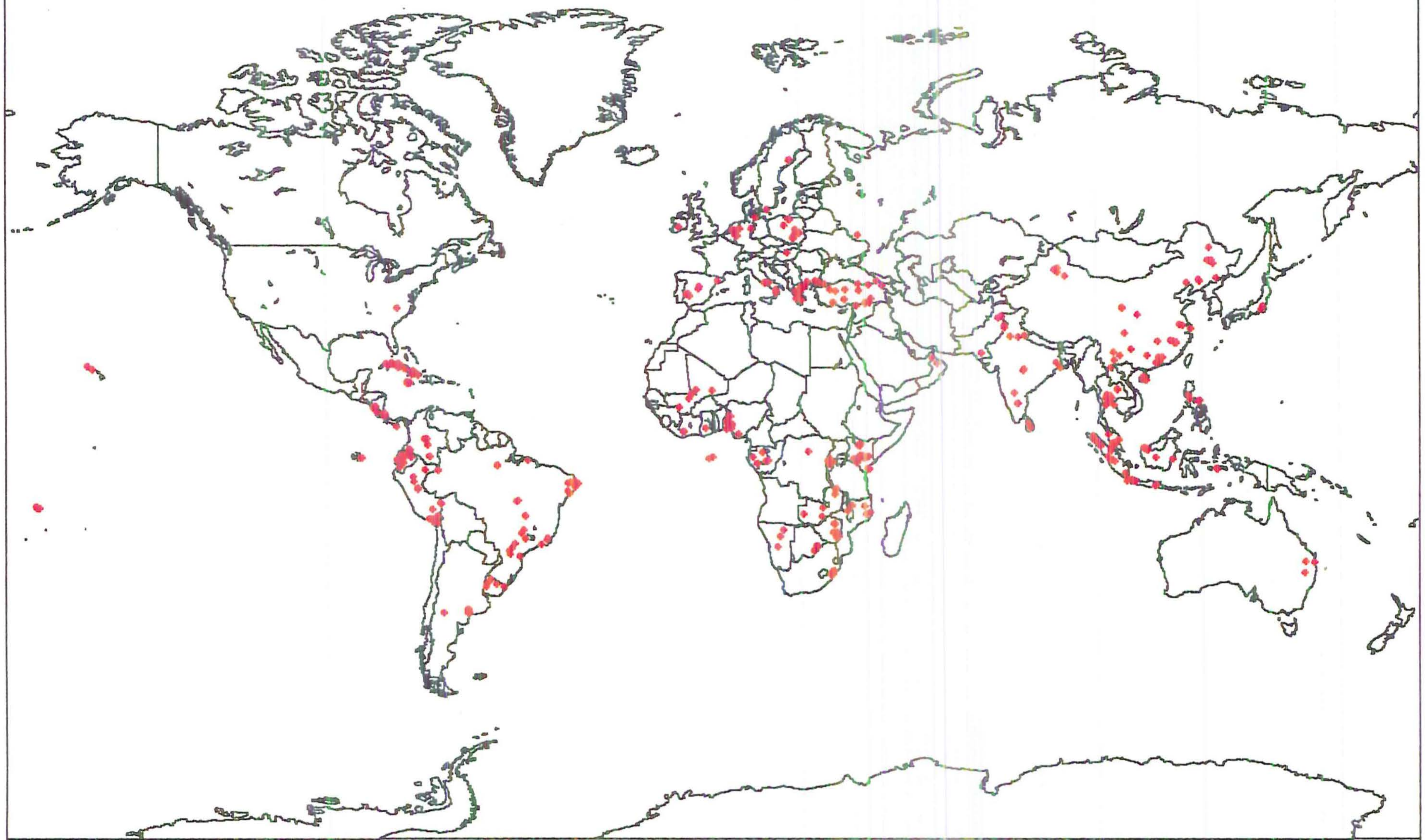
FAO, IIASA, ISRIC; Global Agro-Ecological Zones
Projection Miller - October 1995

0 2000 4000 6000 8000 Kilometers

Based on Leemans, R. and W. Cramer (1991)
Derived from 30' Global Terrestrial Grid

Map 4

LOCATION OF ISIS SOIL PROFILES



Derived from the ISIS database
Projection Miller
October 1995

ISRIC International Soil
Reference and Information
Centre, The Netherlands

Map 5

Seasonally dry (sub)tropics

Based on the criteria for the seasonally dry (sub)tropics, 176 reference soils were selected from ISIS. They originate from 19 countries: Brazil (17), China (14), Costa Rica (1), Cuba (18), Ecuador (5), India (8), Indonesia (3), Kenya (28), Mali (3), Mozambique (9), Nicaragua (7), Nigeria (12), South Africa (11), Sri Lanka (2), Thailand (10), Turkey (1), Uruguay (7), Zambia (10) and Zimbabwe (10). The profiles are well distributed throughout the seasonally dry (sub)tropics, but soils from Cuba and Kenya are over-represented.

3 SOILS OF THE HUMID TROPICS

3.1 Dominant soils

Six major soil groups (FAO-Unesco, 1974) are dominant in the set of 148 soil profiles of the humid tropics: Acrisols, Ferralsols, Luvisols, Arenosols and Podzols, and Cambisols (Table 2). Arenosols and Podzols are grouped in this study because both are characterized by a sandy texture and usually occur in close spatial association in the humid tropics. Other major soil groups represented include: Andosols (6 %), Gleysols (5 %) and Fluvisols (4 %); they are not considered in this paper because there are still too few reference profiles to permit meaningful statistical analyses.

Compared to the revised legend of the Soil Map of the World (FAO, 1988) there are no major shifts in classification for the considered dominant soils, except that the former Acrisols (FAO-Unesco, 1974) include the Alisols (FAO, 1988) and that the former Luvisols (FAO-Unesco, 1974) include the Lixisols (FAO, 1988). More information on the correlation of the major soil groups in the FAO-Unesco (1974) and revised FAO (1988) system will be given in section 3.5.

The representation of the six dominant soils of the humid tropics in ISIS correlates well with the extent of major soils groups in the climate zone 'Humid Tropics and Subtropics' as summarized in World Soil Resources (FAO, 1993, p. 33). The six major soil groups cover approximately 72 % of the total area of this climatic zone (Table 2). Gleysols, covering 167 million ha, are also important in this zone (FAO, 1993).

The most frequent subgroups of the dominant soils considered are:

Acrisols	Ferric (50 %) with an equal distribution over Gleyic, Humic, Orthic and Plinthic subgroups.
Ferralsols	Xanthic (40 %), followed by Acric and Orthic subgroups.
Arenosols and Podzols	no dominant subgroups
Cambisols	Ferralic (50 %), followed by Dystric and Eutric subgroups.

Table 2 Dominant soil groups in the humid tropics

Dominant soil group (FAO, 1974)	ISIS database Number	*(%)*	Area in the tropics[1)] million ha	*(%)*
Acrisols	33	*22*	589	*30*
Ferralsols	30	*20*	507	*26*
Arenosols and Podzols	11	*7*	138	*7*
Cambisols	33	*22*	95	*5*
Luvisols	9	*6*	53	*3*
Other	33	*22*	544	*28*

[1)]Including sub-tropics (FAO, 1993)

Soil classification according to international systems such as FAO (1988) and Soil Taxonomy (1994) is based on a necessarily limited number of characteristics, used in the definitions of diagnostic horizons and properties, which allows uniform classification and international correlation. However, it is difficult to obtain quantitative information on key soil properties (frequently used in agricultural land use assessment) and their variation within each taxonomic units from these classifications. The data available in ISIS are used to provide quantitative information on environment and soil properties of the six dominant soils. In the remaining part of this chapter these will be referred to as 'dominant soils' of the humid tropical zone.

3.2 Ecological characterisation

General environmental characteristics of the sites are described in this section, including precipitation, vegetation, parent material, landform and hydrology.

Precipitation

Precipitation at the 148 selected sites, ranges from 1500 to 4500 mm yr^{-1}. Monthly precipitation (P) exceeds evapotranspiration (ETp, Penman) in most months. Leaching Rainfall (LR), which is defined as the monthly excess of P over ETp, ranges from almost 0 to 3000 mm yr^{-1} with a mean of 1400 mm yr^{-1}. LR is a parameter for the amount of water that potentially percolates through the soil to the zone below the roots and drains to the groundwater aquifer or laterally to a river system.

Vegetation

The original vegetation at the considered sites is mainly evergreen rainforest. About 25 % of the sites are under semi-deciduous forest. Rooting in most cases is > 2 m. The original forest vegetation has been cleared in about 70 % of the sites studied, and secondary forest is frequently observed near these sites. Arable land and grazing are dominant land-use types for cleared land. The perennial crops most frequently were rubber, stimulants, fruit and oil trees. Common annuals were cereals and root, oil and protein crops.

Parent material

Parent material is an important determinant for the properties and agricultural potential of (tropical) soils. About 50 different types of parent materials are considered in ISIS. For soil fertility and soil genesis correlation purposes, these have been grouped according to composition in five categories: acid, intermediate, basic, calcareous and unconsolidated. Acid refers to rocks with > 10 % of free quartz (formerly defined as rocks containing > 66 % silica). Basic refers to quartz-free rock containing feldspars which are generally more calcic than sodic (formerly defined as rocks containing between 45 and 55 % of silica). Intermediate refers to rocks in between the acid and basic types (Whitten, 1974; Young, 1976). The unconsolidated sediments/materials include predominantly alluvium, with some colluvium and eolian sediments. All rock and sediment types, both consolidated and non-consolidated, which contain free calcium carbonate are grouped under the heading calcareous parent material.

The frequency of occurrence of these five groups of parent materials in ISIS for the considered dominant soils is: acid (38 %), intermediate (12 %), basic (17 %), calcareous (7 %) and unconsolidated (26 %). Although the dominant soils are formed on all rock types, some trends can be observed:

acid	all soil groups
intermediate	Luvisols dominant
basic	all soil groups, Ferralsols dominant
calcareous	all soil groups
unconsolidated	all soil groups, Acrisols, Cambisols and Arenosols/Podzols dominant

Landform, topography and position of site

Over 30 landforms are described for the sites of the reference profiles, which for correlation purposes are grouped in four major relief categories. These groups and their frequencies are:

- lowland alluvial and coastal plains	22 %
- upland dissected and non-dissected plains	38 %
- hills, including for a minor part plateaus	35 %
- mountains, including volcanoes	5 %

Frequency of five topography classes, according to FAO (1977 and 1990), at the site are:

- flat 26 %
- undulating 38 %
- rolling 17 %
- hilly 10 %
- steep 10 %

For sloping landscapes, the sites studied are situated principally on middle or upper slope positions. Less than 25% are located on a lower slope or crest position. The dominant soils are represented in all landform, topography or position classes, except for the Arenosols and Podzols, which are found in flat to undulating alluvial or coastal plain situations.

Hydrology

Most of the dominant soil sites studied are well drained (70 %) or moderately well drained (20 %), a minor part is imperfectly (5 %) and (somewhat) excessively drained (5 %). In 95 % of the sites no groundwater table was observed, which corresponds with the upland position of the dominant soils.

3.3 Soil properties

Selected key analytical properties, relevant for land use analysis and ecological research, are presented in this section. When appropriate, they are correlated with field information. The mean ($\bar{x}$) and standard deviation (s) for the considered properties are given by dominant soil in Table 3a and 3b, and histograms were plotted.

For most physical and chemical properties considered in this paper, the mean was considered a suitable parameter to show trends and differences between soils units. From the standard deviations in Table 3a and 3b it follows that ranges are large for nearly all properties of the dominant soils. Therefore, comparisons are only valid for the major soil group as a whole. The mean values of properties may be different for individual sub groups of a major soil group.

3.3.1 Physical properties

Particle size distribution

Data on the sand, silt and clay fraction are presented in Table 3a. Reflecting their sandy parent materials, Podzols and Arenosols have a very low silt and clay content. Ferralsols, Acrisols, Luvisols and Cambisols have a higher clay content. For these soils a correlation of clay content with parent material composition is more striking. The mean clay content of soils formed on acid parent materials is 23 %, compared to 58 % for those formed on basic materials. Ferralsols, dominantly derived from basic parent materials, have a slightly higher clay content than the other major soil groups.

A distinct increase in clay content between topsoil and subsoil is not a manifest feature in most dominant soils of the humid zone. The most pronounced increase is found in Acrisols, with a mean clay increase of 11 % in the first metre of the soil. Although for the Acrisols in the world the increase takes place over a shorter depth range, such a gradual increase of clay content in the Acrisols of the humid tropics will have only limited influence on e.g. root development and soil hydraulic properties. This is also evidenced by the field morphology, where horizon boundaries are usually gradual or diffuse, caused by bio-homogenization.

The silt fraction is relatively low in soils of the humid tropics, being lowest in Ferralsols and highest in Cambisols. This is reflected in the silt/clay ratio. The mean ratio is 0.3 in subsoils of Ferralsols and double for the other major soil groups. In the revised legend of the Soil Map of the World (FAO, 1988) a silt/clay ratio of < 0.2 is introduced as a diagnostic criterion in the classification of Ferralsols. When rigidly applied, a large part of the former Ferralsols (FAO-Unseco, 1974) will no longer classify as Ferralsols in the revised legend (FAO, 1988). A discussion about the silt/clay ratio is given in section 4.3.1. In view of the poor dispersing properties of tropical soils before measuring the silt and clay fractions it is recommended that further investigation of the applicability of the silt/clay ratio take place.

Bulk density, rootable pore volume and plant available moisture

The results of bulk density, potential Rootable Pore Volume (RPV) and potential Plant Available Moisture (PAM) for the dominant soils are presented in Table 3a. The mean bulk density of topsoils of the humid tropics is low (1.1 - 1.3 g cm^{-3}), but subsoils approach the average values found elsewhere. There are no large differences comparing the major soil groups, but Ferralsols have the lowest and Acrisols have the highest mean bulk density. The potential Rootable Pore Volume (RPV) for topsoils is comparable for the dominant soils. Acrisols are lower with 13 % RPV, but this is considered not to be limiting for root development in their topsoils. Large differences are found in the subsoil, where Ferralsols and Cambisols have a high RPV and Acrisols and Luvisols have a lower RPV. Possible explanations for this are: a) the occurrence of illuviated clay and the formation of clay skins on structural elements in Acrisols and Luvisols; b) Ferralsols have more stable micro-aggregates and biopores.

As expected the potential Plant Available Moisture (PAM) is higher in the topsoil than in the subsoil due to a higher organic matter content and a better structure. Cambisols show the highest potential PAM and Ferralsols the lowest, with Acrisols and Luvisols taking intermediate positions. As dry periods are relatively short in the humid zone, if present at all, mean PAM values should not form a constraint for crop production.

Table 3a Physical properties of dominant soils in the humid tropics

		FERR		ACRI		LUVI		CAMB		AREN		PODZ	
		$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*
Sand (%)	*top*	35	27	52	23	40	32	25	23	92	5	86	12
	sub	29	25	36	21	30	21	26	25	94	4	85	8
Silt (%)	*top*	15	11	19	12	20	11	27	13	5	4	11	9
	sub	15	12	19	13	21	12	25	15	4	4	6	4
Clay (%)	*top*	49	25	29	18	35	19	46	22	3	3	3	4
	sub	52	27	40	21	40	20	40	28	7	7	4	5
Silt/Clay ratio	*top*	0.4	0.3	0.9	0.7	0.6	0.2	0.9	0.8	5.1	6.2	18	32
	sub	0.3	0.3	0.6	0.7	0.5	0.4	0.8	0.6	1.7	2.3	3.0	3.6
Bulk Density (g cm^{-3})	*top*	1.1	0.2	1.3	0.2	1.2	0.2	1.1	0.2	1.2	0.1	1.3	0.0
	sub	1.2	0.2	1.4	0.2	1.3	0.1	1.2	0.3	1.4	0.2	1.5	-
Rootable Pore Volume (%)	*top*	16	7	13	4	16	5	14	7	23	9	14	3
	sub	15	8	9	3	8	3	13	7	26	13	11	-
Plant avail. moisture (%)	*top*	12	5	14	6	14	5	17	5	18	6	22	1
	sub	10	3	10	6	11	4	8	1	12	6	-	-

Table 3b Chemical properties of dominant soils in the humid tropics

		FERR		ACRI		LUVI		CAMB		AREN		PODZ	
		$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*
pH-H_2O (1:2.5)	*top*	4.8	0.6	4.8	0.5	6.4	0.5	5.3	1.0	5.3	0.9	4.5	0.3
	sub	5.0	0.5	4.8	0.2	5.9	0.8	5.5	0.9	5.8	1.6	4.8	0.5
pH-KCl (1:2.5)	*top*	4.1	0.4	4.1	0.3	5.5	0.7	4.6	0.8	4.1	1.0	3.7	0.5
	sub	4.5	0.7	4.0	0.2	4.6	0.8	4.5	0.7	5.1	1.6	4.4	0.5
Organic Carbon (%)	*top*	2.3	1.5	2.0	1.0	2.2	1.0	2.3	1.4	0.8	1.8	5.0	8.3
	sub	0.4	0.2	0.4	0.2	0.3	0.1	0.4	0.4	0.1	0.0	0.7	0.7
C/N ratio	*top*	16	10	14	5	17	15	11	4	16	3	23	9
	sub	9	5	8	3	7	1	8	4	12	-	11	6
Sum of bases ($cmol_c$ kg^{-1})	*top*	1.8	2.3	2.2	2.5	21.2	16.1	11.5	18.0	2.0	2.0	1.0	1.0
	sub	0.7	1.7	0.6	0.8	16.8	21.3	9.0	15.0	2.0	3.1	0.1	0.1
Exch. Al ($cmol_c$ kg^{-1})	*top*	1.4	1.8	1.5	1.4	0.0	0.1	0.1	1.6	0.1	0.1	1.0	2.2
	sub	1.1	1.8	2.2	2.1	0.3	0.5	0.0	1.7	0.0	0.0	0.2	0.4
CEC_{pH7} ($cmol_c$ kg^{-1})	*top*	8.8	5.4	9.9	6.4	22.7	16.2	19.3	13.8	6.6	5.5	20.0	36.0
	sub	4.0	3.0	6.9	5.6	25.0	19.5	14.9	12.0	3.2	3.6	4.7	6.0
Base Saturation (%)	*top*	19	16	26	23	87	17	49	54	44	35	18	17
	sub	19	26	12	15	67	38	52	43	39	43	43	36

$\bar{x}$= Mean; *s*= standard deviation; *top* = topsoil, 0 - 20 cm; *sub*= subsoil, 70 - 100 cm

FERR = Ferralsols (30/22), ACRI = Acrisols (33/22), LUVI = Luvisols (9/5), CAMB = Cambisols (30/18), AREN = Arenosols (5/2), PODZ = Podzols (6/2). The numbers between the brackets indicate the number of profiles in ISIS available for statistical analysis. The first number refers to the number of profiles for which sand, silt and clay content and chemical properties are available. The second number to Bulk Density, Rootable Pore Volume and Plant Available Water.

