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WORLD SOIL CARBON STOCKS AND GLOBAL CHANGE

N.H. Batjes
August 1995

INTERNATIONAL SOIL REFERENCE AND INFORMATION CENTRE

Related ISRIC Publications:

World Inventory of Soil Emission Potentials. Proceedings of an International Workshop organized in the framework of the Netherlands National Research Programme on Global Air Pollution and Climate Change. WISE Report 2, ISRIC, Wageningen, iv + 122 pp., 1992. [ISBN 90-6672-049-2].

A Review of Soil Factors and Processes that Control Fluxes of Heat, Moisture and Greenhouse Gases. Technical Paper 23, ISRIC, Wageningen, viii + 201 pp., 1992 [ISBN 90-6672-048-4].

World Inventory of Soil Emission Potentials: WISE 2.1 - Profile Database User Manual and Coding Protocols. Technical Paper 26, ISRIC, Wageningen, vi + 59 pp., 1995 [ISBN 90-6672-058-1]

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Paper prepared for: International Workshop on Combatting Global Warming by Combatting Land Degradation (UNEP; Nairobi, 4-8 September 1995).

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Abstract

World soils are important sources and sinks for CO_2, CH_4 and N_2O, radiatively trace gases which enhance the greenhouse effect. The global soil database, developed for a World Inventory of Soil Emission Potentials (WISE), has been used to compile a global data set of soil carbon and nitrogen pools. WISE currently holds 4,353 globally distributed profiles considered to be representative of the 106 soil units shown on a ½° latitude by ½° longitude version of the corrected and digitized 1:5 M FAO-Unesco Soil Map of the World.

Primary stratification of profiles is per FAO-Unesco soil unit. Soil organic carbon (SOC) reserves in the upper 1.0 m of the world's soils — corrected for amounts of coarse fragments (> 2mm) — is estimated to be 1462 Pg C (10^{15} g), approximately twice the amount held in the atmosphere (≈ 750 Pg C) and about 2.5 times that held in biota (≈ 600 Pg C). Although the soil-vegetation carbon pool is relatively small compared with that of the oceans (≈ 39,000 Pg C), potentially it is much more labile in the short term.

Dominant soils of drylands, mainly from arid and semi-arid tropical and mid-latitude regions of the world, contain about 251 Pg C of SOC and 509 Pg C of carbonate carbon (CAC), amounting to 760 Pg C in total. These totals do not include data for minor associated soils. The total amounts of SOC, CAC and N held in the first 1.0 m of dryland soils of the world have been approximated by overlying the WISE data with the digital Holdridge life-zones map. Soils of life-zones corresponding with "dryland" areas of the world, hold 300-369 Pg SOC-C, 473-546 Pg CAC-C, and 41-50 Pg N. Ranges are from 20 Pg SOC-C and 49.6 Pg CAC-C for the Cool Deserts, increasing to 118 Pg SOC-C and 174.2 Pg CAC-C for soils of the Tropical Dry Forest life-zone. Highest SOC pools are found under Boreal forests (346 Pg C), pointing to a possible large release of CO_2 from soils of these regions upon predicted climate warming. Globally, the soil carbon pool for the first 1.0 m is estimated to be 2157 Pg C and the nitrogen pool to be 133 Pg N. Large amounts of organic carbon are stored below a depth of 1.0 m, notably in Histosols and some deeply weathered tropical soils. This "deeper" carbon is old, refractory and of limited importance in gaseous exchanges with the atmosphere.

Increasing population pressure, land use changes and predicted global warming, through their effects on net primary productivity, organic matter composition and decomposition as well as soil chemical and physical conditions, have important effects on plant composition, SOC pools and atmospheric concentrations of CO_2, CH_4 and N_2O. The possible effects of land use changes and land degradation on C-fluxes from dryland soils to atmosphere and soil management for carbon sequestration are reviewed, and recommendations for further studies made.

Keywords: soil carbon; soil nitrogen; digital soil database; global change; land management; drylands; land degradation; global change

1. Introduction

Deciphering the role of terrestrial ecosystems in the global carbon (C) cycle has become increasingly important as policy makers address issues associated with global environmental change, particularly controlling land degradation and climate change (Houghton *et al.* 1990; UNEP 1992). Recent overviews of the carbon cycle may be found in various papers (Houghton *et al.* 1990; Smith *et al.* 1993; Schlesinger 1995; Schimel 1995). Four main reservoirs regulate this cycle on earth: fossil carbon (≈ 6,000 Pg or 10^{15} g C); the oceans (≈ 39,000 Pg C); the atmosphere (≈ 750 Pg C); and terrestrial systems including soils and biomass (≈ 2200 Pg C).

Although the soil-vegetation carbon pool is relatively small compared with that of the oceans, potentially it is much more labile in the short term. The most important natural processes in the exchange of carbon are those of photosynthesis, autotrophic (i.e., CO_2 production by the plants) and heterotrophic (i.e., essentially microbial) respiration which convert the organic material back into CO_2. The amounts and dynamics of carbon and nitrogen in the world's soils are still relatively poorly known (Houghton *et al.* 1990; Legros *et al.* 1994; Lal *et al.* 1995). Of particular interest is the 'missing sink' of 2.0 - 3.4 Pg C yr^{-1}, which arises in global C budgets from the difference in CO_2 released by fossil fuel combustion and the annual CO_2 increase in the atmosphere (Tans *et al.* 1990; Broeckner & Peng, 1990). Part of the 'missing carbon' has been attributed to a 'CO_2-fertilization effect' (Sombroek *et al.* 1993; Francey *et al.* 1995), associated with increased atmospheric CO_2 levels on plant growth (Bazzaz & Fajer 1992; Idso & Idso 1994).