3.3.2 Chemical properties

Soil reaction

Soil reaction of the dominant soils ranges from extremely acid to neutral (Table 3b). Ferralsols, Acrisols and Podzols have similar pH ranges and are predominantly strongly acid, Cambisols and Arenosols are acid, and Luvisols are neutral. Comparing the soil reaction of topsoil and subsoil, except for the Luvisols, the other dominant soils have a pH-H_2O level of the topsoil similar or slightly lower than the subsoil.

A measure for the net charge status of the soil is delta pH, referring to the difference between pH-KCl and pH-H_2O. Ferralsols in ISIS have an average delta pH of -0.7 pH unit and the other soils around -1.0 pH unit (net negative charge: CEC). A frequency analysis of the delta pH for all soil samples shows that a positive delta pH is rare, as expected. Positive delta pH's, indicative for a net positive charge, are mainly observed in Geric Ferralsols (FAO, 1988).

Exchangeable aluminium

In general, the exchangeable aluminium content is negligible when pH-KCl exceeds 4.8 (which corresponds approximately to a pH-H_20 > 5.5), as free aluminium is neutralized. Soils with pH values below these levels can have a high level of exchangeable aluminium, inducing aluminium toxicity and limiting rootgrowth. A correlation of pH-KCl and aluminium saturation for all soil samples is presented in Figure 1. Additional information on exchangeable aluminium is given in this section under 'nutrients'.

Organic Carbon

Organic carbon and organic nitrogen content are widely used as a measure of organic matter quantity and quality in a soil, and as a crude measure of the fertility status (Landon, 1991). The interpretation of the content of organic carbon and organic nitrogen is complex, because many other factors influence soil nutrient status and soil physical properties. Organic matter fulfils an important role in soils, especially in the tropics. In sandy soils and clay soils consisting dominantly of 1:1 lattice clays, a large part of the plant nutrients and about 90 % of the capacity of the soil nutrient retention originates from organic matter. In unfertilized soils, organic matter is the source of 90-95 percent of nitrogen. Organic matter can be the major source of available phosphorus and available sulphur when humus is present in appreciable amounts (Miller and Donahue, 1990). Organic matter has also a strong positive influence on soil structure and resistance to erosion, especially in sandy soils.

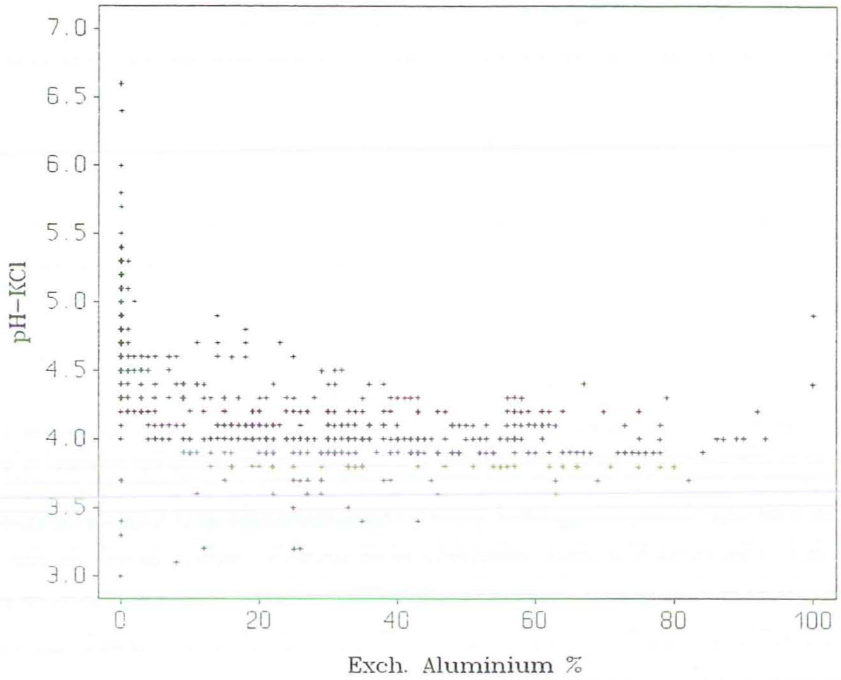


Fig. 1 Scatter plot of exchangeable aluminium against pH-KCl for 148 referencne profiles from the humid tropics.

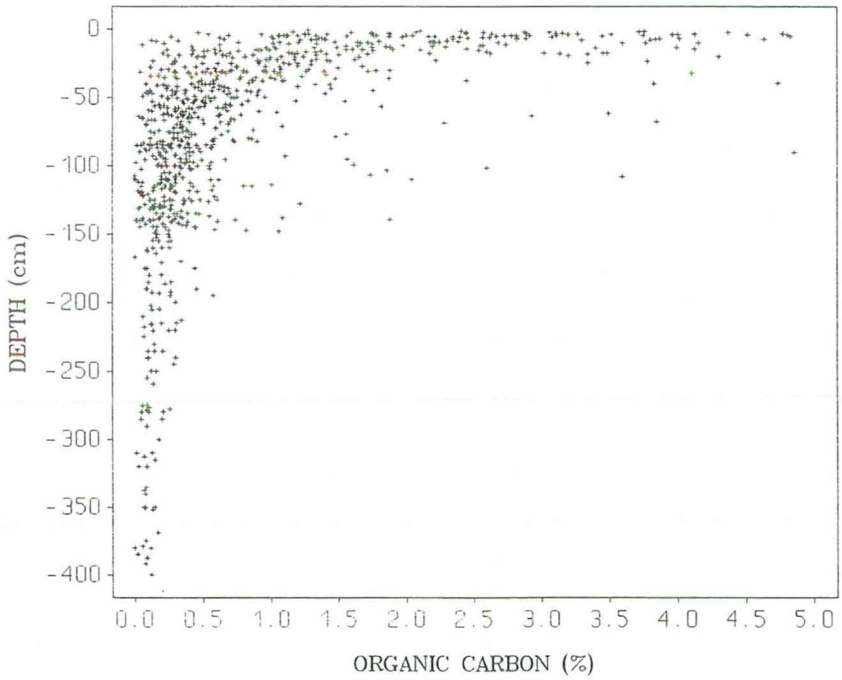


Fig. 2 Scatter plot of Organic Carbon content versus Depth for 148 reference soils from the humid tropics.

A plot of organic carbon content with depth of all samples not only shows the expected highest level of organic carbon in the upper 50 cm of the soil profiles, but also that substantial amounts can occur in the deeper subsoil of some soils (Figure 2). The organic carbon content and C/N ratio of topsoil and subsoil is given in Table 3b.

Ferralsols, Acrisols, Luvisols and Cambisols have a comparable mean distribution of organic carbon within their profiles. Arenosols and Podzols clearly form a separate group with a much lower organic carbon content. However, some subsoil horizons of individual Podzol profiles have a much higher level, associated with the presence of a podzol B horizon, i.e. an accumulation of organic material and iron in the subsoil, partly as an indurated layer ("ortstein"). In the humid tropics, the podzol B horizon may occur at a great depth.

Contrary to the general expectation, organic carbon (OC) also accumulates in the subsoils of the humid tropics (Figure 3). Part of the soils have 1 % OC at a depth of 50 cm, and 0.5 % OC at a depth of 100 cm. Comparing field descriptions and analytical data of soils from Brazil and Indonesia, it is observed that such relatively high organic carbon levels in the subsoil are not matched by a darker soil matrix colour. These subsoils have clear yellowish or reddish soil matrix, with Munsell color codes of hue 5 to 10 YR and value/chroma combinations of 4/5 to 6/8, which outside tropical areas are indicative of a much lower content of organic carbon. The accumulation of organic carbon in the deeper subsoil and its importance for plant available water and nutrient retention is also reported from deeply weathered clay soils (Xanthic Ferralsols) in the states of Pará and Amazonia, Brazil (Nepstad *et al.*, 1994). Therefore, a study of the organic carbon in the deeper subsoil is advocated, irrespective of observed soil matric colour.

The degree of decomposition (or mineralisation) of organic matter is reflected by the C/N ratio. High C/N ratios are indicative for a low degree of decomposition and low values for a high degree of decomposition. The following interpretation is mainly used in temperate zones. Fresh organic matter may have a C/N ratio of around 15 (leguminous biomass) to about 80 (cereal straw). A C/N ratio above 12 to 14 point to a shortage of nitrogen in the soil, resulting in a stagnation of the organic matter decomposition process. A C/N ratio from 8 to 10 is indicative for 'stabilized' humus (Miller and Donahue, 1990).

The mean C/N ratios for the dominant soils are presented in Table 3b. Cambisols have the lowest C/N ratio in the topsoil, indicative of good quality organic matter. High C/N ratios in Podzols and Arenosols indicate that humified organic matter has a very low nitrogen content; especially in Podzols the C/N ratio is very high, which is a reflection of the sandy and acid parent material and poor quality of organic materials. The relatively high C/N ratios in the topsoils of Ferralsols and Luvisols also point to a nitrogen shortage.

The overall difference of the C/N ratios between topsoil and subsoil is large. This may be explained by a better decomposition of organic matter with depth and age. In addition, transport of the more decomposed, finer, organic fraction from the topsoil to the subsoil may contribute to this difference. However, the influence of the latter can not be large, because of the pronounced bio-homogenisation. Ferralsols, Acrisols, Luvisols and Cambisols have comparable low C/N ratios in the subsoil.

No correlation was found between organic carbon content and soil reaction for acid soils (pH-H_20 < 5.5), at any depth, nor is a correlation of organic matter content and exchangeable aluminium content apparent. The correlation of organic carbon content with parent material has also been studied. For soils derived from acid parent materials the mean organic carbon content of the topsoil is 0.8 % lower than that of soils developed from basic parent materials.

Nutrients

In addition to soil reaction and soil organic carbon content, nutrient availability is characterized by the exchangeable bases (calcium, magnesium, potassium and sodium), the exchangeable acidity (dominantly exchangeable aluminium), and the cation exchange capacity (CEC) at pH 7. Means for the sum of exchangeable bases, cation exchange capacity and base saturation are low or very low in topsoils and subsoils of Ferralsols, Acrisols, Arenosols and Podzols (Table 3b). Cambisols and Luvisols form a separate group with moderate to high values.

There is no good relation between the content of bases and the parent material classes. Generally, soils developed from basic parent materials have a slightly higher CEC, sum of bases, and base saturation compared with those formed from acid, intermediate and old alluvial parent materials. This very low correlation can be explained because the Leaching Rainfall (see section 3.2) is very high and therefore old, i.e. (very) deeply developed, soils in the humid tropics are strongly leached, irrespective of the original base richness of the parent material. As observed before, physical properties, such as clay percentage and structure, are stronger correlated with parent material. For example, basic parent material results in soils with a high clay content. However, it is noted that in a restricted area correlation between parent material and chemical properties of soils can be stronger.

The exchangeable aluminium content in Acrisols and Ferralsols is high, and nil or very low in the other dominant soils. The absolute value of exchangeable aluminium is low in the subsoil of the Ferralsols. Nonetheless, the mean aluminium saturation expressed as percentage of the ECEC is high, about 50 % and comparable with Acrisols (the ECEC is calculated from the sum of exchangeable bases and exchangeable acidity and is considered to approximate the actual nutrient retention capacity of the soil under field conditions). In addition to the use of organic materials, liming is usually recommended to prevent aluminium toxicity by raising the pH value to about 5.5 (Landon, 1991).

3.3.3 Mineralogical properties

The mineralogical composition of the 148 reference profiles, as determined by X-ray analysis of the clay fraction is summarized in Table 4. The semi-quantitative classification is based on the presence and intensity of the peak in the clay mineralogy diagram. All soils have a predominance of kaolinite. Nearly all soils have some goethite and haematite but these oxides are not included in the table. Moderate amounts of gibbsite are found in Ferralsols and remarkably also in Cambisols and Arenosols. Acrisols, Cambisols and Luvisols have minor amounts of chlorite and illite. It should be noted that the amount of clay in Arenosols is low in comparison to the other soils.

Table 4 Clay mineralogy of dominant soils in the humid tropics

	FERR	ACRI	LUVI	CAMB	AREN
Gibbsite	+	-		+	+
Kaolinite	++	+++	++	++	+
Halloysite		++		+	
Illite		-	-	-	
Chlorite		-	-	-	
Smectite			+		-
Vermiculite		-			

+++ = dominant, ++ = sub-dominant, + = moderate and - = minor presence of a clay mineral

3.4 Major agronomic constraints

3.4.1 All dominant soils

For the purpose of highlighting major soil/land constraints for agriculture, a qualitative evaluation of 15 land qualities was made based on the procedures of the Framework for Land Evaluation (FAO, 1976, 1983). The land quality assessment is generally based on 2 or more single land characteristics. Critical values and other class limits for single soil parameters are adapted from several publications (Ilaco, 1981; Landon, 1984). To make the assessment applicable for all tropical regions, criteria have been developed for a 'standard' crop, i.e. a deep rooting annual crop, assuming low technology and low inputs. In 'Framework' terms this corresponds with a major kind of land use, viz. "rainfed agriculture, annual cropping". Each land quality is rated in 5 classes which indicate the degree of limitation for the specified use.

Rating procedures have been computerized with ALES, the Automated Land Evaluation System (Rossiter and Van Wambeke, 1993), to assess the present status of the land using the reference profiles (Mantel and Kauffman, 1995). Depending on the land quality, an assessment is made for a specific depth range. For topsoil characteristics the first soil horizon is evaluated; for nutrient status related characteristics it is assessed over 0 - 50 cm, and for others over the depth 0 - 120 cm. For the land quality 'erosion hazard' the erodibility of the soil is rated. Climate factors are not considered.

This, briefly described, qualitative assessment should not be regarded as an absolute judgement, but rather as a first identification of constraints for agriculture. The assessment was executed for all soils, and results, i.e. the frequencies in the five classes for the all dominant soils, are expressed in percentages in Table 5. High frequencies in the classes moderate, serious and very serious are indicative for the occurrence of a constraint. The most common constraints are: a low level of plant nutrients, a low level of nutrient retention capacity, and toxicity caused by high exchangeable aluminium levels. Less frequent occurring constraints are potential for mechanisation, erosion hazard and potential soil moisture content.

Table 5 Frequency (%)[1] of constraints by land quality of all dominant soils

degree of constraints[2] > land quality	no	weak	moderate	serious	very serious
length of growing period	70	30	0	0	0
drought hazard	100	0	0	0	0
soil moisture availability	5	39	36	13	6
oxygen availability	68	18	6	7	1
nutrient availability	2	9	13	33	43
nutrient retention capacity	7	5	12	38	38
rootable volume	58	29	10	3	0
conditions for germination	97	2	1	0	0
salinity	99	0	1	1	0
sodicity	79	7	7	1	6
aluminium toxicity	24	0	33	13	30
workability	21	57	15	7	0
potential for mechanisation	38	22	19	16	5
erosion hazard	41	28	10	11	9
flooding hazard	77	14	8	0	1

[1] Because of rounding, the sum of percentages for each land quality may be 99 or 101.
[2] The qualitative degree of limitation reads as follows:

no	= no constraint or limitation, no yield reduction
weak	= slight limitation, slight yield reduction
moderate	= moderate limitation, moderate yield reduction
serious	= severe limitation, clear yield reduction
very serious	= very severe limitation, strong yield reduction or no yield.

3.4.2 Individual dominant soils

In the preceding section, the constraints for the dominant soils as one group are summarized. Here a similar assessment is presented for each dominant soil. For ease of comparison the results of the dominant soils are summarized in one table. For each dominant soil, the median of the land quality ratings (1= no limitation to 5= severely limiting) was calculated. In Table 6, the six major limitations - that were moderately or (very) severely limiting for at least one soil profile - are given for the dominant soils.

Table 6 Major limitations of dominant soils of the humid tropics

land quality	FERR	ACRI	LUVI	CAMB	AREN/PODZ	ALL
soil moisture availability	x	x	x		xxx	x
nutrient availability	xxx	xxx		xx	xxx	xx
nutrient retention capacity	xxx	xx	x	xx	xxx	xx
aluminium toxicity	xx	xx		x	x	x
potential for mechanisation			x			
erosion hazard			x			

x = moderately limiting, xx = severely limiting, xxx = very severely limiting.
FERR = Ferralsols, ACRI = Acrisols, LUVI = Luvisols, CAMB = Cambisols, AREN = Arenosols, PODZ = Podzols and ALL = overall figure of the 6 dominant soils.

From this table it can be seen that of the five dominant soils, Luvisols have the most favourable properties for agriculture. Cambisols in the humid tropics have frequently severe limitations for availability and retention of nutrients and have a moderately toxic aluminium level. Ferralsols and Acrisols have as limitations: (very) severe limiting nutrient retention and nutrient availability, severely aluminium toxicity and moderate soil moisture retention. Arenosols and Podzols have the most unfavourable properties for agriculture.

3.5 Some notes on the classification of soils in the humid tropics

ISIS holds classification data according to the original Legend (FAO-Unesco, 1974) and Revised Legend (FAO, 1988) of the Soil Map of the World, as well as Soil Taxonomy (1975; 1992). The expert system DIAGNISIS, under development at ISRIC, was used to determine the major soil groupings in the Revised Legend for 113 profiles from the humid tropics (Table 7).

DIAGNISIS determines the diagnostic horizons and properties present for the reference soils entered in ISIS by checking data held in the morphological, physical, chemical and mineralogical files. It displays the single property values which occur in the soil and gives an account of the diagnostic horizons and properties found or why a diagnostic horizon or property has been rejected.

Since the revision of the Legend of the Soil Map of the World in 1988, much discussion has taken place about newly entered requirements. In particular, the silt-clay ratio of less than 0.2 needed for the ferralic B horizon, a diagnostic horizon of importance in the humid tropics, is being questioned as many soil specialists familiar with soils from this region feel the requirement is much too strict. In comparison, the Brazilian Soil Classification uses a silt-clay ratio of 0.7 to distinguish the "Latosolic B" from other horizons.

Table 7 Comparison of classification of soils from the humid tropics according to FAO-Unesco (1974) and FAO (1988) as held in the ISIS database, and the FAO 1988 classification obtained using DIAGNISIS

Major Soil Grouping	FAO-Unesco (1974)		FAO (1988)			
			ISIS-held		DIAGNISIS	
	Number	%	Number	%	Number	%
Ferralsols	29	25.7	15	13.3	28	24.8
Acrisols	30	26.5	21	18.6	27	23.9
Cambisols	26	23.0	17	15.0	33	29.2
Podzols	5	4.4	3	2.7	6	5.3
Arenosols	5	4.4	3	2.7	6	5.3
Luvisols	8	7.1	0	0.0	2	1.8
Alisols	-	-	2	1.8	2	1.8
Lixisols	-	-	1	0.9	2	1.8
Regosols	0	0.0	2	1.8	0	0.0
Andosols	0	0.0	0	0.0	2	1.8
Nitisols	-	-	1	0.9	0	0.0
Calcisols	-	-	0	0.0	1	0.9
Anthrosols	-	-	1	0.9	1	0.9
Not classified	10	8.8	47	41.6	3	2.7
Total	113	99.9	113	100.2	113	100.2

Strong micro-aggregation, which is not destroyed using conventional or "routine" particle size analyses, or somewhat siltier parent materials, may cause such soils failing to meet the silt-clay ratio requirement of less than 0.2, while otherwise all characteristics of Ferralsols are present. This could lead to a major shift of Ferralsols to Acrisols/Lixisols, if a sufficient increase in clay content is present, or to Ferralic Cambisols.

Comparison of the FAO-Unesco (1974) with the FAO (1988) classification, determined using DIAGNISIS (Table 8), shows that eight 1974-Ferralsols are classified as 1988-Cambisols (about 28 % of the total Ferralsols) and five 1974-Ferralsols became 1988-Acrisols (about 17 % of the total Ferralsols). Ten 1974-Acrisols are classified as 1988-Ferralsols (about 32 % of the total Acrisols) and two 1974-Luvisols became 1988-Ferralsols because a ferralic B horizon has precedence over an argic B horizon (FAO, 1988). Also one 1974-Cambisol was reclassified as a 1988-Ferralsol. In addition, four 1974-Acrisols (about 13 % of the total Acrisols) are 1988-Cambisols because of lack of sufficient increase in clay content in absence of clay coatings.

Table 8 Main shifts in major soil grouping classification (FAO-Unesco, 1974; FAO, 1988) as entered in ISIS and determined by DIAGNISIS

FAO-Unesco (1974)		FAO (1988)	Occurrence
Ferralsols	→	Cambisols	8x
Ferralsols	→	Acrisols	5x
Acrisols	→	Ferralsols	10x
Acrisols	→	Cambisols	4x
Luvisols	→	Ferralsols	2x
Cambisols	→	Ferralsols	1x

Interpretation of these data shows that in absolute terms large shifts do not occur; thirteen 1974-Ferralsols classified differently in 1988, are replaced by thirteen 1974-Acrisols, 1974-Luvisols and 1974-Cambisols. However, considering the fact that a large number of the 1988-Ferralsols were classified in 1974 as Acrisols and Luvisols, a important shift has taken place towards Ferralsols which show a pronounced increase in clay content. This may warrant recognition of a "Lixic" soil unit at the second level of classification in the Revised Legend, as is proposed in the World Reference Base for Soil Resources (Spaargaren, 1994).

4 SOILS OF THE SEASONALLY DRY (SUB)TROPICS

4.1 Dominant soils

Based on the Legend of the Soil Map of the World (FAO-Unesco, 1974) nine major soil groups are dominant in the set of 176 soil profiles of the seasonally dry (sub)tropics:
Luvisols, Arenosols, Acrisols, Ferralsols, Vertisols, Cambisols, Nitosols, Planosols, and Phaeozems. Other major soil groups represented include: Fluvisols, Gleysols, Regosols, Calcisols, Kastanozems, Solonetz, Solonchaks, Andosols, Podzols and Chernozems, but these soil groups are not considered in this paper because the number of reference profiles is insufficient for statistical analysis. Compared to the revised FAO-Unesco Legend (1988) there are no major shifts in classification for the nine dominant soils, except that the Acrisols (FAO-Unesco, 1974) now include the Alisols (FAO, 1988) and Luvisols (FAO-Unesco, 1974) now include the Lixisols (FAO, 1988).

The representation of the nine dominant soils of the humid tropics present in ISRIC's database correlates fairly well with the dominant extent of major soils groups in the climate zone 'Seasonally dry tropics and subtropics' as summarized in World Soil Resources (FAO, 1993, p. 33). The nine major soil groups cover approximately 74% of the total area of this climatic zone (Table 9). For Arenosols, the number of profiles in ISIS is small in comparison to its large extent on the Soil Map of the World (SMW) (FAO, 1971 - 1981). Phaeozems in ISIS are over-represented in comparison to their world extent on the SMW.

Table 9 Dominant soil groups in the seasonally dry (sub)tropics

Dominant soil group (FAO, 1974)	ISIS database Number[1]	*(%)*	Area in the (sub)tropics million ha	*(%)*
Luvisols	26	*15*	429	*17*
Arenosols	8	*5*	320	*13*
Acrisols	26	*15*	238	*10*
Ferralsols	26	*15*	231	*9*
Vertisols	16	*9*	223	*9*
Cambisols	24	*14*	192	*8*
Nitosols	8	*5*	102	*4*
Planosols	8	*5*	74	*3*
Phaeozems	13	*7*	15	*1*
Other	21	*9*	647	*26*

1) Number of reference profiles in ISIS database

The most frequently occurring subgroups of the nine dominant soils in the dataset are:

Luvisols	Calcaric, ferric and orthic subgroups
Arenosols	Ferralic, Albic and Luvic subgroups
Acrisols	Ferric and Orthic subgroups
Ferralsols	Rhodic, Acric and Orthic subgroups
Vertisols	Pellic and Chromic subgroups only
Cambisols	Ferric and Gleyic subgroups
Nitosols	Humic, Eutric and Dystric subgroups
Planosols	Solodic subgroup
Phaeozems	Humic and Luvic subgroup

In the following sections the data available in ISIS are used to provide quantitative information on environmental and soil properties of the nine dominant soils listed above, which in the remaining part of this chapter will be referred to as the 'dominant soils' of the seasonally dry (sub)tropics.

4.2 Ecological characterisation

Precipitation

Mean annual precipitation at the 176 sites selected, ranges from 800 to 1800 mm with a mean of 1200 mm (s= 280). In the seasonally dry tropics the precipitation is concentrated in one or two rainy periods and the other months are dry. Mean annual evapo-transpiration (ETp, Penman) ranges from 1100 to 2100 mm with a mean of 1560 mm (s= 210 mm). At an annual base, the mean annual ETp exceeds the mean annual precipitation. Leaching Rainfall (LR) ranges from almost 0 to a maximum of about 1000 mm, with a mean of 270 mm (s= 170 mm).

Vegetation

The predominant original vegetation types are woodland and grassland, accounting for 60% in the ISIS database, followed by shrubland and forest. Forest and woodland are of a deciduous or semi-deciduous nature. In the data set used, common annual crops are cereals, fibre, oil and protein crops. Most frequently observed perennial crops were stimulants and fruit trees.

Parent material

Parent material is pragmatically grouped according to composition in five categories (see section 3.2). The frequency for the dominant soils are: acid (43 %), intermediate (11 %), basic (23 %), calcareous (9 %) and unconsolidated parent material (15 %). The unconsolidated materials include mainly alluvium and for a minor part colluvium. The representation of the dominant soils in each group:

acid	all soil groups except Phaeozems and Vertisols, Arenosols are restricted to acid parent materials
intermediate	all soil groups, Luvisols dominant
basic	all soil groups, Ferralsols and Vertisols dominant
calcareous	all soil groups
unconsolidated	all soil groups except Ferralsols, Nitosols and Phaeozems

Landform, topography and position of site

The large number of landforms described for the sites are grouped in four major relief categories:

- lowland alluvial and coastal plains 12 %
- upland (non) dissected plains 41 %
- plateaus 21 %
- hills 19 %
- other (a.o. mountains and depressions) 7 %

Frequency of the topography classes, described according to FAO (1988), at the sites are:

- flat 26 %
- undulating 51 %
- rolling 11 %
- hilly 5 %
- steep 7 %

For sloping landscapes, the sites studied are situated principally on middle or flat slope positions. About 30 % is located on a lower, or upper slope or crest position. No correlation was found between landform and soil types. The dominant soils are represented in all landform, topography or position classes, except for the Ferralsols, which are not found in an alluvial plain situation and Planosols which are only found in flat to undulating plain landforms.

Hydrology

Most of the dominant soils are well drained (53 %) or moderately well drained (25 %), a minor part of the sites is imperfectly to poorly drained (14 %) and (somewhat) excessively drained (7 %). In 80 % of the sites no groundwater table was observed. In the other sites the presence of groundwater was observed or inferred from the soil morphology.

4.3 Soil properties

A selection of key analytical properties, relevant for land use analysis and ecological research, is presented in this section and, where appropriate, correlated with field information. In tables 10a and 10b the mean *($\bar{x}$)* and standard deviation *(s)* values of the key analytical properties of the dominant soils in the seasonally dry (sub)tropics are given. From the standard deviations given in tables 10a and 10b it appears that ranges for the given properties are generally large for all dominant soils.

Table 10a Physical properties of dominant soils in the seasonally dry (sub)tropics.

		FERR		ACRI		LUVI		NITO		CAMB		PHAE		VERT		PLAN		AREN	
		$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*	$\bar{x}$	*s*
Sand (%)	*top*	43	27	53	28	51	25	29	27	35	25	27	20	13	8	63	20	86	5
	sub	37	23	40	24	43	20	20	20	38	22	24	15	17	11	51	19	84	6
Silt (%)	*top*	16	11	19	13	19	13	25	17	30	14	35	10	34	17	25	15	9	5
	sub	16	12	19	12	19	13	19	9	30	13	39	15	30	12	14	11	9	5
Clay (%)	*top*	40	19	27	23	30	18	46	25	36	20	38	15	53	16	12	8	5	1
	sub	47	17	40	19	37	14	62	20	36	18	37	16	54	19	36	19	6	4
Silt/Clay ratio	*top*	0.4	0.2	1.1	0.8	0.9	0.8	0.7	0.6	1.2	1.2	1.0	0.4	0.8	0.6	2.6	2.2	2.2	1.7
	sub	0.4	0.3	0.6	0.4	0.6	0.6	0.3	0.2	1.2	1.2	1.3	0.7	0.8	0.7	0.5	0.4	2.7	3.1
Bulk Density (g cm^{-3})	*top*	1.2	0.2	1.4	0.1	1.4	0.2	1.1	0.2	1.2	0.3	1.2	0.2	1.2	0.2	1.6	0.1	1.4	0
	sub	1.2	0.2	1.4	0.2	1.4	0.2	1.1	0.1	1.4	0.1	1.3	0.2	1.2	0.2	1.6	0.1	1.6	0
Rootable Pore Volume (%)	*top*	20	7	16	7	17	8	19	8	15	7	13	7	4	3	12	7	33	0.2
	sub	20	8	10	5	10	7	14	3	12	8	9	5	2	3	9	2	28	1.6
Plant Avail. Moisture (%)	*top*	10	3	11	5	11	3	10	2	15	6	17	6	12	3	12	8	5	0.1
	sub	10	3	10	6	11	4	8	1	12	6	16	9	15	6	10	5	5	0

$\bar{x}$= Mean; *top*= topsoil, 0 - 20 cm
s= Standard deviation *sub*= subsoil, 70 - 100 cm

FERR = Ferralsols (26/18), ACRI = Acrisols (26/12), LUVI = Luvisols (26/14), NITO = Nitosols (8/3), CAMB = Cambisols (24/11), PHAE = Phaeozems (13/9), VERT = Vertisols (16/7), PLAN = Planosols (8/5), AREN = Arenosols (8/2).

The numbers between brackets indicate the number of reference profiles in ISIS database available for statistical analysis. The first number refers to the sand, silt and clay content and chemical properties. The second number refers to Bulk Density, Rootable Pore Volume and Plant Available Water.

Table 10b Chemical properties of dominant soils in the seasonally dry (sub)tropics.

		FERR $\bar{x}$	FERR s	ACRI $\bar{x}$	ACRI s	LUVI $\bar{x}$	LUVI s	NITO $\bar{x}$	NITO s	CAMB $\bar{x}$	CAMB s	PHAE $\bar{x}$	PHAE s	VERT $\bar{x}$	VERT s	PLAN $\bar{x}$	PLAN s	AREN $\bar{x}$	AREN s
pH-H_2O (1:2.5)	*top*	5.3	0.6	5.7	0.6	6.3	0.9	5.8	0.0	5.6	1.1	6.5	1.0	7.1	0.8	5.8	0.7	5.5	0.6
	sub	5.4	0.7	5.2	0.5	6.4	1.0	6.1	1.0	5.9	1.4	7.5	0.8	8.1	0.7	6.4	1.3	5.7	0.8
pH-KCl (1:2.5)	*top*	4.4	0.5	4.8	0.6	5.3	0.8	5.0	0.7	4.8	1.0	5.4	1.0	5.8	0.8	4.5	0.7	4.8	0.7
	sub	4.9	0.8	4.4	0.5	5.2	0.9	5.2	0.8	4.8	1.2	5.7	0.8	6.6	0.8	5.0	1.4	4.7	0.5
Organic Carbon (%)	*top*	1.5	0.8	1.0	0.7	1.0	0.7	2.1	1.3	1.9	1.3	2.3	0.8	1.5	0.7	0.7	0.4	0.5	0.1
	sub	0.4	0.4	0.3	0.3	0.3	0.2	0.8	0.6	0.6	1.0	0.4	0.2	0.5	0.3	0.4	0.4	0.1	0.1
C/N ratio	*top*	18	9	16	5	11	3	11	4	12	5	16	13	18	21	12	3	13	2
	sub	11	7	9	6	7	3	11	8	7	4	8	3	15	12	13	7	5	3
Sum of bases ($cmol_c\ kg^{-1}$)	*top*	2.2	3.1	3.9	3.0	13.5	15.3	8.3	6.3	13.1	21.1	28.1	17.6	53.4	24.5	4.8	2.7	2.1	1.0
	sub	1.3	2.2	2.3	2.1	12.2	12.1	7.2	4.5	13.1	21.1	30.0	17.3	62.7	23.0	13.0	5.5	1.0	0.8
Exch. Al ($cmol_c.kg^{-1}$)	*top*	0.7	0.8	0.5	1.2	0.0	0.1	0.8	2.0	1.2	2.4	0.0	0.0	0.0	0.0	0.1	0.3	0.0	0.0
	sub	0.8	1.8	0.9	2.1	0.0	0.0	0.6	1.3	1.1	2.4	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
CEC_{pH7} ($cmol_c.kg^{-1}$)	*top*	7.6	4.4	7.1	4.8	13.6	12.9	17.6	6.6	18.3	15.9	31.9	14.0	54.0	18.3	6.8	4.0	3.0	1.0
	sub	4.8	3.8	6.5	3.6	12.8	10.0	14.8	5.6	13.2	11.9	28.6	10.2	50.6	16.3	20.4	9.1	1.4	1.0
Base Saturation (%)	*top*	26	25	57	23	88	41	51	32	57	42	85	34	95	21	66	22	72	26
	sub	28	37	40	25	88	43	54	37	73	80	100	33	100	29	78	27	67	57

$\bar{x}$= Mean *top*= topsoil, 0 - 20 cm

s= Standard deviation *sub*= subsoil, 70 - 100 cm

FERR = Ferralsols (26/18), ACRI = Acrisols (26/12), LUVI = Luvisols (26/14), NITO = Nitosols (8/3), CAMB = Cambisols (24/11), PHAE = Phaeozems (13/9), VERT = Vertisols (16/7), PLAN = Planosols (8/5), AREN = Arenosols (8/2).

The numbers between brackets indicate the number of reference profiles in ISIS database available for statistical analysis. The first number refers to the sand, silt and clay content and chemical properties. The second number refers to Bulk Density, Rootable Pore Volume and Plant Available Water.

4.3.1 Physical properties

Particle size distribution

The sand, silt and clay fractions are given in Table 10a. Reflecting their sandy parent material, Arenosols have a low silt and clay content. Also the topsoils of Planosols have a high sand content. Vertisols, Nitosols and Ferralsols have a high clay content in the subsoil. Acrisols, Luvisols and Cambisols have a moderately high clay content. A correlation of clay content with the five parent material composition categories was made. The mean clay content of topsoils formed on acid parent materials is 25 %, compared to about 50 % for intermediate and basic materials, and about 60 % for calcareous materials.

An increase in clay content between topsoil and subsoil is often present in soils of seasonally dry (sub)tropics. This increase is most prominently expressed in Planosols with a mean clay increase of 24 %, which, in most cases takes place abruptly over a short distance and as such forms an impediment to root development and affects soil hydraulic properties.