The favourable effects of organic matter on the physical and chemical properties of soils, on biological activity, and by implication in sustaining soil productivity, are well documented (Russell 1980). Important factors controlling organic matter levels in soils, include climate, hydrology, parent material, soil fertility, soil biological activity, vegetation patterns and land use (Jenny 1980). In the short-term, the carbon balance of terrestrial ecosystems is particularly sensitive to impact of human activities, including deforestation, biomass burning, land use changes and conversion, and environmental pollution (Mann 1986; Mulongoy *et al.* 1993; Fisher *et al.* 1994). During the period 1850-1980 soil carbon pools have decreased by 40 Pg C from the original 1471 Pg C and carbon held in vegetation by 80 Pg C down from 672 Pg C in 1850 (Houghton 1995). Global release of carbon to the atmosphere from land use change in 1990 was between 1.1 and 3.6 Pg C yr^{-1}, as compared to 5.5-6.5 Pg C yr^{-1} from fossil fuel combustion (see Houghton 1995). Some 5.7 Pg C of the about 1500 Pg C held in soils is displaced annually due to global soil erosion (Lal 1995b).

As a whole, the natural resources for food production have shown a marked deterioration during the last two decades; land has been degraded, water resources have been depleted, desertification has increased, biodiversity has decreased, and there have been negative impacts on human health (FAO 1979a; Oldeman *et al.* 1991; Le Floc'h *et al.* 1992; UNEP 1992).

In view of the scope of UNEP's workshop on "Combatting Global Warming by Combatting Land Degradation", possible effects of land degradation and predicted global warming for soil C and N reserves will be discussed with special reference to dryland regions. Globally, drylands — defined as having a rainfall (R) over potential evapotranspiration (PET) ratio smaller than <=

0.65 (UNEP, 1992) — occupy about one third (49-51x10^6 km^2) of the Earth's land surface and are inhabited by about one quarter of the world's population (Le Floc'h *et al.* 1992; UNEP, 1992). The UNCED at Rio de Janeiro in 1992 highlighted desertification as a special problem, with both marked political and technical dimensions.

A comprehensive discussion of the features of drylands and processes of desertification is beyond the scope of this paper and excellent reviews have been published elsewhere (Van Baren 1980; Beaumont 1989; Le Floc'h *et al.* 1992; Mainguet 1994). Drylands have in common their aridic nature and are characterized by low, erratic and infrequent rainfall, intense evaporation and limited water resources. The pervasive aridic nature of drylands limits their carrying capacity and potential for rural development. Increased demands for food, feed and fuel (wood) have increased the pressure on existing arable land and resulted in increased utilization of marginal lands (Wainwright, 1994).

The natural vegetation of drylands is mainly characterized by savannas and some dry-tropical wooded areas. With increasing aridity, the density of trees decreases and thorny, xerophitic and drought-resistant species gain in importance. Most of these species grow slowly and many of these naturally fragile ecosystems regenerate slowly when degraded (Beaumont 1989; Kotschi & Adelhelm 1986; Schutz 1994; Ihori *et al.* 1995). As a result, natural dryland ecosystems are easily damaged in areas where human pressure on the land increases, and this is particularly obvious in arid and semi-arid regions (Van Baren, 1980; West *et al.* 1994).

Livestock rearing and irrigated farming are possible in the arid zones. Rainfed farming is generally practised in the semi-arid zones, yet risky due to uncertain rainfall distribution and risk of drought during the growing period(s). Agriculture requires special methods including dry-farming, growing of fast-growing and drought tolerant crops, or irrigation.

Pressure on the natural resources is highest in the semi-arid zone where livestock rearing and rainfed farming compete for land (Kotschi & Adelhelm 1986), and towards the wetter (subhumid) margins where human population pressure tends to be highest (Biswas 1994; Wainwright 1994). So far, over-exploitation has lead to over 1035x10^6 ha of drylands being degraded, notably by water and wind erosion (Oldeman *et al.* 1991) and by soil compaction and crusting. Sustainable land management practices for maintaining soil quality, improving C sinks and managing long-term C sequestration, which increase the soil's resilience against water and wind erosion, need to be identified (Le Floc'h *et al.* 1992; Kern & Johnson 1993; Peterson *et al.* 1993).

The aim of this paper to provide global estimates of current carbon and nitrogen in soils, with special reference to dryland regions, using the WISE database (Batjes & Bridges, 1994). In addition to this, land management procedures for sequestering soil carbon and reducing land based CO_2 emissions are reviewed and priorities for further work identified.

2. Materials and Methods

2.1 The WISE soil database

The primary soil data for this study have been derived from the database developed at ISRIC for the World Inventory of Soil Emission Potentials (WISE) project. The central aim of this activity has been to compile a basic set of uniform soil data for a wide range of global studies, including assessments of crop production potentials, soil vulnerability to pollution, and soil gaseous emission potentials (Batjes *et al.* 1995).

The WISE database consists of two main components (Fig. 1):

(1) 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.

(2) Soil profile data for the respective soil units, with associated files listing the analytical methods used and source of primary data.

The 1:5 M Soil Map of the World (FAO-Unesco 1971-1981) remains the most consistent map of the world's soil resources, even though sections of it are known to be out-dated (Sombroek, 1990). The cartographic database of WISE has been built up mechanically, by identifying the soil associations which occur in each 5' x 5' grid-cell of an edited and digital version of the Soil Map of the World (FAO, 1991). The next step involved computing the percentage area of each soil unit present in the 36 cells which make up the ½° x ½° grid cell (Nachtergaele, *unpublished data*, 1994), using FAO's standard composition rules. This information was then aggregated to generate the soil geographic data relevant to each terrestrial ½° latitude by ½° longitude grid cell, forming the new cartographic units. 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). Inclusions of minor soils that may be of critical importance for crop production or greenhouse gas emissions are accounted for, in contrast to what was the case for the Zobler (1986) data file.

The properties of the component soil units of individual grid cells can be quantified using a set of regionally representative and georeferenced soil profiles. These profiles were compiled from 5 main sources: (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) profiles obtained from an international data gathering activity coordinated by WISE project staff, in which national soil survey organisations were asked to supply descriptions and analyses of profiles representative of the units of the Soil Map of the World present in their individual countries; and (e) suitable profiles gathered from survey monographs held at ISRIC's library.

The 4,353 profiles currently held in the WISE database originate from the following regions: Africa (1799); South, West and North Asia (522); China, India and the Philippines (553); Australia and the Pacific Islands (122); Europe (492); North America (266); and South America and the Caribbean (599). No attempt was made in this study to locate where individual profiles occur, because all 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 explicitly.

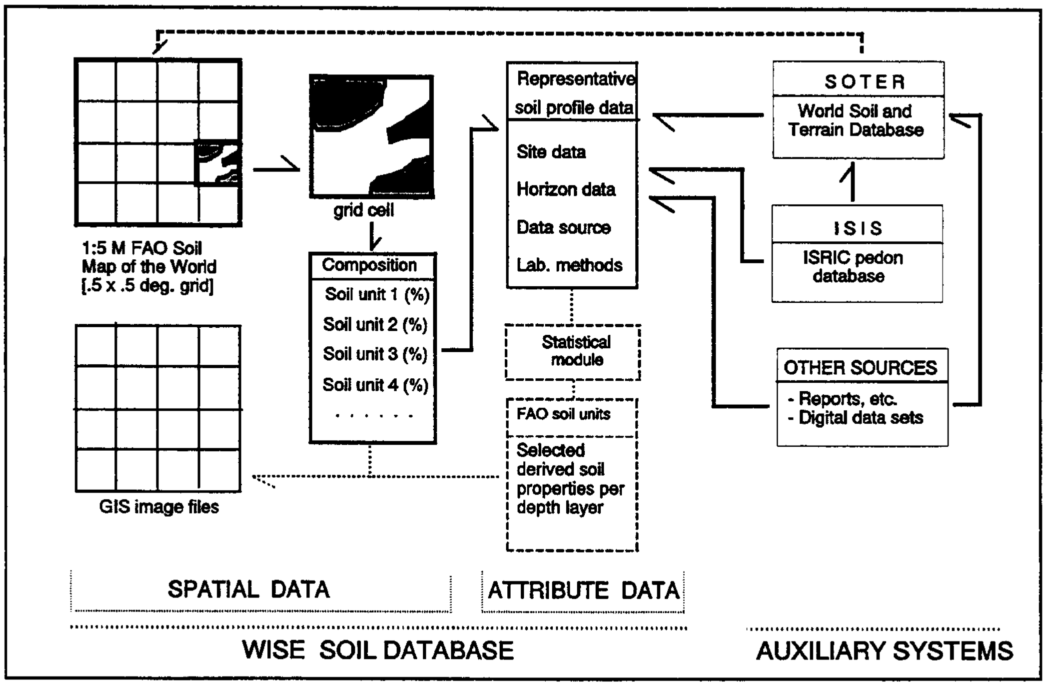


Fig. 1. Schematic representation of the WISE database.

Special attention was given to the systematic collection and recording of data as well as careful consideration of the laboratory methods by which the analytical results were obtained. For each individual set of data, the laboratory name and methods used have been recorded in the database.

2.2 *Soil carbon and nitrogen files*

In a preceding paper, Batjes (*submitted*) studied the variability in soil organic carbon (SOC), carbonate carbon (CAC) and total nitrogen (N) density of the soil units considered on the Soil Map of the World (FAO-Unesco 1974; FAO 1991). First, calculations were made for individual soil profiles taking into account (a) the bulk density, SOC, CAC and N content of individual soil horizons, and (b) the comparability of the analytical methods used. Where measured bulk density data were lacking, a scheme of pedotransfer rules was used to generate surrogate data. In view of the importance of coarse fragments (> 2 mm) in determining actual SOC, CAC and N reserves, a correction factor has been introduced. This was done on a soil unit basis, using the data on coarse fragments held in the WISE database. The resulting 'derived' files provided the basic input for the current study.

Mean SOC, CAC and N density (kg m^{-3}) by soil unit, computed for two depth ranges (i.e. 0-30 cm and 0-100 cm), was combined with information on the geographic extent of the corresponding soil units throughout the world, giving estimates of global soil C and N mass. In the case of Lithosols (0-10 cm), Rankers and Rendzinas (0-30 cm) a shallower default depth has been utilized. If there were no representative profiles for a soil unit, a 'best estimate' was assigned to this soil unit with reference to values computed for similar soils.