The second largest clay increase is found in Nitosols with a mean increase of 16 %. In Nitosols, the clay increase is gradual within the first metre. Acrisols have a modest clay increase of 13 %. Ferralsols and Luvisols have a slight increase, with 7 %. In these soils the clay increase is generally gradual. Such gradual increases will have only limited influence on root development and soil hydraulic properties. This is also evidenced by the field morphology, where horizon boundaries are usually gradual or diffuse. For part of the Acrisols and Luvisols, topsoil colour is more greyish in comparison with the subsoils and/or the deeper subsoil may have some mottling. Both features are indicative for water saturation in high rainfall periods. All other dominant soils do not have a clay increase with depth.

Cambisols, Phaeozems and Vertisols have a mean silt content of 30 to 40 %, while in the other dominant soils it is from 10 to 20 %. In the past the silt/clay ratio was often used as a criterion to differentiate soil by age. A silt/clay ratio above 0.15 would be indicative for 'young' soils, i.e. soils in an early stage of weathering, and a ratio of less than 0.15 would be indicative for 'old', strongly weathered soils (Van Wambeke, 1962). A silt/clay ratio of less than 0.2 is one of the requirements of the Ferralic B horizon in the revised FAO system (FAO, 1988).

The silt/clay ratios of the dominant soils in Table 10a confirm the trend that strongly weathered soils have a low silt/clay ratio and 'young' soils a high ratio. Ferralsols and Nitosols have a silt/clay ratio of 0.4 in the subsoil, Acrisols and Luvisols take an intermediate position (0.6), and Cambisols and Phaeozems have a silt/clay ratio of 1.3. However, all these ratios are clearly above mentioned criteria of 0.15 and 0.20. Also, our dataset shows clearly exceptions on the general age trend. For example, the silt/clay ratio of Nitosols is similar to that of the strongly weathered Ferralsols, while Nitosols are less strongly weathered than Ferralsols. It is proposed that the silt/clay ratio should only be seen as an indication for the weathering stage and not be used as a rigid classification criterion. Additionally, it is noted that the silt and clay percentages of a soil are strongly depending on the dispersion procedure applied. As mentioned in section 3.3.1, the use of the silt/clay ratio of less than 0.2 as diagnostic criterion in the revised FAO system (1988) for soils in the humid tropics is also disputable for the Ferralsols of the seasonally dry (sub)tropics, because a considerable part of these soils have a silt/clay ratio higher than 0.2

Bulk density, rootable pore volume and plant available moisture

The mean and standard deviation of bulk density, potential Rootable Pore Volume (PRV) and potential Plant Available Moisture (PAM) for the dominant soils are presented in Table 10a. The mean bulk density of Ferralsols, Nitosols, Cambisols, Phaeozems and Vertisols ranges from 1.1 to 1.3 g cm^{-3}, in comparison to figures of 1.4 to 1.6 g cm^{-3} published elsewhere for similar soils. Except for the Cambisols, for most soils there are no significant differences between the bulk density of the topsoil and the subsoil in the considered data set. This is remarkable, because topsoils tend to have a somewhat lower bulk density because of a higher porosity produced by a higher bio-activity. Except for Vertisols, the RPV of all dominant soils is adequate for most crops in the topsoil. Generally subsoils have lower RPV, with Arenosols, Ferralsols and Nitosols having the highest values.

The potential PAM data of the dominant soils show no large differences between topsoil and subsoil. Phaeozems and Vertisols show the highest potential PAM (16 %) and Arenosols the lowest (5 %). The other soils have moderate to low values (10 to 12 %). A large potential PAM is favourable in view of the long dry period and risk of dry spells during the growing season in the considered agro-ecological zone.

4.3.2 Chemical properties

Soil reaction

Soil reaction of the dominant soils considered range from acid to slightly alkaline (Table 10b). Ferralsols, Acrisols and Arenosols are acid or slightly acid. Luvisols, Nitosols, Cambisols and Planosols are slightly acid to neutral. Phaeozems and Vertisols are neutral to slightly alkaline. For most dominant soils the pH-H_2O of the topsoils is similar or slightly lower than than in the subsoils. Only Acrisols have a more acid subsoil in comparison to the topsoil. Ferralsols have an average delta pH of -0.7 pH unit, whereas most other soils have about -1.0 pH unit. A frequency analysis of the delta pH for all soil samples shows that a positive delta pH is rare, as expected. Positive delta pH's, generally are mainly observed in Geric Ferralsols (FAO, 1988).

Exchangeable aluminium

In general, the exchangeable aluminium content is negligible when pH-KCl exceeds 4.8, corresponding approximately with a pH-H_20 > 5.5, as free aluminium is neutralized at these pH values. Soils with pH below these levels can have exchangeable aluminium contents which induce Al-toxicity and limit for rootgrowth. Figure 3 shows the correlation between pH-KCl and exchangeable aluminium saturation.

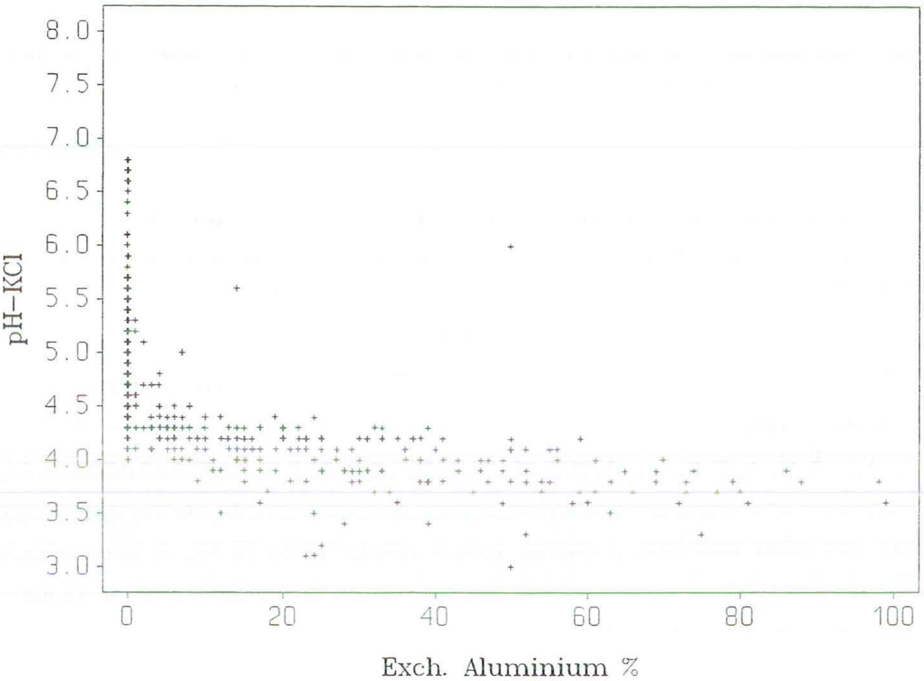


Fig. 3 Scatter plot of exchangeable aluminium saturation against pH-KCl for 176 reference soils from the seasonally dry (sub)tropics

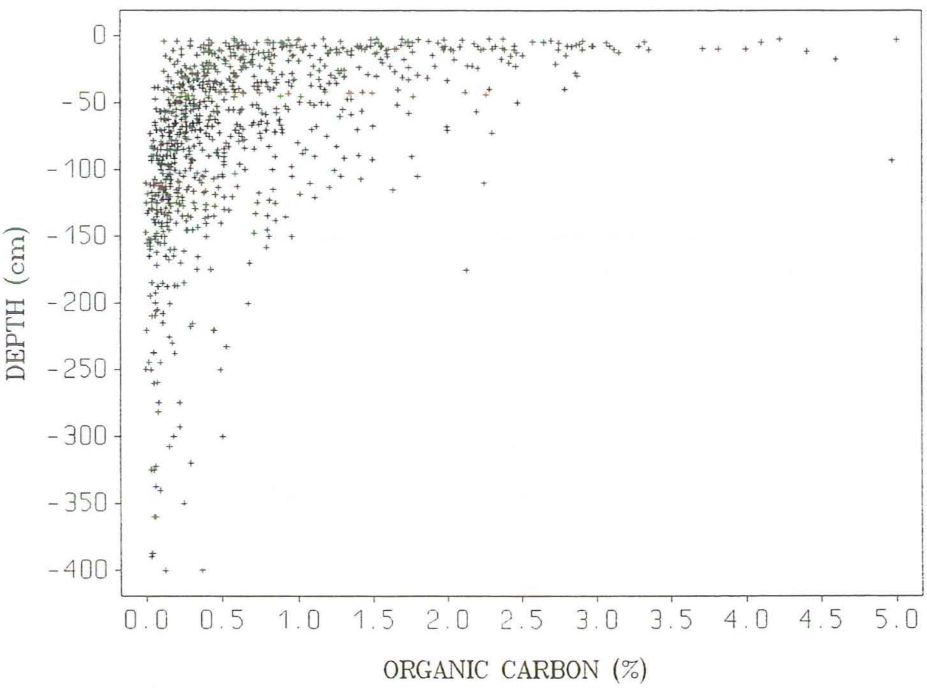


Fig. 4 Scatter plot of organic carbon versus depth for 176 reference soils from the seasonally dry (sub)tropics)

Organic Carbon

Information about soil organic matter is presented as organic carbon. The organic carbon content of topsoil and subsoil for each dominant soil is presented in Table 10b. Arenosols and Planosols have a mean organic carbon content of 0.5 to 0.7 % in the topsoil, which is the lowest level of all dominant soils. An intermediate position is taken by Acrisols and Luvisols with a mean content of 1.0 % and Ferralsols and Vertisols with 1.5 %. Nitosols, Cambisols and Phaeozems have a high mean organic carbon content of 1.9 to 2.3 % in the topsoil.

A plot of organic carbon content with depth of all samples shows an expected highest level of organic carbon in the upper 50 cm of the soil profiles, but also that substantial amounts are found in the deeper subsoil of some soils (Figure 4). The organic carbon in the subsoil (70 - 100 cm) is > 0.5 % in about 30% of all cases. As discussed in section 3.3.2, the relatively high organic carbon levels in the subsoil are not always matched by a darker soil matrix colour. A study of organic carbon in the deeper subsoil is therefore again advocated.

The mean C/N ratios for the dominant soils are presented in Table 10b. Except for Nitosols, Vertisols and Planosols, the overall difference of the C/N ratio between topsoil and subsoil is large. The possible explanation for this feature has been discussed in section 3.3.2. Cambisols, Luvisols and Nitosols have the lowest C/N ratio in the topsoil, indicative of good quality organic matter. High C/N ratios in Ferralsols, Acrisols, Phaeozems and Vertisols indicate that organic matter in these soils is less decomposed.

No correlation was found between organic carbon content and soil reaction at any depth, nor was a correlation observed with the exchangeable aluminium content apparent. The correlation of organic carbon content with parent material has also been studied. For soils derived from acid parent materials the median organic carbon content of the topsoil is 1.0 % less than that of soils developed on basic or intermediate parent materials.

Nutrients

Mean data on exchangeable bases (calcium, magnesium, potassium and sodium), exchangeable acidity (hydrogen and aluminium), and cation exchange capacity (at pH 7) are given in Table 10b. Mean values for the sum of exchangeable bases, cation exchange capacity and base saturation are low for the Ferralsols, Acrisols and Arenosols. Planosols have an intermediate level. Cambisols, Luvisols and Nitosols have high values and Phaeozems and Vertisols have very high values.

There is a correlation between the content of bases in a soil profile and the nature of the parent material; soils developed on basic, calcareous or alluvial parent materials tend to have a considerable higher CEC, sum of bases, and base saturation than those formed from acid parent materials.

Although less frequent in comparison to the humid tropical zone, a high exchangeable aluminium content can also be found in a part of the Acrisols, Ferralsols, Nitosols and Cambisols. A nil or very low exchangeable Aluminium content is present in the other dominant soils. Similarly to the situation of the humid tropics, the mean absolute values of exchangeable aluminium are not very high. Nonetheless, when the aluminium saturation is expressed as percentage of the ECEC it is high in Ferralsols and Acrisols.

4.3.3 Mineralogical properties

The mineralogical composition of the dominant soils, as determined by X-ray analysis of the clay fraction is summarized in Table 11. The semi-quantitative classification is based on the presence and intensity of the peak in the clay mineralogy diagram. Nearly all soils contain some goethite and haematite, but these oxides are not considered in the table. Ferralsols, Acrisols and Nitosols have a strong predominance of kaolinite and minor presence of chlorite. Moderate amounts of gibbsite are only found in Ferralsols. The Luvisols, Cambisols and Phaeozems have various amounts of kaolinite, illite, and mixed layered silicate clays. Expectedly, Vertisols have a predominance of smectite. Planosols and Arenosols have minor presences of kaolinite and smectite.

Table 11 Clay mineralogy of dominant soils in the seasonally dry (sub)tropics

	FERR	ACRI	LUVI	NITO	CAMB	PHAE	VERT	PLAN	AREN
Gibbsite	+				-				-
Kaolinite	+++	+++	++	++	++	+	+	-	++
Halloysite			++		+	+	+		
Illite									
Chlorite	-	-	++	-			-		
Smectite			+		+	+	+++	-	-
Vermiculite					+				

+++ = dominant, ++ = sub-dominant, + = moderate and - = minor presence of a clay mineral

4.4 Major agronomic constraints

4.4.1 All dominant soils

For the purpose of highlighting major soil/land constraints for agriculture, a qualitative evaluation of 15 land qualities was made, according to the procedure given in section 3.4. Frequencies of the five degree classes for the dominant soils are expressed in percentages in Table 12. The assessment should not be regarded as an absolute judgement but rather as a first identification of constraints for agriculture.

Table 12 Frequency[1] (%) of constraints by land quality of all dominant soils

degree of constraints[2] > land quality	no	weak	moderate	serious	very serious
length of growing period	7	74	16	4	0
drought hazard	12	33	39	16	0
soil moisture availability	3	21	45	22	10
oxygen availability	60	23	13	4	0
nutrient availability	6	22	26	32	13
nutrient retention capacity	12	13	22	22	32
rootable volume	55	31	3	2	9
conditions for germination	89	2	8	1	0
salinity	100	0	0	0	0
sodicity	77	10	10	1	3
aluminium toxicity	66	5	11	9	9
workability	21	47	28	5	0
potential for mechanisation	52	18	8	7	15
erosion hazard	52	27	11	4	6
flooding hazard	90	6	4	0	0

1) Because of rounding, the sum of percentages for each land quality may be 99 or 101.

2) The qualitative degree of limitation reads as follows:

no	= no constraint or limitation, no yield reduction
weak	= slight limitation, slight yield reduction
moderate	= moderate limitation, moderate yield reduction
serious	= severe limitation, clear yield reduction
very serious	= very severe limitation, strong yield reduction or no yield.

Severe and very severe constraints with a high probability of occurrence for dominant soils of the seasonally dry (sub)tropics are: a low level of nutrient retention capacity, a low level of plant nutrients, and low potential soil moisture availability. Moderate and severe constraints with a lower probability of occurrence are: a restricted potential for mechanisation, toxicity caused by high exchangeable aluminium level, drought hazard, reduced rootable volume and erosion hazard. The rather low frequency for predicted water erosion hazard is surprising, because water erosion is one of the factual major land degradation hazards in the seasonally dry (sub)tropics. This low outcome should be contributed to the few erosion hazard indicators in ISIS database, such as dominant slope, estimated basic infiltration rate (often unavailable) and evidence of capping/sealing. In addition, it is noted that in the analysis only soil erodibility was assessed and that neither soil cover factors nor climate factors were taken into account. A separate analysis of soil erosion risk using reference soils of ISIS was made by Dijkshoorn (1995). Especially in the seasonally dry tropics rainfall intensity and soil cover are major factors determining soil erosion risk.

4.4.2 Individual dominant soils

In section 4.4.1 the constraints for the dominant soils as one group are presented. In this section the results of a similar assessment was made for each of the dominant soils. Each dominant soil was evaluated for the land qualities indicated in Table 12. Then, for each dominant soil, the median of the land quality ratings was calculated. In Table 13, the resulting major limitations -those that were moderately or (very) severely limiting for at least one soil type- are given for the dominant soils.

Table 13 Major limitations of dominant soils in the seasonally dry (sub)tropics

land quality	ACRI	AREN	CAMB	FERR	LUVI	NITO	PHAE	PLAN	VERT	ALL
drought hazard	x				x		x		x	x
soil moisture	x	xxx	x	x	x	x	x	x		x
rootable volume								xxx		
oxygen availability								x	x	
nutrient availability	xx	xxx	x	xx	x	x		xx	x	x
nutrient retention	xx	xxx	xx	xxx	xx	x		xx		xx
aluminium toxicity				x						
workability								x	x	
mechanisation					x	x		xxx		

x = moderately limiting, xx = severely limiting, xxx = very severely limiting.
ACRI = Acrisols, AREN = Arenosols, CAMB = Cambisols, FERR = Ferralsols, LUVI = Luvisols, NITO = Nitosols, PHAE = Phaeozems, PLAN = Planosols and ALL = overall figure of the 9 dominant soils.

From Table 13, it can be seen that the Nitosols, Phaeozems and Vertisols have the most favourable properties for agriculture. Luvisols and Cambisols have a severe limitation for nutrient retention. Acrisols, Arenosols, Ferralsols and Planosols have (very) severe limitations for nutrient retention and nutrient availability. In addition Arenosols are very severely limited in potential soil moisture and Planosols have very severe limitations for rooting possibilities and potential for mechanisation. Other limitations that can occur in this agro-climatic zone are salinity and sodicity. However, according to FAO (1993) Solonchaks and Solonetz are not dominant in this agro-ecological zone and consequently not included in the set of nine dominant soils.

5 DISCUSSION AND CONCLUSIONS

The number of reference profiles in ISIS by major soil grouping per ecological zone is limited (between 10 to 30) in comparison to the large areas involved (between 50 to 500 million ha). On the other hand, careful selection of the reference profiles, well distributed over each major ecological zone, and uniform analytical procedures (one soil laboratory), makes correlation justified for the ISIS datasets at major soil group level. Results, presented in chapters 3 and 4, and the conclusions below should be seen as indicative only. Departures from these trends will be common in view of the natural spatial variability in soil characteristics, especially when looking at sub-group level. Currently, for most major soil groups the number of reference profiles in ISIS is insufficient for statistical analyses at sub-group level. For such analyses, databases with larger number of soil profiles by major soil grouping are needed (see Part II, this volume).