Software for the various data file selections and computations was written in dBASE IV, the language used for programming the WISE data handling system.

3. Soil C and N Reserves

3.1 Global estimates

Soil organic carbon

World estimates of soil organic carbon mass, held in the first meter, range from 1000 to 3000 Pg C with three of the most recent published estimates being 1220 (Sombroek *et al.*, 1993), 1431 (Houghton 1995) and 1555 Pg C (Eswaran *et al.*, 1995). Sombroek *et al.* (1993) used the recently corrected Soil Map of the World (FAO 1991) and about 400 soil profiles classified according to the FAO-Unesco (1974) legend. Eswaran *et al.* (1995) used the map of 'Major Soil Regions of the World' (still in press) and about 1000 profiles from 45 tropical countries and a selection of 15,000 profiles from the USA, classified according to Soil Taxonomy (USDA 1994 and earlier versions). Houghton (1995) derived his estimates from soils in major ecosystems.

Table 1 shows estimates of SOC, CAC and soil N pools per 10° latitudinal band. Globally, SOC in the first 1.0 m amounts to 1462 Pg C. This is about 240 Pg C higher than the estimate of Sombroek *et al.* (1993) and about 90 Pg C lower than found by Eswaran *et al.* (1995). In this context, it should be observed that it is unclear whether the above authors used any corrections for coarse fragments. In there is no correction for coarse-fragments, the global estimate would become 1548 Pg C which is very similar to the estimate of Eswaran *et al.* (1995). Nonetheless, estimates presented for individual soil units still vary widely among the various studies.

Calculations of world soil C and N reserves are complicated by a number of factors, notably: (a) the still limited reliability of areas occupied by different kind of soils; (b) the limited availability of reliable, complete and uniform data for these soils; (c) the high spatial variability in carbon and nitrogen content, stoniness and bulk density of similarly classified soils; (d) the comparability of analytical methods used (Pleijsier 1987; Vogel 1994), and (e) the effects of climate, relief, parent material, vegetation and land use.

Soil carbonate carbon

The current estimate of 695 Pg C — or 748 Pg C, when no correction for coarse fragments is applied — compares well with the 720 Pg CAC-C published by Sombroek *et al.* (1993). These authors used average carbonate-carbon contents for soil types published by Schlesinger (1982) and soil area estimates derived from the Soil Map of the World (FAO 1991). The initial estimate of Eswaran *et al.* (1995) amounted to 1,738 Pg C of carbonate-carbon, which was about twice the amount estimated by Sombroek *et al.* (1993), the 930 Pg C of Schlesinger (1985) and the present findings. Eswaran *et al.* (1995) estimated carbonate carbon contents arbitrarily where

Table 1. Estimated soil carbon and nitrogen reserves per 10° latitudinal band (Pg of C and N for specified depth zone: A) 0-30 cm, B) 0-100cm; corrected for coarse fragments).

A) *d= 0-30 cm*

	Latitude		SOC-C	CAC-C	TOT-C	N	area†
N	90	80	1.0	0.0	1.0	0.0	0.1
N	80	70	26.3	0.9	27.2	1.7	2.3
N	70	60	128.4	7.5	135.9	8.3	12.2
N	60	50	127.4	14.8	142.2	10.3	14.1
N	50	40	83.6	33.7	117.2	8.6	15.6
N	40	30	49.2	43.3	92.5	5.9	15.1
N	30	20	41.0	38.7	79.6	5.0	15.0
N	20	10	33.3	23.7	57.0	3.9	11.2
N	10	0	48.7	11.0	59.7	4.5	10.0
S	0	-10	53.4	6.8	60.2	4.8	10.3
S	-10	-20	39.1	10.5	49.6	4.0	9.4
S	-20	-30	29.7	18.9	48.6	3.5	9.3
S	-30	-40	16.4	10.0	26.4	1.8	4.1
S	-40	-50	4.7	2.0	6.7	0.5	1.0
S	-50	-60	1.9	0.2	2.1	0.2	0.2
S	-60	-70	0.0	0.0	0.0	0.0	0.0
S	-70	-80	0.0	0.0	0.0	0.0	0.0
S	-80	-90	0.0	0.0	0.0	0.0	0.0
All	90	-90	684.1	222.0	906.1	63.0	129.8

B) *d= 0-100 cm*

	Latitude		SOC-C	CAC-C	TOT-C	N	area†
N	90	80	4.6	0.0	4.6	0.1	0.1
N	80	70	80.0	1.2	81.4	3.8	2.3
N	70	60	331.9	12.7	345.1	19.1	12.2
N	60	50	268.0	44.0	312.2	21.4	14.1
N	50	40	166.3	114.3	280.6	18.2	15.6
N	40	30	97.2	147.4	244.3	11.8	15.1
N	30	20	78.7	116.1	194.6	10.7	15.0
N	20	10	63.1	65.9	128.9	8.4	11.2
N	10	0	93.7	30.1	123.8	9.4	10.0
S	0	-10	103.7	14.8	118.6	9.7	10.3
S	-10	-20	73.0	29.6	102.6	7.9	9.4
S	-20	-30	56.0	70.1	126.0	7.3	9.3
S	-30	-40	31.7	40.9	72.6	4.0	4.1
S	-40	-50	9.4	7.1	16.5	0.9	1.0
S	-50	-60	4.8	0.6	5.4	0.3	0.2
S	-60	-70	0.0	0.0	0.0	0.0	0.0
S	-70	-80	0.0	0.0	0.0	0.0	0.0
S	-80	-90	0.0	0.0	0.0	0.0	0.0
All	90	-90	1462.0	695.0	2157.0	133.0	129.8

†Area in 10^6xkm^2, excluding land glaciers.
SOC-C = soil organic carbon; CAC-C= soil carbonate carbon; TOT-C= (SOC-C + CAC-C); N= total nitrogen; sums may not exactly add up to totals shown due to rounding.

petrocalcic horizons occurred, whereas only actually measured soil carbonate data are used in this study.