Humid tropics

A large extent of the humid tropics is covered by low fertile Ferralsols, Acrisols, Arenosols and Podzols, all presenting various degrees of limitations when forests are cleared for (low input) arable farming. Major constraints are a low plant nutrient content, a low nutrient retention capacity and a high exchangeable aluminium content. The combination of these soil-related constraints with a high Leaching Rainfall makes fertilization of these soils difficult. It is disputed whether high fertilizer input, low biomass turn-over, mono-cropping agro-systems are sustainable and whether it could be easily introduced to the farmers on these soils in the humid tropics (Weischet and Caviedes, 1994). A sustainable agro-ecosystem in the humid tropics should aim at a closed nutrient cycle (thus minimalising nutrient losses to the deeper subsoil). Agroforestry systems imitating the rainforest, thus mimicking a permanent vegetative coverage of the soil, crop/plant diversity and a large biomass turn-over, seem to be most promising from the point of view of sustainability. The required higher (manual) labour input and the need of education are probably the main limitations to the adoption of these sustainable agro-forestry systems by the farmers in the humid tropics. Some of the highly unfertile soils need a cropping system with long fallows. In reality this is often not feasible any longer. Technically in those conditions a well-timed and -spaced, moderate fertilizer gift (leading to more biomass and thus more crop residue), combined with topsoil organic matter conservation may improve rooting and fertility conditions. In some of the very acid soils, liming or the use of aluminium tolerant crop varieties may be imperative. However, economic conditions will dictate such, generally costly, fertilizers and soil amendments.

The relatively fertile Cambisols and Luvisols have much less limitations. In view of the persistent ecological constraints of the low fertile soils mentioned before, these fertile soils, covering a smaller area in the humid tropics, should get the maximum attention of more governments and farmers to use these soils for highly productive sustainable agricultural systems.

Arenosols and Podzols can easily be distinguished from the Ferralsols and Acrisols on the basis of their diagnostic properties. The overall data presented in this paper show that Ferralsols and Acrisols, covering 57 % of the humid tropics, have rather similar key properties. The separation is based on a relatively small increase in clay content with depth, which will not affect the major vegetation type or crop productivity level. These conclusions tally with recent research in the Colombian Amazon (Duivenvoorden and Lips, 1995). On the other hand, variability of each key property for both Ferralsols and Acrisols is large. Agricultural land assessment studies and soil vegetation/biodiversity correlation studies should be based on measurements of key soil properties, reflecting the biophysical functioning of the soil, and should not rely only on a soil taxonomic approach.

In view of the very low to low nutrient content of topsoil and subsoil, the decomposing organic materials covering the mineral soil as litter layer should be regarded as an important source of soil fertility. Organic matter should be included as a potential key property.

More focus on topsoil classification is needed in present international soil taxonomic systems, which usually put emphasis on stable subsoil parameters. The topsoil classification of FAO (1992) may also contribute to an improved assessment of the soil fertility status, because initial testing in West Africa shows its potential (Hebel *et al.*, 1994).

Seasonally dry (sub)tropics

A large extent of the seasonally dry (sub)tropics is covered by nine dominant soils. In addition to the Acrisols, Arenosols, Cambisols, Ferralsols and Luvisols, which are the dominant soils of the humid tropics, this ecological zone includes Nitosols, Phaeozems, Vertisols and Planosols. The dominant soils of this ecological zone can be grouped as: a) low fertility soils: Arenosols, Acrisols, Ferralsols and Planosols; and b) high fertility soils: Cambisols, Luvisols, Nitosols, Phaeozems and Vertisols.

In the moister part of the seasonally dry (sub)tropics, Ferralsols, Acrisols, Nitosols and Cambisols have a substantial amount of exchangeable aluminium, although less prominent than in soils of the humid tropics.

Significant differences between physical properties of the topsoil and the subsoil are restricted to clay content of Planosols and Nitosols and Rootable Pore Volume of Acrisols, Luvisols and Nitosols. The difference between topsoil and subsoil is considered minor or nil for the other physical properties. For chemical properties a significant topsoil versus subsoil difference is restricted to organic carbon content for all soils.

Comparing soils of the humid tropics and seasonally dry (sub)tropics

For the low fertility soils, Ferralsols and Acrisols, the nutrient content (expressed by sum of bases) is somewhat higher in the seasonally dry (sub)tropics than in the humic tropics. Nutrient retention capacity, expressed as effective cation exchange capacity CEC (ECEC), is similar for both zones. However, soil fertility management of Ferralsols and Acrisols remains a major constraint in both eco-zones (considering a sum of bases of 1 to 2 $cmol_c\ kg^{-1}$ and a

ECEC of 3 to 4 $cmol_c$ kg^{-1} as critical values, below which soil fertility becomes a major constraint).

On average, topsoil organic carbon content is lower in the seasonally dry (sub)tropics than in the humid tropics. Organic carbon content in the subsoils of the low fertility soils is remarkably constant in both ecological zones, with an average content of 0.4 % for all major soil groups (at a depth of 70 to 100 cm). The topsoil/subsoil ratio of the organic carbon content is higher in the humid tropics, around 5 to 6, whereas this ratio is 2 to 4 in the seasonally dry (sub)tropics. In these low fertility soils, organic matter largely determines the soil nutrient level and the nutrient retention capacity. It is therefore remarkable that this large topsoil/subsoil ratio of organic carbon content is much less reflected in the nutrient level (expressed as sum of bases), with a topsoil/subsoil ratio around 2 to 4. It becomes even less when considering the topsoil/subsoil ratio of the ECEC[1], with a ratio between 1 to 2. This means that the mineral part of the soil, including the subsoil, fulfils a more important role then one would expect from the general accepted dominant role of organic carbon.

Concluding comments

The ISIS database contains a large number of properties of observed and measured land and soil characteristics, which enable the user to make land assessment for selected reference profiles. Nonetheless, it is felt that in order to improve the land assessment exercises some properties, such as effective soil depth, need refinement and sometimes additional properties are required, especially with time dependant properties.

There is a need for better parameters to describe land degradation. For example, the status of erosion is currently assessed with one observation of type and degree of sheet and rill erosion. However, the status of both forms depends much on the time in the year, the type of land use and soil preparation. More observations during the year, preferably also during the rainy season are needed. In addition, other terrain and soil parameters such as structure stability, infiltration rate and/or soil hydraulic conductivity would make the ISIS data even more valuable for use in erosion hazard assessment, crop growth and hydrological modelling.

ACKNOWLEDGEMENTS

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[1] Effective CEC = sum of bases and exchangeable acidity

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PART II

A CHARACTERIZATION OF FERRALSOLS USING THE WISE DATABASE

A CHARACTERIZATION OF FERRALSOLS USING THE WISE DATABASE

N.H. Batjes

ABSTRACT

Selected properties of Ferralsols, including organic carbon and nitrogen pool size, soil reaction, nutrient status, and soil water holding properties are analyzed. The primary physical and chemical data have been derived from WISE, the World Inventory of Soil Emission Potentials database, which holds descriptions for 261 Ferralsols from 35 countries worldwide. In studying the data sets, special attention was paid to the comparability of the analytical methods used to analyze the various data sets. Mean organic carbon content of Ferralsols to a depth of 100 cm is 10.3 kg m^{-2}. Median pH(H_2O) ranges from 4.5 to 5.5 with extremes of 3.3 and 7.6, respectively. Median effective cation exchange capacity (ECEC) is 2.1 $cmol_c$ kg^{-1}, ranging from 0.6 $cmol_c$ kg^{-1} for Acric Ferralsols to 5.3 $cmol_c$ kg^{-1} for Humic Ferralsols. A large fraction of this ECEC is due to the presence of organic matter. Median bulk density is 1.3 Mg m^{-3}, and available moisture held between a matric potential of -10 KPa and -1500 KPa is 0.11 cm^3 cm^{-3} by volume, while it is 0.07 cm^3 cm^{-3} between -33 KPa and -1500 KPa. The study serves to illustrate the potential of soil databases, such as WISE, in identifying and quantifying major soil constraints and soil indicators of sustainability at the continental level.

1 INTRODUCTION

Soils of the Humid Tropics and Subtropics vary widely in their properties. To understand this variation and its consequences for land use, it is necessary to know their modes of formation and the genetic pathways that shaped the characteristics attributes of the various soil types. Acrisols, Ferralsols, Gleysols, Arenosols, Cambisols and Nitosols account for about 82% of the Humid Tropics and Subtropics (Table 1). This climatic zone is characterized by high temperatures throughout the year and only a short dry season. It is typical of some $1926x10^6$ ha globally which are located mainly in the Amazon basin, central and coastal Africa, Southeast Asia, and the islands of the Pacific Ocean (FAO, 1993).

The long growing period in excess of 270 days combined with high air temperatures (Tm > 18 degrees C are conditions that favour growth of tropical rainforests. Broadly these climatic conditions correspond with the Af, Am and part of the Aw class of Köppen (Kauffman *et al.*,

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Edited by J.H. Kauffman

1995), but other Köppen climate classes are represented also. The pervasive humid and perhumid conditions permit agricultural activities throughout the year. High rainfall and continuous humid

Table 1 Main soil units of the humid tropics and subtropics (after FAO, 1993)

Soil unit	Area	
	10^6 ha	%
Acrisols	589.4	30.6
Ferralsols	507.2	26.3
Gleysols	167.7	8.7
Arenosols	127.3	6.6
Cambisols	95.6	5.0
Nitisols	87.3	4.5
Other units	351.5	18.3
Total	1926.0	100.0

Note: 1990 FAO-Unesco Legend.

conditions, however, can form a limitation for annual crops that require a dry period at ripening (e.g. cereals) and are conducive to the incidence of pests and mildew. In addition to socio-economic issues, intensification and extension of agriculture to marginal lands have created severe environmental problems, such as soil degradation, pollution of water and land, and increased emissions of trace gases that enhance the "greenhouse effect". As a result of poor management practices, often associated with poverty and uncertain land tenure, soil organic matter content is decreasing (e.g. through deforestation, land use conversion) and as a result cation exchange capacity, water holding properties and structural stability also decrease, seriously reducing the possibility for sustainable agriculture.

In this paper the focus is on Ferralsols which cover ≈ 507×10^6 ha globally (Table 1), and occur mainly in South and Central America, Central Africa with scattered areas elsewhere (Figure 1). Ferralsols are formed by strong and deep weathering and desilication in humid, free-draining environments. Generally, they cover old geomorphic surfaces or characterize soils in recently deposited pre-weathered sediments that originate from old regoliths. They may also occur on young ultrabasic rocks that weather rapidly. Typically, Ferralsols have a good structure and an oxic B horizon caused by destruction of the sorptive complex and accumulation of hydrated oxides as demonstrated by a low CEC (< 16 $cmol_c\ kg^{-1}$ by 1 M NH_4OAc). Ferralsols correlate with Oxisols of the USDA Soil Taxonomy, Latosols of the Brazilian system, and Sols Ferralitiques Typiques of the French system.

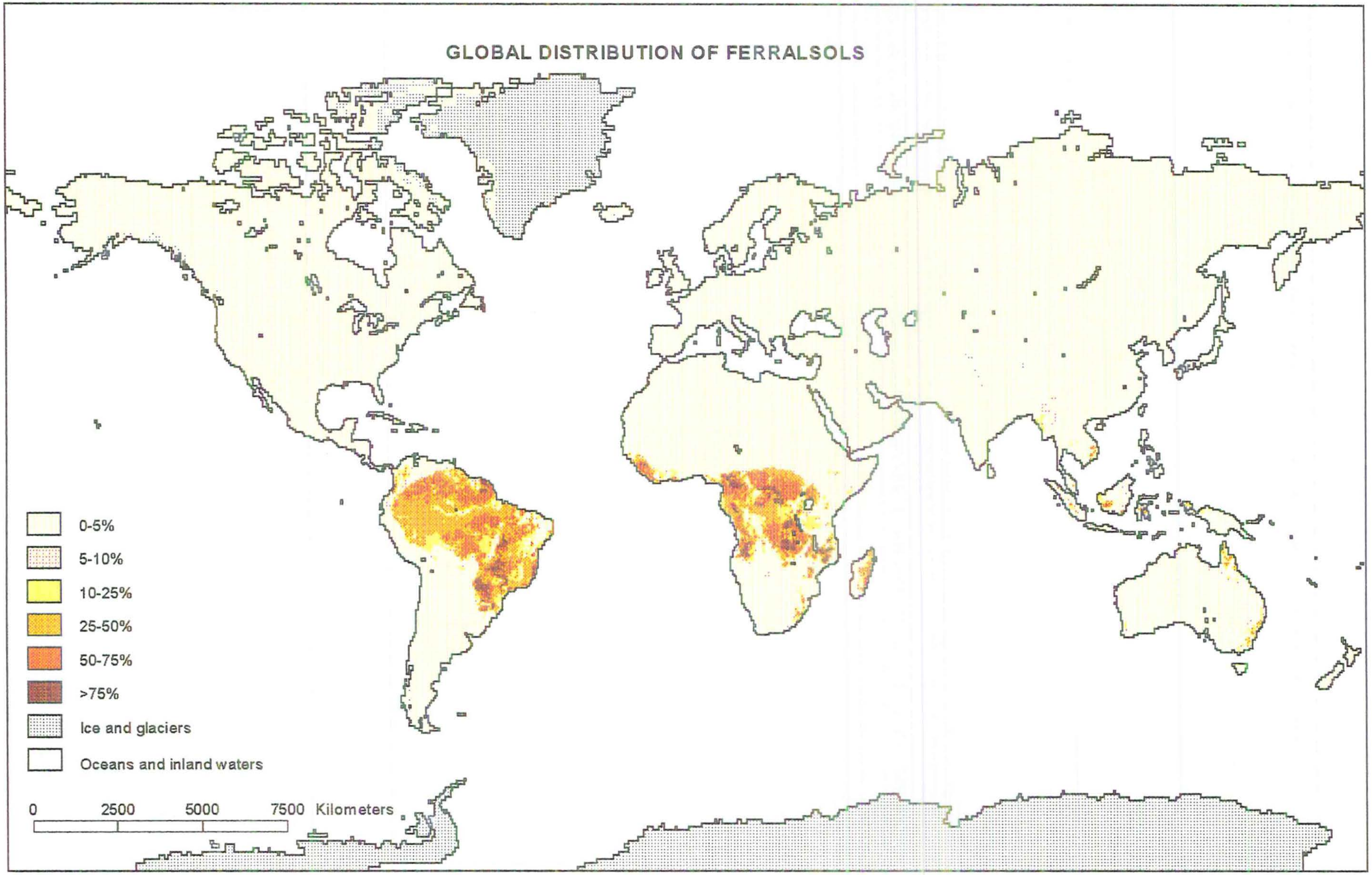
GLOBAL DISTRIBUTION OF FERRALSOLS
0-5%
5-10%
10-25%
25-50%
50-75%
>75%
Ice and glaciers
Oceans and inland waters
0 2500 5000 7500 Kilometers

Fig. 1

The primary, analytical data on Ferralsols have been derived from WISE, the World Inventory of Soil Emissions Potentials (WISE) database (Batjes and Bridges, 1994). The structure of and data sources for compiling WISE are presented in section 2. Section 3 presents results of selected analyses of the data set including soil carbon and nitrogen pool sizes, soil reaction (pH), cation exchange properties, bulk density and available water capacity. In conclusion, the usefulness of soil databases such as WISE for a better characterization of soil conditions - state land quality indicators - is outlined and priorities for further work are identified.

2 MATERIALS AND METHODS

WISE, the World Inventory of Soil Emission Potentials database, consists of spatial data and attribute data (Figure 2). The first holds data on the type and relative extent of the component soil units of each terrestrial ½° latitude by ½° longitude grid cell of the world, and was edited and derived from the digital version of the Soil Map of the World (FAO, 1991; Nachtergaele, *unpublished*). Each of these grid cells consists of up to 10 different soil units of which there are 106 in total (FAO-Unesco, 1974; FAO, 1991).

In order to enable a better characterization of the soil units, the spatial component has been linked to a database of measured profile data using the FAO-Unesco soil unit codes. The profile data were obtained from: (a) ISRIC's Soil Information System; (b) FAO's Soil Database System; (c) the digital soil data set compiled by the Natural Resources Conservation Service of the United States of America (NRCS); (d) profile descriptions selected by national soil survey

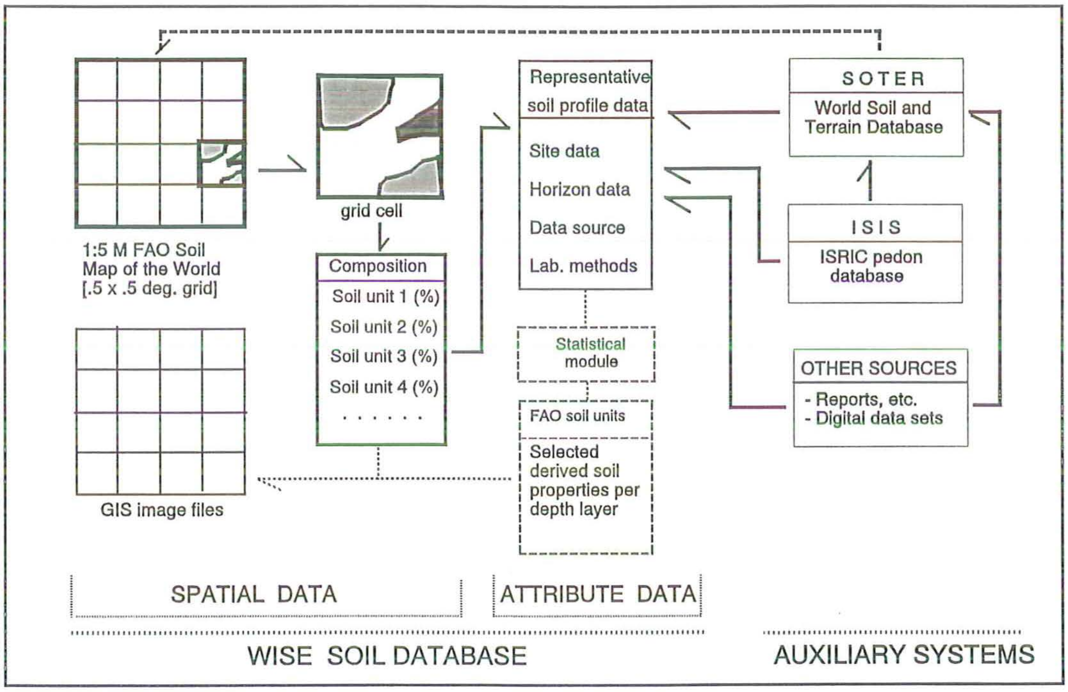

Fig. 2 Schematic representation of the WISE database

organisations considered to be representative for the units of the Soil Map of the World present in their countries; and (e) profile descriptions from survey monographs held at ISRIC's library. The source of data and laboratory methods have been coded in the profile database.

WISE holds data for 4353 globally distributed profiles of which 261 are Ferralsols. These profiles originate from Brazil (53), Zambia (24), Angola (23), Zaire (16), Indonesia (17), Gabon (10), Malaysia (11) and 27 other tropical countries with 107 profiles. The second level units represented include: Acric (24), Humic (50), Orthic (85), Plinthic (8), Rhodic (44) and Xanthic (50) Ferralsols. In view of differences in analytical methods (see Vogel, 1994) the data set was "homogenized" prior to analysis.

The methods considered in the "homogenized" data set are: organic carbon by Walkley-Black; total nitrogen by Kjeldahl; cation exchange capacity (CEC) in 1 *M* NH_4OAc, buffered at pH 7; effective cation exchange capacity (ECEC) as sum of exchangeable bases plus 1 *M* KCl exchangeable acidity; soil reaction, measured in a 1:1 to 1:5 soil to water solution; particle size according to USDA (clay< 0.002 mm < silt <0.05 mm < sand < 2 mm); bulk density and moisture content from core sampling (pF-rings). As a result of this screening on analytical methods, the number of samples available for the various types of analyses varies.

No attempt was made in this study to locate where individual profiles occur because the profiles were collected to be representative for a particular FAO-Unesco (1974) soil unit. As such, differences in landforms, parent material, land use history and native vegetation are not considered.

During initial studies of the "homogenized" data sets it appeared that the frequency distributions for many of the soil attributes considered showed some degree of non-normality (skewness). Therefore it was considered preferable to present summaries of most of the data as medians and interquartiles (see Spain *et al.*, 1983).

3 PHYSICO-CHEMICAL PROPERTIES OF FERRALSOLS

3.1 Soil C and N pools

Global estimates

Prior to discussing estimates of the pool size of soil carbon and nitrogen for Ferralsols, the total amount of C and N in the soil of the humid tropics and subtropics will be estimated. In the ideal situation, a map showing areas of similar length of the growing period and similar ranges in air temperature would have been overlaid on to the WISE database to demarcate the Humid Tropics and Subtropics. Such an Agro-Ecological Zones map is being developed by FAO-IIASA (Van Velthuizen, *pers. comm.*) and as such was not yet available for the present study. As an alternative approach, the Holdridge life-zones database — simplified to 14 zones by Leemans (see Kineman, 1992) — was overlaid on to the WISE database. The Holdridge classification scheme assigns a life-zone based on bio-temperature and annual precipitation. The assumption

Table 2 Estimated organic carbon and nitrogen pools, aggregated per Holdridge life-zone (Pg C respectively N for specified depth zone (d), corrected for fragments > 2mm)

Holdridge life-zone	SOC	CAC	TOT-C	N	Area†
d= 0-30 cm					
Trop. Seasonal Forest	70.8	6.8	77.6	6.7	15.08
Trop. Rain Forest	45.7	2.7	48.4	4.0	8.46
All ecosystems	684.1	222.0	906.1	63.0	135.39
d= 0-100 cm					
Trop. Seasonal Forest	133.0	21.1	154.1	13.5	15.08
Trop. Rain Forest	89.0	8.6	97.6	8.0	8.46
All ecosystems	1462.0	695.0	2157.0	133.0	135.39

†Area in 10^6 km^2, excluding land glaciers. Holdridge life-zones as simplified to 14 classes by Leemans (see Kineman 1992).
SOC = soil organic carbon; CAC= soil carbonate carbon; TOT-C= (SOC + CAC); N= total nitrogen; sums may not exactly add up to totals shown for all life-zones due to rounding.

in the present study is that the Tropical Rain Forest and Tropical Seasonal Forest life-zones correspond with the Humid Tropics and Subtropics. It should be noted, however, that the extent of $23.5x10^6$ km^2 of the Tropical Seasonal Forest and Tropical Rainforest life-zone (Table 2) is somewhat greater than the $19.3x10^6$ km^2 estimated for the Humid Tropics and Subtropics (Table 1).

First the weighted amount of soil organic carbon (SOC), calcium carbonate carbon (CAC) and nitrogen (N) was computed for each ½° terrestrial grid, using the grid's full soil unit composition. Areas of oceans, inland waters and glaciers were assigned zero values by default. Next, the weighted grid averages were combined with data on the geographical distribution of Holdridge life-zones worldwide. Thereby the current (indirect) approach differs from the one used by Post *et al.* (1982) in which profiles were directly allocated to a Holdridge life-zone, where the life-zones were derived from digital maps. It takes into account that different soil types occur in a given Holdridge life-zone. Using the figures for Pg C (10^{15} g) and area estimates, weighted soil organic and carbonate carbon densities were computed for the various life-zones (Figure 3). Mean values to a depth of 1.0 m range from 3.2 kg SOC-C m^{-2} for soils of the Hot Desert life-zone to 23.2 kg SOC-C m^{-2} for soils of the Boreal Forest life-zone. Weighted averages for soils of the Tropical Seasonal Forest are 8.8 kg m^{-2} SOC-C and 10.5 kg m^{-2} SOC-C for the Tropical Rain Forest (to a depth of 100 cm). Comparison of these figures with those of other researchers (e.g. Post *et al.* 1982; Houghton 1995; Sampson *et al.* 1993) is complicated by differences in definitions and procedures for aggregating life-zones or ecosystems.

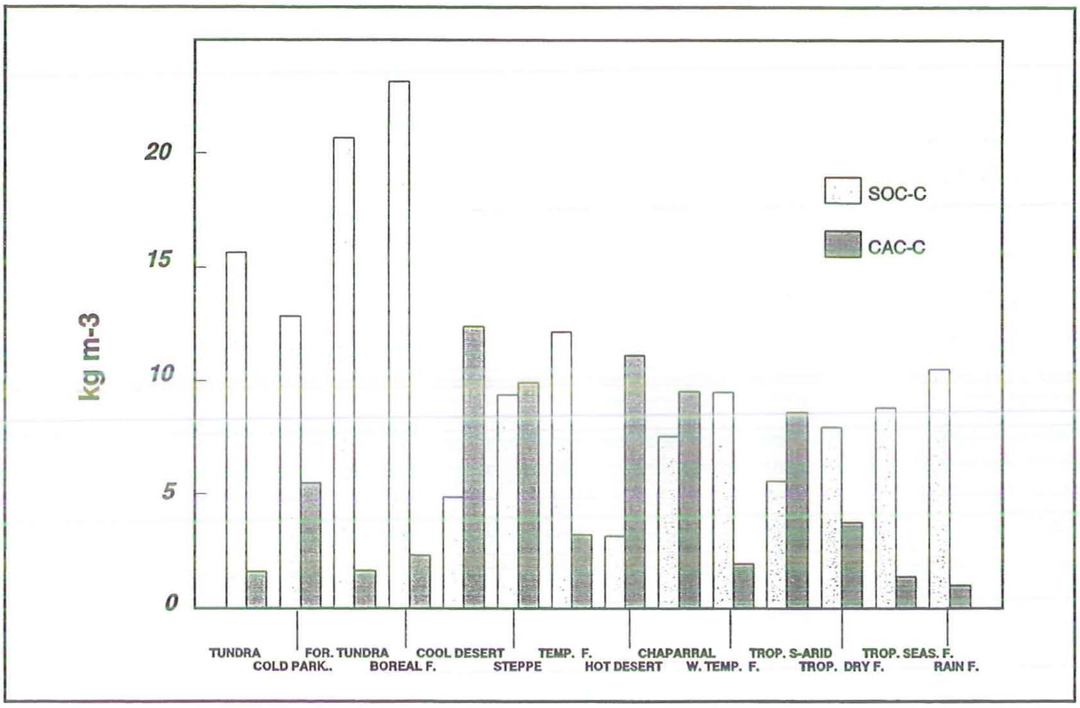

Fig. 3 Weighted soil carbon density by simplified Holdridge life-zones (kg m^{-2} to 100 cm depth; SOC-C= soil organic carbon; CAC-C= soil carbonate carbon; corrected for coarse fragments; Batjes, 1995b

About 117 Pg SOC-C is held in the upper 30 cm and 222 Pg SOC-C in the first 100 cm of soils of the Tropical Seasonal Forest and Tropical Rain Forest life-zones (Table 3). With respect to CAC, these estimates are 9.5 Pg C and 29.6 Pg C, respectively, corresponding with estimates for total carbon of 126 Pg C in the first 30 cm and 252 Pg C for the upper 100 cm.

Table 3 shows there is about 140 Pg SOC-C in the upper 100 cm of Ferralsols, corresponding to about 36% of the 384 Pg of SOC-organic in soils of the Tropics (defined as bounded by 23.5° N and 23.5 °S). The latter value compares well with the 393 Pg of SOC-C estimated for soils of the Tropical Semi-Arid, Tropical Dry Forest, Tropical Seasonal and Tropical Rainforest Life Zones of Holdridge (Batjes, 1995b).

Table 3 Global estimates of soil C and N pools in Ferralsols (for 0-30 cm and 0-100 cm depth; Pg; totals corrected for fragments > 2mm)

Soil name	SOC-C	CAC-C	Tot-C	N
d= 0-30 cm				
Acric Ferralsol	2.5	0.0	2.5	0.2
Humic Ferralsol	2.5	0.0	2.5	0.2
Orthic Ferralsol	21.0	0.0	21.0	1.8
Plinthic Ferralsol	3.3	0.0	3.3	0.2
Rhodic Ferralsol	3.1	0.0	3.1	0.3
Xanthic Ferralsol	8.1	0.0	8.1	0.6
Ferralsols, undiff.	75.8	0.0	75.8	6.4
d= 0-100 cm				
Acric Ferralsol	4.8	0.0	4.8	0.5
Humic Ferralsol	5.0	0.0	5.0	0.3
Orthic Ferralsol	37.4	5.7	43.1	3.8
Plinthic Ferralsol	6.3	0.0	6.3	0.4
Rhodic Ferralsol	5.7	0.7	6.4	0.6
Xanthic Ferralsol	15.5	0.0	15.5	1.4
Ferralsols, undiff.	139.9	6.4	146.3	14.3

Effect of climate

Ferralsols are found under almost any kind of tropical vegetation, with moisture regimes being mainly udic and occasionally ustic, such as in the *cerrado* in Brazil. The temperature regime of Ferralsols generally is isomesic to isohyperthermic, but in the southern part of South America and Africa this may become hyperthermic and thermic (Van Wambeke, 1992). This fairly wide range in climatic conditions is reflected in Table 4, which shows that Ferralsols in WISE occur in the Af to Bs categories of Köppen's classification system. Seventy five percent of the profiles considered are from tropical rainy climates (A type).

Estimates of the pool size of organic carbon of Ferralsols as a function of climate are presented in Table 4. Average soil carbon content to a depth of 100 cm is 10.3 kg m^{-2} and ranges from 6.3 kg m^{-2} in the "Humid mesothermal climate with dry summer" (Cs) to 18.5 kg m^{-2} in the "Humid mesothermal climate, moist in all seasons" (Cf) category. Within the Tropical rainy climates (A) mean organic carbon content ranges from 9.6 kg m^{-2} for Aw climates to 12.4 kg m^{-2} for monsoonal climates (Am). Lowest amounts are recorded in climates with a dry season in the summer of the respective hemispheres (Cs and Bs). It should be noted, however, that Ferralsols in the Bs and Cs zones have been formed in the past under more humid conditions facilitating the extreme weathering typical of these soils.

Table 4 Organic carbon content of Ferralsols grouped by Köppen (kg C m^{-2} to a depth of 100 cm)

Köppen Soil unit	Am	Af	Aw	Cf	Cw	Cs	Bs	All
Acric Ferralsol	2 8.65 14%	6 9.7 33%	6 11.9 38%	0 - -	4 14.0 42%	3 8.6 41%	0 - -	21 10.6 44%
Humic Ferralsol	3 17.9 19%	3 14.7 6%	13 18.3 21%	6 19.1 70%	5 20.2 24%	0 - -	0 - -	30 18.5 59%
Orthic Ferralsol	9 13.4 34%	9 11.4 51%	35 8.53 54%	1 13.7 -	7 6.9 69%	4 5.9 31 %	2 5.1 43%	67 8.5 54%
Plinthic Ferralsol	0 - -	0 - -	3 9.9 30%	0 - -	0 - -	0 - -	0 - -	3 9.9 30%
Rhodic Ferralsol	4 10.8 18%	4 8.8 41%	17 10.1 10%	1 13.1 -	4 13.6 63%	3 6.3 34%	2 7.2 9%	35 10.1 50%
Xanthic Ferralsols	7 11.9 26%	18 10.2 34%	16 6.0 36%	0 - -	2 8.41 -	0 - -	0 - -	7 11.9 26%
Ferralsols, undiff.	25 12.4 35%	40 10.2 39%	90 9.6 69%	8 18.5 74%	22 12.9 54%	10 6.3 36%	4 6.7 29%	199 10.3 66%

Shown per column are the number of observations, the mean and coefficient of variation.

When considering second level units irrespective of climate, the general pattern observed for organic carbon pools to a depth of 100 cm is as follows: humic > xanthic > acric ≈ rhodic >plinthic > orthic. When looking at the effect of Köppen climate on soil organic carbon reserves by second level units no single clear pattern can be observed, which may be a reflection of the importance of other soil forming factors that were not considered explicitly in the analyses (e.g. land use history, parent material, landform).

With respect to humic Ferralsols of the Af zone, the computed mean of 14.7 kg m^{-2} to a depth of 100 cm is lower than the 16 kg m^{-2} which FAO-Unesco (1974) defines as being diagnostic. This kind of "discrepancies" are likely the result of missing, measured bulk density data; in the classification stage a higher bulk density may have been assumed (1.4 Mg m^{-3}) than the average bulk density computed by soil subunit during the analyses using the "homogenized" data set.

3.2 Soil pH and nutrient status

Soil pH is a useful attribute, in that whether a soil is acidic, neutral or alkaline influences the solubility of various compounds, the relative bonding of ions to exchange sites, and the activity of various microorganisms. Median pH of Ferralsols ranges from 4.5 to 5.5 with extremes of 3.3 and 7.6, respectively (Table 5). The general pattern, when going from acid to basic conditions, is: Xanthic (Fx) ≈ Acric (Fa) ≈ Humic (Fh) < Orthic (Fo) ≈ Plinthic (Fp) ≈ Rhodic (Fr). A pH below 5.5 points to the likely occurrence of exchangeable Al^{3+}, toxic to sensitive crops. Below a pH of 4.5 a significant amount of exchangeable H^{+} is probably present in addition to exchangeable Al^{3+}. The low pH values also point at low nutrient reserves (Table 6). In view of the overall low amounts of exchangeable bases no further data are presented for the subunits.

Table 5 Median pH(H_2O) for Ferralsols (source: Batjes, 1995)

FAO unit	0 to 30 cm				30 to 100 cm			
	N	Med.	Min.	Max.	N	Med.	Min.	Max.
Fx	112	4.5	3.3	6.2	104	4.8	3.8	5.9
Fa	45	4.7	3.9	5.9	41	5.1	4.0	6.7
Fh	96	4.9	3.0	6.6	107	5.1	3.9	6.9
Fo	170	5.0	3.5	7.4	157	5.2	4.2	7.9
Fp	15	4.9	4.1	6.2	19	5.4	4.4	6.2
Fr	82	5.5	4.0	7.6	70	5.5	3.8	8.0

Table 6 Exchangeable bases ($cmol_c$ kg^{-1}) and exchangeable aluminium (% of ECEC) for Ferralsols.

Quartile	Exch. Ca^{2+}	Exch. Mg^{2+}	Exch. Na^{+}	Exch. K^{+}	Exch. Al^{3+}
First	0.1	0.1	0.0	0.0	8 %
Median	0.2	0.2	0.0	0.1	24 %
Third	1.0	0.6	0.1	0.1	38%

Note: The number of samples (N) is 958 for exchangeable bases and 322 for exchangeable Al^{3+}.

Median extractable phosphorus (Bray-1) in the topsoil is 4.4 mg P_2O_5 kg^{-1}, with upper and lower quartiles of 2.0 and 6.4 mg P_2O_5 kg^{-1} respectively, which indicates that responses to P-fertilizers are likely to be positive (Landon, 1991).

3.3 Cation exchange capacity

As a result of strong weathering and leaching over a long period of time Ferralsols are rich in kaolinite and oxides of aluminium and iron. Whereas kaolinite has a permanent charge, sesquioxides have variable charge that varies with the pH of the soil and the concentration of potential determining ions in the soil solution. Given the high amounts of variable charge particles in Ferralsols — including organic matter — the cation exchange properties determined in 1 *M* NH_4OAc at pH 7 (CEC) will overestimate the effective cation exchange capacity (ECEC) that exists under field conditions. This aspect is illustrated in Table 7 and 8.