Although reserves of carbonate C globally are large, this source of C does not participate in the C flux to other carbon systems as rapidly as organic carbon, except if soils are irrigated or become acidified with increased S and N inputs (Lal *et al.* 1995). Nonetheless, more data are needed on the rates of storage and release of carbonate-carbon in soils under projected climatic and vegetational changes (Schlesinger 1985). Changes in pedogenetic carbonate may have great effects on both phosphorus (P) availability and the biogeochemical cycle of P in dryland systems (West *et al.* 1994). The reason for this is that most inorganic P is present as soluble Ca-phosphates in these soils (Lathja & Bloomer 1988).

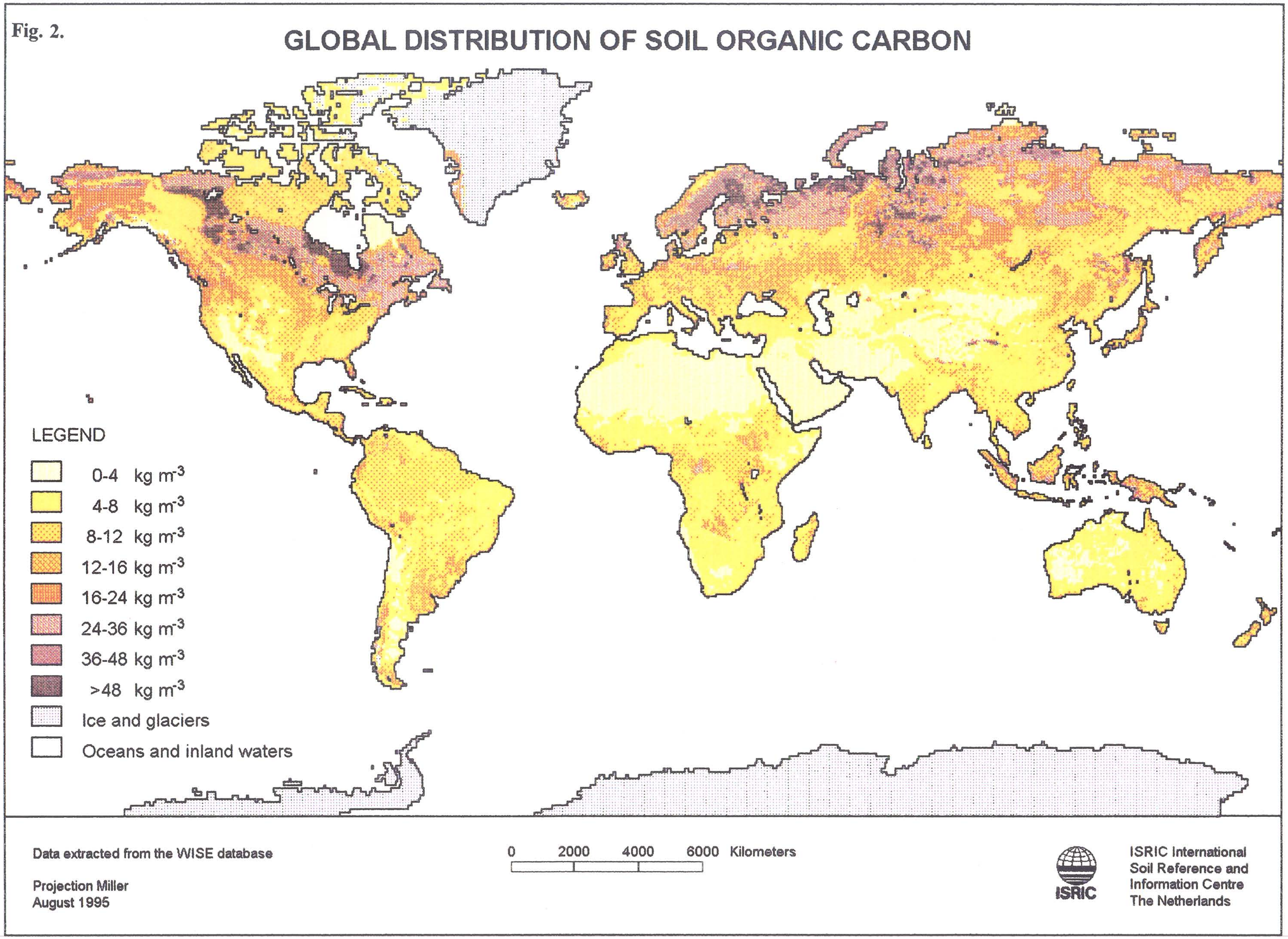
Total soil carbon

Recently published estimates of soil carbon in the upper 1.0 m of the soils of the world range from 1940 Pg C (Sombroek *et al.* 1993), 2157 Pg C (this study) to 3293 Pg C (Eswaran *et al.* 1995). These figures show that global estimates of carbon are still not very reliable as a result of the lack of uniform and representative data from different parts of the world, notably China and the former USSR, as well as to uncertainties attached to the geographic data used. It is well known that parts of the Soil Map of the World are outdated (Sombroek, 1990), necessitating a concentrated effort in updating the information on the world's soil resources (Oldeman & Van Engelen 1993; Arnold 1995; Madsen & Jones 1995).