Table 7 ECEC properties of Ferralsols ($cmol_c$ kg^{-1})

FAO		ECEC			$ECEC_{clay}$		
	N	Qu1	Med	Qu3	Qu1	Med	Qu3
Undiff.	240	1.1	2.1	3.9	2.9	4.7	8.6
Fa	35	0.3	0.6	1.2	0.6	1.1	2.7
Fh	34	2.8	5.3	16.9	4.1	7.9	29.1
Fo	72	1.0	1.8	3.0	3.4	4.8	6.9
Fp	3	2.2	4.0	4.6	3.4	6.5	6.9
Fr	22	1.2	1.8	4.0	2.6	3.4	6.5
Fx	74	1.7	2.7	4.2	3.8	6.4	10.7

ECEC is the effective cation exchange capacity measured as sum of bases plus exchangeable acidity in 1 *M* KCl. Qu1 and Qu3 stand for 1st and 3rd quartile, respectively. Med is the median and N the number of observations.

Table 8 CEC properties of Ferralsols ($cmol_c$ kg^{-1})

FAO		CEC			CEC_{clay}		
	N	Qu1	Med	Qu3	Qu1	Med	Qu3
Undiff.	980	3.2	5.5	8.7	8.0	12.2	18.7
Fa	100	1.4	2.6	5.5	2.5	5.5	10.8
Fh	242	3.8	7.1	9.8	8.7	13.7	21.5
Fo	306	3.1	5.1	8.9	9.0	12.7	20.0
Fp	22	4.8	6.2	8.0	8.5	10.5	13.0
Fr	149	4.1	6.4	8.8	8.4	12.4	16.7
Fx	161	3.2	4.8	7.6	9.2	14.1	22.1

CEC is the cation exchange capacity measured in a 1 *M* NH_4OAc solution buffered at pH 7. Qu1 and Qu3 stand for 1st and 3rd quartile, respectively. Med is the median and N the number of observations.

Median ECEC of Ferralsols is 2.1 $cmol_c$ kg, ranging from 0.6 $cmol_c$ kg^{-1} for Acric Ferralsols to 5.3 $cmol_c$ kg^{-1} for Humic Ferralsols. In the latter, a large fraction of ECEC is due to the organic matter. $ECEC_{clay}$ is 4.7 $cmol_c$ kg^{-1} for Ferralsols, ranging from 1.1 $cmol_c$ kg^{-1} for Acric to 7.9 $cmol_c$ kg^{-1} for Humic Ferralsols. A large fraction of the so-called $ECEC_{clay}$ — i.e. the value obtained by dividing ECEC of fine earth fraction by the clay percentage without correcting for the contriibution of organic matter to ECEC — of Humic Ferralsols is due to organic matter. The low ECEC values indicate limited ability to retain nutrient cations against leaching.

Table 8 reflects the effect of electrolyte type and concentration on CEC with median value of 5.5 cmol kg^{-1} for Ferralsols, ranging from 2.6 $cmol_c$ kg^{-1} for Acric Ferralsols to 7.1 $cmol_c$ kg^{-1} for Humic Ferralsols.

Table 9 shows linear regressions of ECEC and CEC, respectively, against the ratio of organic carbon over clay sized particles (<2 μm). The relatively low coefficients of determination of the regressions point at a relatively low predictive capability.

Table 9 CEC and ECEC properties of Ferralsols.

Soil unit	Linear regression	r^2	n
ECEC:			
Ferralsols	$Y_{ecec} = 3.527^{**} + 2.169X^{***}$	0.25	240
Acric	$Y_{ecec} = 0.093^{ns} + 0.827X^{***}$	0.48	35
Humic	$Y_{ecec} = 1.258^{ns} + 5.521X^{***}$	0.73	34
Orthic	$Y_{ecec} = 2.518^{*} + 1.609X^{***}$	0.40	72
Plinthic	$Y_{ecec} = 4.741^{ns} + 0.316X^{ns}$	0.16	3
Rhodic	$Y_{ecec} = 2.950^{ns} + 2.372X^{ns}$	0.19	22
Xanthic	$Y_{ecec} = 9.325^{***} + 0.193X^{ns}$	0.01	74
CEC:			
Ferralsols	$Y_{cec} = 7.890^{***} + 2.785X^{***}$	0.56	980
Acric	$Y_{cec} = 3.381^{***} + 2.137X^{***}$	0.44	100
Humic	$Y_{cec} = 7.796^{***} + 2.585X^{***}$	0.59	242
Orthic	$Y_{cec} = 7.160^{***} + 3.410X^{***}$	0.65	306
Plinthic	$Y_{cec} = 6.126^{***} + 2.705X^{***}$	0.53	22
Rhodic	$Y_{cec} = 8.030^{***} + 3.098X^{***}$	0.58	149
Xanthic	$Y_{cec} = 11.667^{***} + 2.308X^{***}$	0.46	161

CEC is cation exchange capacity in 1 *M* NH_4OAc, buffered at pH 7; ECEC is effective cation exchange capacity determined as sum of exchangeable bases plus exchangeable aluminium in 1 *M* KCl; levels of significance: ns (not significant); P<0.01 (*); P<0.001 (**); P<0.001 (***). X is the ratio of organic carbon over clay sized particles.

3.4 Soil physical properties

Table 10 shows selected physical attributes for Ferralsols, including bulk density and available water capacity for the pF range from 2.0 to 4.2 (AWC1) and from pF 2.5. to pF 4.2 (AWC2), respectively. Median bulk density of Ferralsols is 1.3 Mg m^{-3}, with lowest median value of 1.1 Mg m^{-3} observed for Acric Ferralsols and the highest value of 1.4 Mg m^{-3} for Orthic Ferralsols.

Table 10 Bulk density and available water capacity of Ferralsols

FAO unit	Bulk density				AWC1				AWC2			
	N	Qu1	Med	Qu3	N	Qu1	Med	Qu3	N	Qu1	Med	Qu3
Undiff.	512	1.11	1.29	1.42	281	8.0	11.0	15.0	307	5.0	7.0	10.0
Fa	55	0.90	1.11	1.27	36	7.0	9.0	11.0	9	5.5	6.0	8.5
Fh	163	1.07	1.23	1.34	60	9.0	11.0	13.0	130	6.0	8.0	11.0
Fo	135	1.24	1.41	1.50	103	9.0	13.0	22.0	111	4.0	6.0	9.0
Fp	11	1.26	1.35	1.38	10	7.8	9.0	13.3	10	6.0	7.5	10.0
Fr	80	1.12	1.24	1.37	30	8.0	10.0	12.0	9	6.0	7.0	8.5
Fx	68	1.12	1.37	1.46	42	8.8	11.5	13.3	32	6.0	7.0	8.8

Note: Bulk density is expressed in Mg m^{-3}; available water capacity is for the range pF2.0 to pF2.5 (AWC1), and pF2.5 to pF4.2 (AWC2), respectively, and expressed in 10^{-2}xcm^3 cm^{-3} vol/vol (or %).

Median AWC1 for Ferralsols is 0.11 cm^3 cm^{-3} (% v/v) as opposed to 0.07 cm^3 cm^{-3} for AWC2, reflecting that a fairly large proportion of water is released between a matric potential of -10 KPa (or pF2.0) and -33 KPa (or pF2.5) in Ferralsols. It has therefore been argued that -10 KPa tension is a better upper limit than -33 KPa for estimating plant available water content in Ferralsols (Van Wambeke, 1992). Annual crops grown in deep Ferralsols are more prone to drought than those grown in other soils of comparable clay content because of the low water-holding capacity of oxic horizons. In fact, clayey Ferralsols often resemble sandy soils in their moisture holding properties. This is due to the presence of "pseudo-silt". However, Ferralsols are physiologically dry at higher water contents than sandy soils.

Table 11 shows linear regressions of bulk density, volume water held at selected pF-values, and available water capacity against measured silt, clay and organic matter content. Although all regressions are highly significant, with coefficient of linear determination (r^2) of 0.88 to 0.95, the predictive value was shown to be low. "If the aim is to predict individual responses, a value of r^2 which is less that 90% suggests the predictive power of the equation will almost certainly be too poor to have practical value" (McPherson, 1990 p. 547).

There are very few data on hydraulic conductivity for Ferralsols in WISE. Under water saturated conditions, K_{sat} of freely drained Ferralsols is 8 to 15 cm h^{-1} (Van Wambeke, 1992).

Table 11 Soil physical attributes for Ferralsols

Linear regression	r^2	n
ρ = 0.0211*S^{***} + 0.0.0164*C^{***} + 0.0283*O^{ns}	0.88	149
$\theta_{pF2.0}$= 0.3301*S^{***} + 0.4842*C^{***} + 2.712*O^{***}	0.95	149
$\theta_{pF2.5}$= 0.0317*S^{ns} + 0.5503*C^{***} + 1.811*O^{**}	0.92	149
$\theta_{pF4.2}$= -0.0643*S^{*} + 0.4804*C^{***} + 0.5247*O^{**}	0.90	149
$AWC_{(pF2.0-pF4.2)}$= 0.0960*S^{***} + 0.0699^{***} + 1.287*O^{***}	0.88	149
$AWC_{(pF2.5-pF4.2)}$= 0.3944*S^{***} + 0.0038^{***} + 2.1870*O^{***}	0.94	149

ρ is bulk density (g cm^{-3}); $\theta_{pF2.0}$ stands for percentage moisture (v/v) held at a soil-matric potential of pF 2.0 (or -10 KPa); AWC is available water capacity, calculated over specified pF range. Levels of significance: ns, not significant; P<0.01 (*); P<0.001 (**); P<0.001 (***).

4 DISCUSSION AND CONCLUSIONS

Ferralsols in the WISE database were assessed in terms of organic carbon and nitrogen content, soil pH and nutrient status, bulk density and moisture retention properties. The study reflects the large variation that exists in these properties within the various subunits of Ferralsols. Part of the variation can be attributed to the fact that differences in land use history, parent material and landform were not taken into account. The estimates presented in this paper are median values suitable for continental and global studies but should not be used for presenting national statistics which would require regionally explicit data sets. The study illustrates the potential of macro scale soil databases in identifying and quantifying major soil constraints (or soil indicators of sustainability) at a continental level.

Refinement of the WISE database is scheduled to continue by incorporation of new profiles, notably soils collected worldwide in the framework of ISRIC's programme on National Soil Reference Collections and Databases (NASREC). Several GIS image files with a resolution of ½° latitude by ½° longitude have been generated using the general format of the Global Ecosystems Database (Kineman 1992). These global data sets include: soil pH, organic and carbonate carbon, and water retention properties (Batjes 1995b, 1996a, 1996b). On the longer-term these WISE-derived databases could be used to refine studies of crop production potentials, agro-ecological zoning, and soil gaseous emission potentials (e.g. Bouwman *et al.* 1994; Bachelet & Neue 1993; Luyten 1995). So far, of necessity, these global studies have had to rely on the 1° by 1° resolution data file of Zobler (1986) and a limited profile data set (FAO-Unesco, 1974).

Although the FAO-Unesco Soil Map of the World remains the best available source on type and extent of the soils of the world, it is partly outdated (Sombroek, 1990; Oldeman & Van Engelen, 1993). This is not meant as a criticism but merely emphasizes the need for more detailed and accurate information on the world's soil resources. An internationally endorsed and tested methodology, SOTER, for such a global update has been available since 1993. The SOTER procedures (Van Engelen & Wen, 1995) are currently being used by UNEP, FAO, ISRIC and national soil survey organizations to update the soil and terrain information for South and Central America, inclusive of the Caribbean. Similar activities, at scale 1:5 M, are planned for North Asia (Russia, China and Mongolia) as a joint activity of FAO and IIASA. The aim of FAO, ISRIC, ISSS and UNEP is to have a global 1:5 M scale SOTER for the whole world by the year 2002, for presentation during the XVIIth World Congress of Soil Science.

A full update of the information on the world's soil resources in a 1:5 M scale SOTER would provide much of the primary soil and terrain data which scientists and policy makers require for global studies of terrestrial agro-ecosystems. Databases such as WISE and SOTER can be linked with dynamic models and GIS techniques to identify areas vulnerable to specific types of land degradation and land use change scenarios. The collection and compilation of new profile data sets for the main soils of the world, using the uniform NASREC-ISIS format, remains critical in this context.

"Perhaps the greatest challenge facing farmers, economists and soil scientists today is to develop sustainable farming systems together with the politic and socio-economic conditions in which they can be practised, so that a larger population may be supported by the soils of these less fertile areas" (Greenland, 1994). In this context, it is important to know where specific types of soil occur, what their main properties are, and how each soil type will respond to different processes of environmental change. Addressing these broader environmental issues is the primary responsibility of governmental and international bodies (e.g. FAO, UNEP, CGIAR), and requires a concentrated effort on research, development of databases and analysis techniques.

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PART III
WORLD SOILS AND TERRAIN DIGITAL DATABASE (SOTER)

WORLD SOILS AND TERRAIN DIGITAL DATABASE (SOTER)

W.V.P. Van Engelen and S. Mantel

ABSTRACT

Policy-makers, resource managers and the scientific community at large have repeatedly expressed the need for ready access to soil and terrain resources through geo-referenced databases in order to make assessments of the productive capacity of soils, to have a better understanding about the risks and rates of soil degradation and to better quantify processes of global change.

The World Soils and Terrain Digital Database (SOTER) is a system which can store detailed information on natural resources in such a way that these data can be readily accessed, combined and analyzed from the point of view of potential use, in relation to food requirements, environmental impact and conservation.

1 INTRODUCTION

SOTER provides an orderly arrangement of natural resource information through the creation of a computerized database containing all available attributes on topography, soils, climate, vegetation and land use, linked to a Geographic Information System, through which each type of information or combination of attributes can be displayed as a separate layer or overlay, or in tabular form (Figure 1).

SOTER is an initiative of the ISSS and was adopted at the 13th World Congress of Soil Science in 1986. Under a UNEP project, ISRIC developed a methodology for a World Soils and Terrain Digital Database (SOTER) for use at a scale of 1:1 million, in close cooperation with the Centre for Land and Biological Resources Research of Agriculture Canada, with FAO, and with the ISSS.

SOTER was tested in three areas, involving five countries (Argentina, Brazil, Uruguay, the USA and Canada), using local data. Results were reported at the 14th World Congress of Soil Science in 1990. The ISSS Working Group on World Soils and Terrain Digital Database (DM) endorsed the methodology.

Based on the experience obtained in the pilot areas the SOTER methodology was further refined and a training programme and course materials were developed by ISRIC. In 1993 the Procedures Manual for Global and National Soils and Terrain Digital Databases was jointly published by UNEP, ISSS, FAO, and ISRIC (in English and Spanish), accompanied by attribute input software. Revised editions were published in 1995 together with a French version. FAO made the methodology the cornerstone of its revision of the Soil Map of the World and issued the Procedures Manual in its own series of World Soils Resources Reports (#74).

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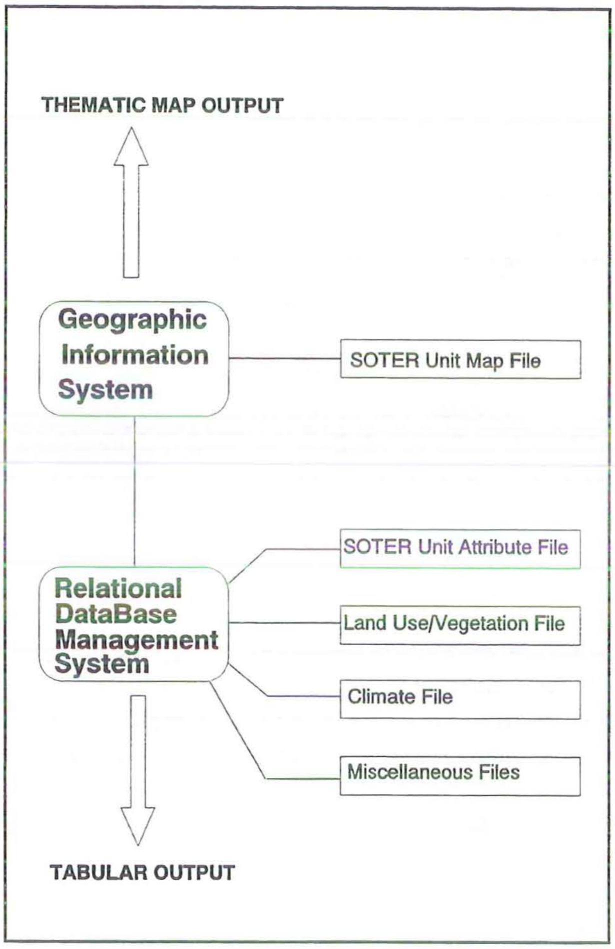


Fig. 1 Schematic representation of SOTER database

A SOTER based methodology for an assessment of water erosion risk (SWEAP) and for Automated Land Evaluation (using ALES) was developed. In 1993 the SOTER programme was implemented at national level in four countries (Argentina, Uruguay, Kenya, and Hungary). In Argentina and Uruguay, SOTER windows at scales up to 1:100,000 are also executed. In 1995, Syria and Jordan joined the programme. At a continental level a 1:5 million database of Latin America is currently being made.

The national SOTER programmes are all formulated and financed by UNEP with technical support and coordination provided by ISRIC. The programmes are carried out by the national soil research organisations.

In 1992, the SOTER programme was evaluated by an international panel, convened by UNEP. The panel recommended not only SOTER activities at national level, but also the development of small-scale continental SOTER databases. In 1993, a joint action plan was formulated and jointly financed by UNEP, FAO, and ISRIC for the compilation of a Latin American SOTER at a scale of 1:5 million. Some adaptations of the original methodology (designed for 1:1 million scale) were necessary, such as the reduction of the number of attributes. In the first phase, six countries (Argentina, Brazil, Cuba, Mexico, Uruguay, and Venezuela) were involved and have finished their contributions. The second phase, now under way, will involve the remaining countries in South and Central America as well as those in the Caribbean.

A Latin American SOTER workshop was held in April 1994 in Buenos Aires under the UNEP project as a starter for regular SOTER training workshop in the region. Representatives of many Latin American countries indicated their interest in participating in this continental SOTER programme. Compilation of its final phase depends on the availability of external funding. A workshop of the Data Information Systems on Soils task force of the International Geosphere-Biosphere Programme (IGBP-DIS), held in Washington DC, in April 1994, recommended the use of a continental SOTER database for environmental global change modelling activities.

A workshop for East and Southern Africa was held in March 1995 in Nairobi were the results of the programme in Kenya were presented. Participants from 11 countries indicated their interest in starting SOTER activities at a national level.