Data on amounts of carbon stored at different depths in various soils of the world have been discussed elsewhere (Sombroek *et al.* 1993; Eswaran *et al.* 1995; Batjes, *submitted*). Large amounts of SOC occur at greater depth in Histosols and some deeply weathered tropical soils such as the Ferralsols. High concentrations of carbonate-carbon may occur below 1.0 m in petrocalcic horizons. Available data sets, so far, have precluded detailed estimates of these 'deep' reserves worldwide (e.g., Sombroek *et al.* 1993; Eswaran *et al.* 1995). Fisher *et al.* (1994) drew attention to the important role of deep tropical soils and tropical land use in the global carbon cycle. However, in soils where this deeper carbon is old and refractory it will be of limited importance in gaseous exchanges with the atmosphere. Batjes (*submitted*) estimated the global SOC pool for the first 2.0 m at 2376-2456 Pg C, of which 616-640 Pg C is stored in tropical soils. No estimates could be proposed yet for carbonate-carbon, because of a paucity of data for carbonate carbon held below 1.0 m depth. The amount of organic carbon held in either resistant charcoal or in litter layers remain difficult to estimate. Litter layers are particularly important in the cooler regions of the world and in soils under forest.

The global amounts of SOC and CAC sequestered in the soils of the world are shown in Figures 2 and 3. The first map reflects the possible large effects of global warming on C effluxes in high northern latitude areas, notably in peatland, boreal forest and tundra ecosystems (Sampson *et al.* 1993). Soils of arid and semi-arid regions have low SOC contents and high CAC reserves, a subject that will be discussed below.

Fig. 2.


GLOBAL DISTRIBUTION OF SOIL ORGANIC CARBON
LEGEND
0-4 kg m-3
4-8 kg m-3
8-12 kg m-3
12-16 kg m-3
16-24 kg m-3
24-36 kg m-3
36-48 kg m-3
>48 kg m-3
Ice and glaciers
Oceans and inland waters
Data extracted from the WISE database
Projection Miller
August 1995
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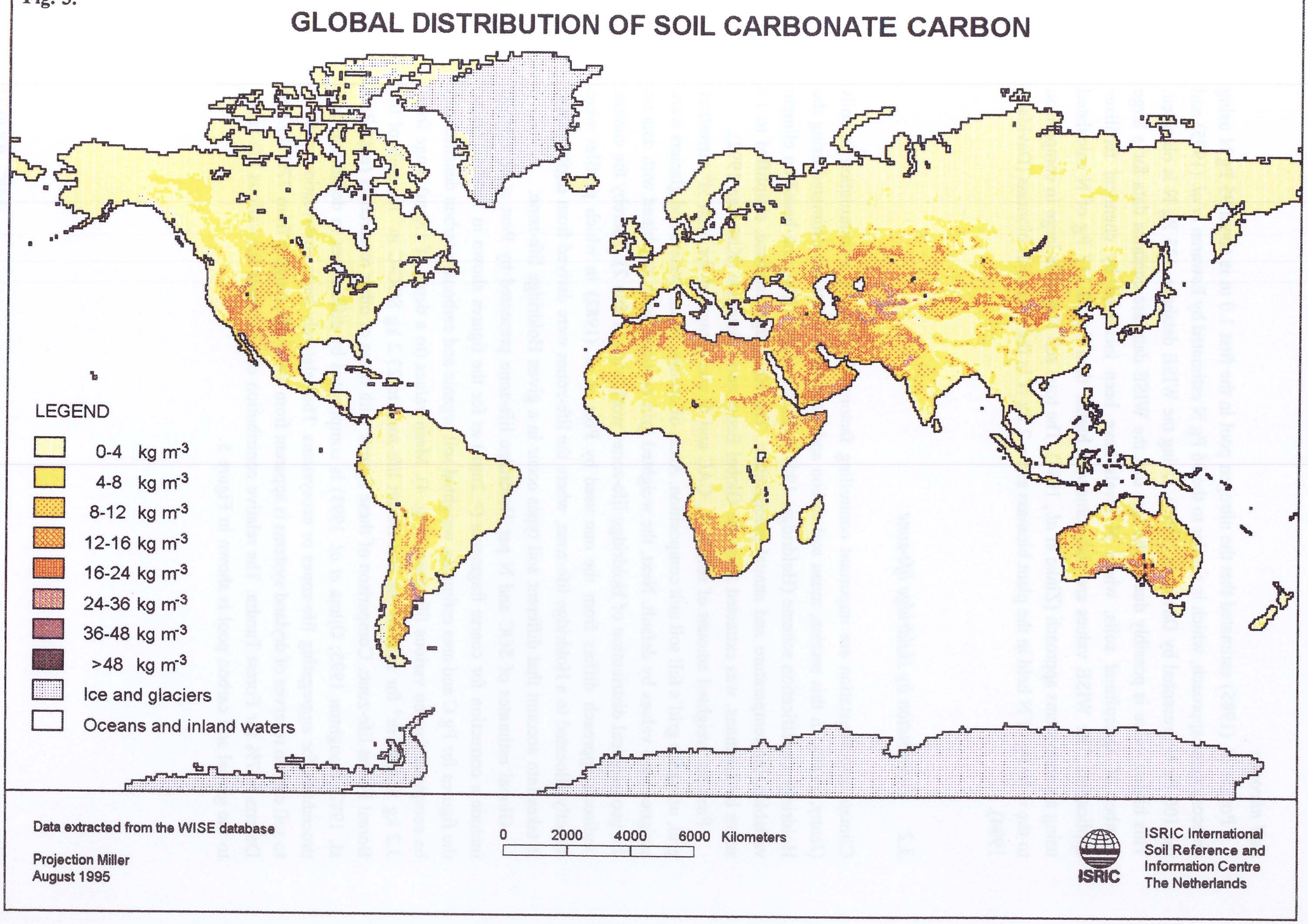
ISRIC
ISRIC International
Soil Reference and
Information Centre
The Netherlands

Fig. 3.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Soil nitrogen

Post *et al.* (1985) estimated that the nitrogen pool in the first 1.0 m is about 95 Pg N using an ecosystems approach, which is similar to the 96 Pg N estimated by Eswaran *et al.* (1995) and the 100 Pg N presented by Davidson (1994). Using the WISE database, 133 Pg N is obtained. This higher value is possibly due to the fact that the WISE database contains data for a large number of agricultural soils, where N levels have been increased by chemical fertilizer application. The WISE values are also somewhat higher than the 92-117 Pg of N calculated using an ecosystems approach (Zinke *et al.*, 1984). The total soil N pool is large in comparison to the ≈ 10 Pg of N held in the plant biomass and ≈ 2 Pg N in the microbial biomass (Davidson 1994).

3.2 *Distribution by Holdridge life-zone*

Climate and vegetation are important controlling factors of organic C accumulation in soils (Jenny, 1980). In this section, mean soil carbon and nitrogen contents are estimated using the Holdridge classification scheme (Holdridge, 1947) which assigns a life-zone based on climate variables, bio-temperature and annual precipitation. The Holdridge database, simplified to 14 zones by Leemans, was extracted from the Global Ecosystems Database (Kineman 1992).

First the weighted amount of soil SOC, CAC and 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 (Table 2). 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.

Global estimates of SOC and N per Holdridge life-zone presented by Post *et al.* (1982), include a correction for coarse fragments (> 2mm) as for the figures shown in Table 2. Using the figures for Pg C and area estimates, weighted soil organic and carbonate carbon densities can be computed for the various life-zones (Fig. 4). 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. Comparison of these figures with those of other researchers (e.g., Post al. 1982; Houghton 1995; Ojima *et al.* 1993) is complicated by differences in definitions and procedures for aggregating life-zones or ecosystems. The relatively large contribution of CAC to soil carbon reserves of dryland systems is apparent from Table 2B, ranging from 77% for Hot Deserts to 7% for Forest Tundra. The relative contribution of soils from the various life-zones to the global soil carbon pool is shown in Figure 5.

Table 2. Estimated organic carbon and nitrogen pools, aggregated per Holdridge life-zone (Pg C respectively N for specified depth zone: A) d= 0-30 cm, B) d= 0-100 cm; corrected for coarse fragments)

A) *d= 0-30 cm*

Holdridge life-zone	SOC-C	CAC-C	TOT-C	N	Area†
Tundra	54.0	9.5	63.5	3.9	10.16
Cold Parklands	16.1	5.1	21.2	1.5	2.78
Forest Tundra	74.2	8.5	82.7	5.3	8.72
Boreal Forest	152.1	12.6	164.7	11.1	14.94
Cool Desert	9.6	14.4	24.0	1.3	4.00
Steppe	35.3	19.0	54.3	4.3	7.35
Temperate Forest	63.9	11.3	75.2	6.2	9.90
Hot Desert	36.6	71.3	107.9	4.9	20.80
Chaparral	21.8	15.0	36.8	2.5	5.62
Warm Temperate Forest	15.9	2.8	18.7	1.6	3.20
Trop. Semi-Arid	27.0	24.3	51.3	3.3	9.53
Trop. Dry Forest	61.1	18.7	79.8	6.6	14.85
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

B) *d= 0-100 cm*

Holdridge life-zone	SOC-C	CAC-C	TOT-C	N	Area†
Tundra	158.8	16.4	175.2	8.3	10.16
Cold Parklands	35.7	15.3	51.0	3.4	2.78
Forest Tundra	180.2	14.4	194.6	11.7	8.72
Boreal Forest	345.9	34.9	380.8	23.4	14.94
Cool Desert	19.5	49.6	69.1	3.0	4.00
Steppe	69.1	73.1	142.2	9.2	7.35
Temperate Forest	120.3	31.9	152.2	11.7	9.90
Hot Desert	66.1	231.6	297.7	11.4	20.80
Chaparral	42.5	53.7	96.2	5.4	5.62
Warm Temperate Forest	30.4	6.3	36.7	3.1	3.20
Trop. Semi-Arid	53.1	82.2	135.3	7.1	9.53
Trop. Dry Forest	118.3	55.9	174.2	13.7	14.85
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 simplified to 14 classes by Leemans (see Kineman 1992); SOC-C = soil organic carbon; CAC-C= soil carbonate carbon; TOT-C= (SOC-C + CAC-C); N= total nitrogen; sums may not exactly add up to totals shown for all life-zones due to rounding.