2 SOTER APPLICATIONS

In this section two examples of SOTER applications are given, viz. SOTER Water Erosion Assessment Programme (SWEAP) and the SOTER Model for Automated Land Evaluation (SOTAL).

2.1 SWEAP

SWEAP is a computer programme for water erosion risk prediction which makes use of the SOTER database. It consists of two parts: (1) the menu and (2) the model. These parts are linked to the SOTER database through an interface which extracts the required data from the SOTER database. SWEAP's menu part is an interface between the user and the model. It enables the user to "tell" the model the conditions that must be taken into account:

- which erosion hazard assessment model is to be used: (a) the Universal Soil Loss Equation (USLE); (b) the Soil Loss Estimation Model for Southern Africa (SLEMSA)
- for what (hypothetical) situation of land use/management (scenario) the calculations are to be made.

The model works with a "time step" of 1 month: hence, seasonal dynamics of crop cover and rainfall erosivity are accounted for. Soil erodibilities are provided in dependence of type of soil development and texture class, with modifiers for conservation practices, internal drainage, sensitivity to capping, abrupt horizon boundaries, shallow soils and salinity. Crop factors (C) can optionally be read from a file, or calculated from relationships of C with leaf area and ground cover. Crop residue management is taken into account by adjustment of the crop protection factor. A simple agro-ecological zone model is built in to calculate potential growing periods, if desired.

Results must be interpreted in terms of "erosion hazard units", rather than as quantified estimates of potential soil loss. SWEAP allows for a rapid appraisal of the effects of different types of land use on soil loss. It also assists in identifying appropriate management options for these land use type. SWEAP facilitates the comparison between different types of land use and land management options with regard to environmental degradation through soil erosion. Hence, SWEAP may prove to be useful tool, particularly in national and regional land use planning.

Currently, SWEAP is being used in the framework of the National Land Degradation Assessment and Mapping in Kenya Project. An example of modelled erosion risk under current land use is shown in Figure 3.

2.2 SOTAL

At a scale of 1:1 M land evaluation will permit identification of the suitability of terrain units for broadly defined land uses as put forward by planners. It can serve to identify broad biophysical potentials and constraints within countries (Batjes, 1990; Fresco *et al.*, 1989). SOTER can accommodate a wide range of soil and terrain attributes and therefore has a good potential for macro-scale land evaluation as support for land use planning.

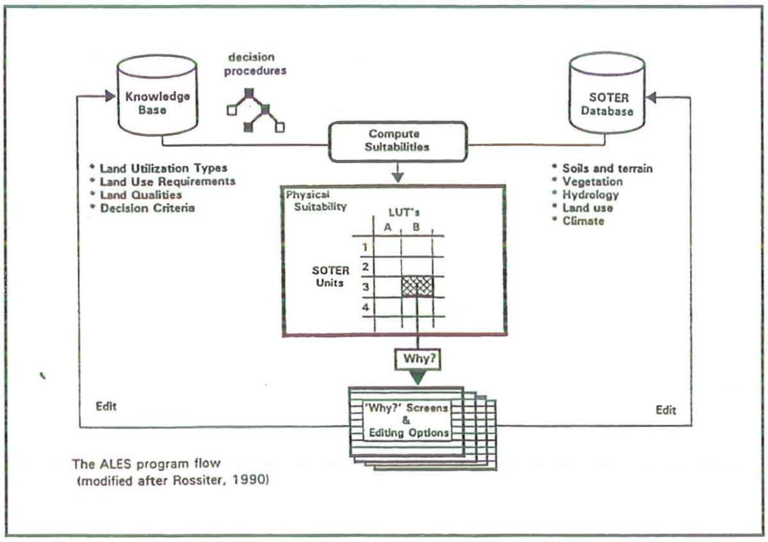


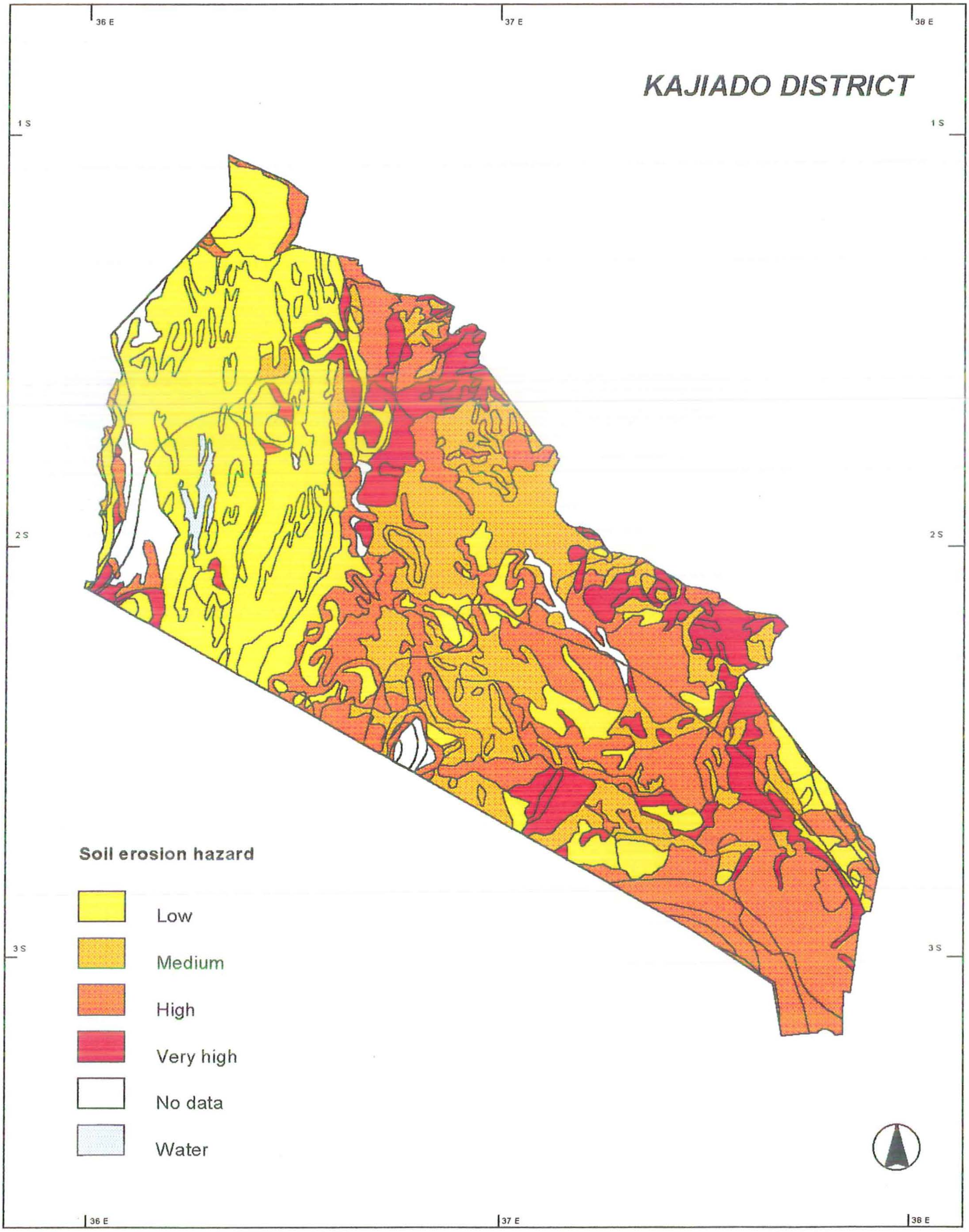
Fig. 2 Flow chart of ALES program

SOTAL, a SOTER-based model for physical land evaluation, was developed using ALES, the Automated Land Evaluation System (see Mantel, 1995). With ALES (Figure 2), knowledge-based systems can be built with which physical and economical suitability of map units can be computed in accordance with FAO's Framework for Land Evaluation (FAO, 1976; Rossiter, 1990). The objective was to design a procedure that allows for a quick separation of potentially suitable

Fig. 3

SOIL EROSION HAZARD UNDER CURRENT LAND USE

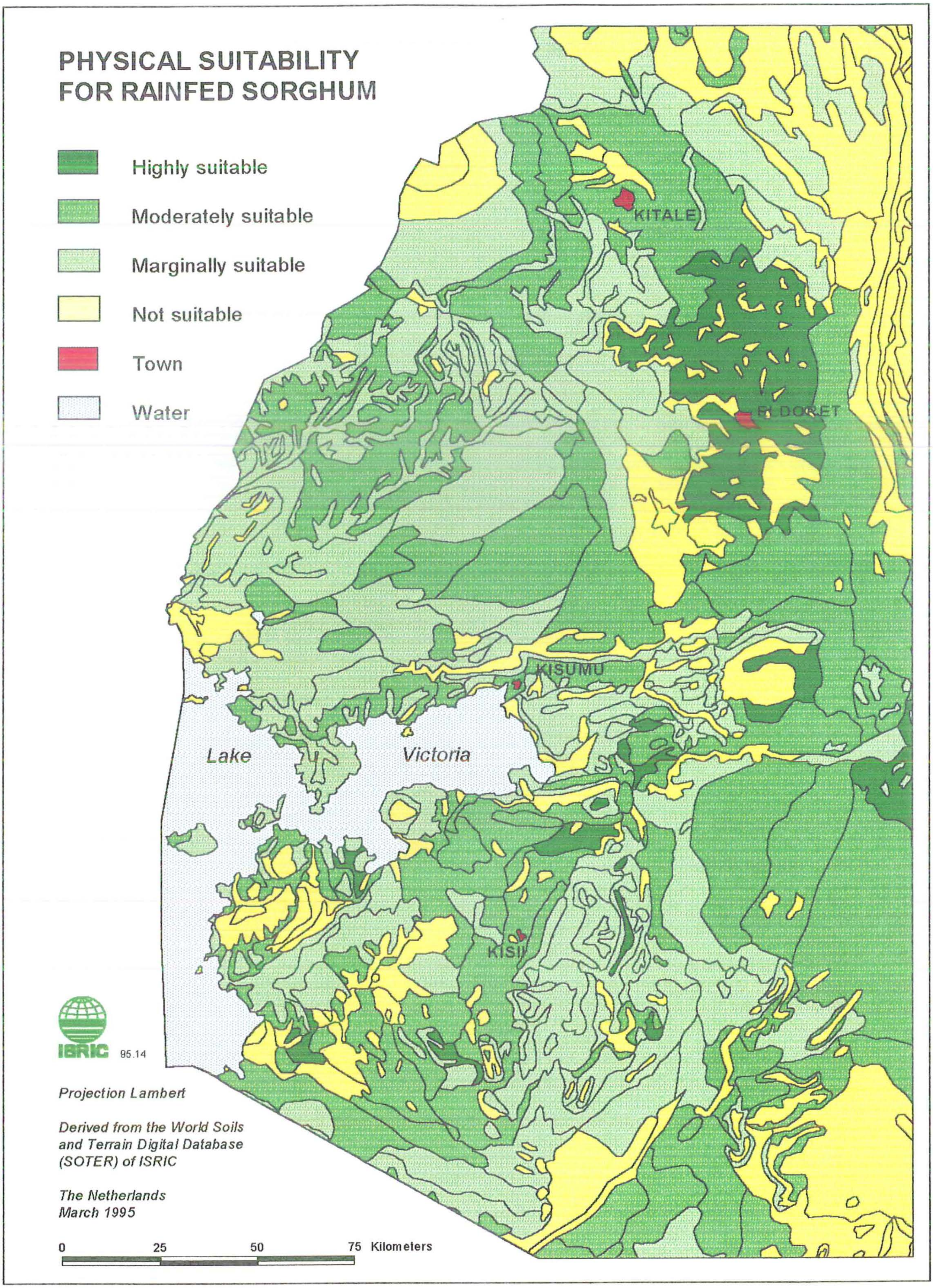
ISRIC



Geographic coordinates
October 1995

0 25 50 75 100 Kilometers

(PROVISIONAL)


PHYSICAL SUITABILITY
FOR RAINFED SORGHUM
Highly suitable
Moderately suitable
Marginally suitable
Not suitable
Town
Water
KITALE
EL DORET
KISUMU
Lake
Victoria
KISII
ISRIC
95.14
Projection Lambert
Derived from the World Soils
and Terrain Digital Database
(SOTER) of ISRIC
The Netherlands
March 1995
0
25
50
75 Kilometers

SOTER-units from non-suitable units for a defined use, indicating constraints to different types of land use. In SOTAL, six land utilization types (LUTs) are presently defined: rainfed maize, sorghum and wheat under two (low/medium - high) technology and input levels, characterized by 11 land use requirements. For determination of the sufficiency of the land quality 'moisture availability during the growing season' a dynamic water balance model, WATSAT, was developed. WATSAT is a capacity-based water balance model, that operates on a daily time step. The sufficiency of moisture availability is expressed as the ratio of actual over maximum transpiration.

SOTAL was applied on data from KENSOTER, compiled by the Kenya Soil Survey. In Figure 4, the physical suitability of SOTER units for rainfed cultivated sorghum under low input and technology in West Kenya are given. The study revealed that in the major part of West Kenya low-input, rainfed sorghum can be grown. However, major limiting factors for this LUT exist including high soil erodibility and low nutrient availability, indicating the need for soil conservation and nutrient management for sustainable cultivation of sorghum in the region.

SOTAL evaluations are based on data of representative profiles, that characterize soil components. The area of each soil component within a terrain unit, which is the basic SOTER mapping unit, is given in the database and thereby allows mapping of the results. SOTAL can be a useful tool in land use planning, as major limitations for different kinds of land use can quickly be determined. However, it should be adjusted to regional or national conditions. The areas indicated as potentially suitable after SOTAL-evaluation, have no major physical limitations for the proposed land use. For more specific statements, like f.i. the potentially attainable yield, a quantified land evaluation is necessary, using crop growth simulation models. The attractive feature of the procedure following the pathway of a qualitative land evaluation in SOTAL, preceding a quantified land evaluation, is that the, time and data demanding, quantified study can focus on suitable areas. This is often referred to as a 'mixed qualitative/quantitative land evaluation approach' (Van Lanen *et al.*, 1992).

3 FUTURE DEVELOPMENTS

The number of requests for SOTER developments at a national level from countries in West and East Africa, South and Central America, Central and Eastern Europe, South and Southeast Asia is indicative of the demand for, and importance attached to the land resource database, land evaluation and land use planning system, which SOTER is capable of providing. Worldwide implementation of SOTER will depend on available donor support. An important activity remains the testing of application programmes for SOTER, including the study of the impact of water erosion on food production.

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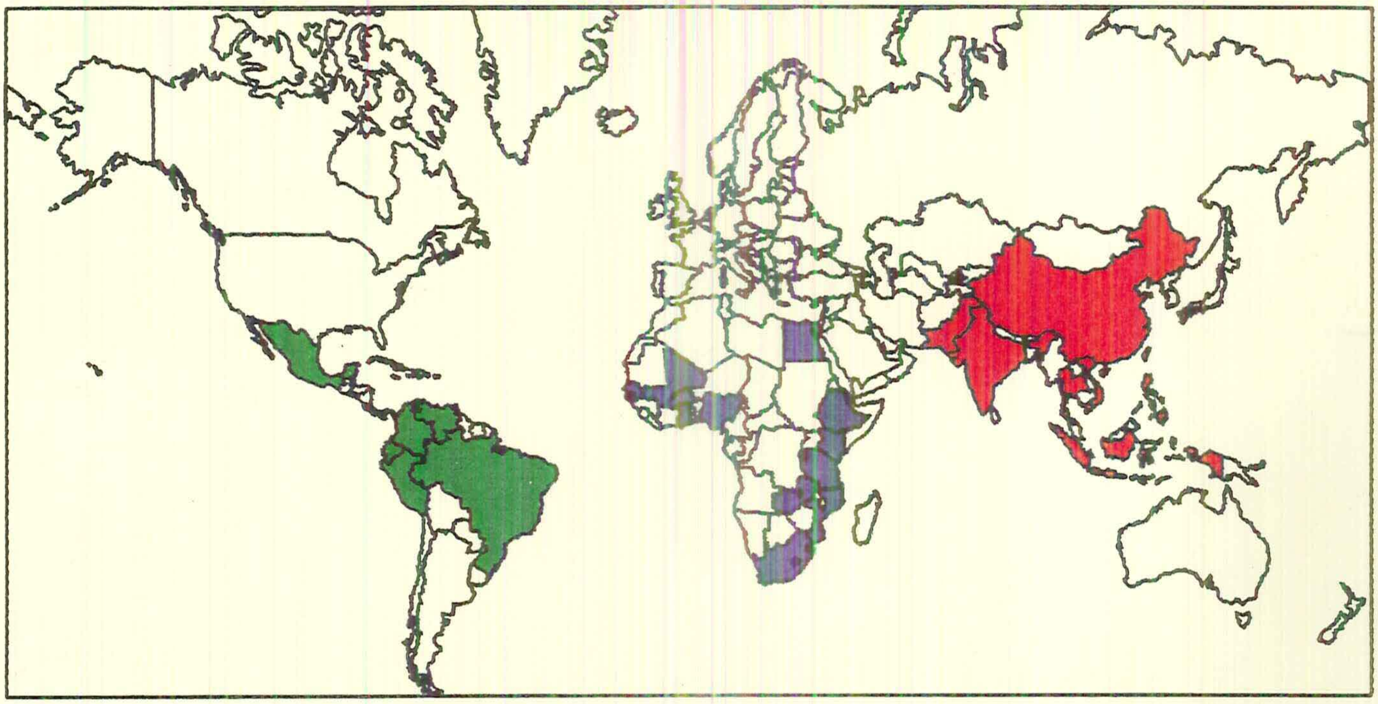
A WORLD WIDE PLEDGE

We undertake to listen to the users demands for soil information and to develop user friendly products to satisfy their needs:



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Cuba
Ecuador
Mexico
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Peru (2)
Venezuela

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Egypt
Ethiopia
Ghana
Kenya
Lesotho
Mali
Mocambique
Nigeria
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India (2)
India (3)
Thailand