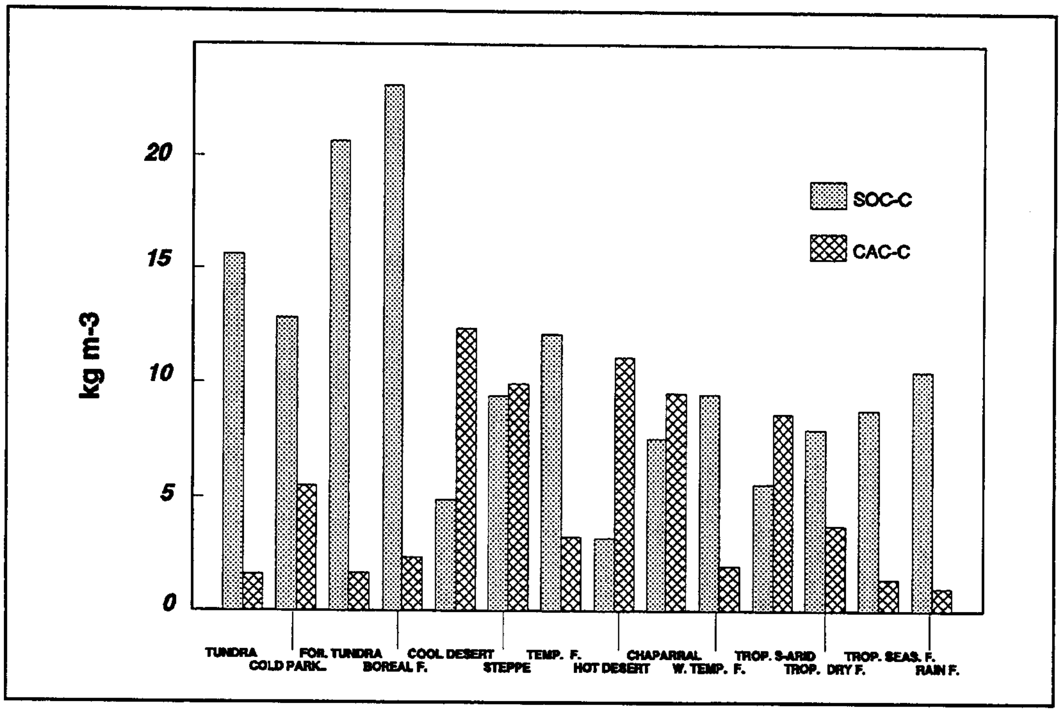

Fig. 4. Weighted soil carbon density by simplified Holdridge life-zones (kg m^{-2} to 1.0 m depth; SOC-C= soil organic carbon; CAC-C= soil carbonate carbon; corrected for coarse fragments)

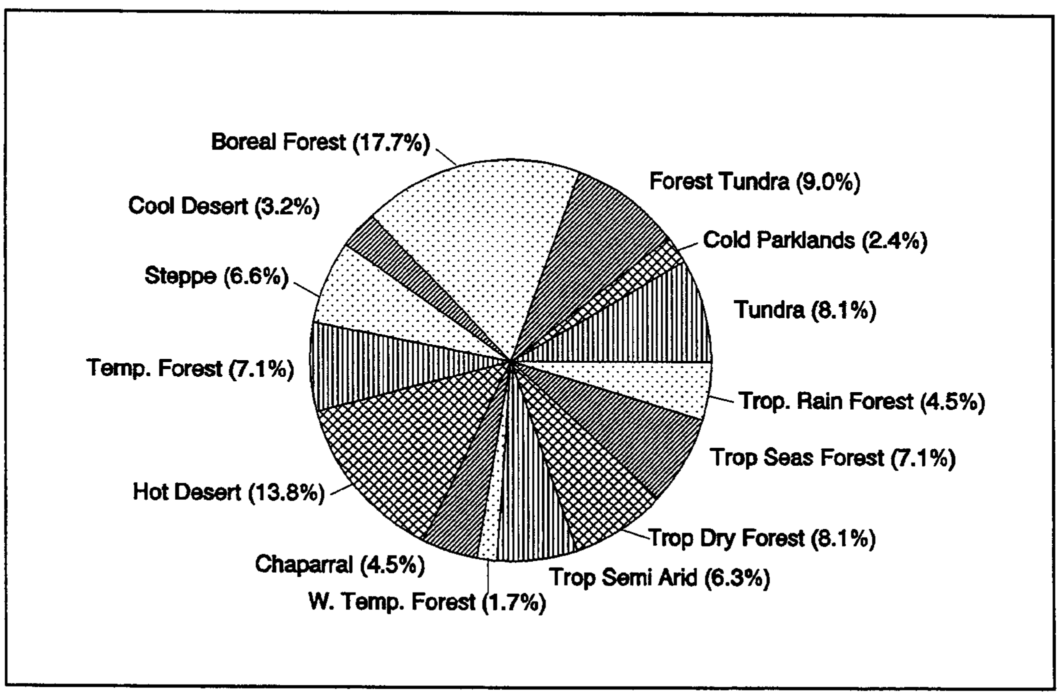

Fig. 5. Relative contribution of soil units, aggregated by Holdridge life-zones, to the global carbon pool (Total is 2157 Pg C to 1.0 m depth, including soil organic carbon and soil carbonate carbon; corrected for coarse fragments).

3.3 *Analyses for dryland soils*

Global estimates

Although a distinct characteristic of dryland regions is their lack of available moisture for plants, it remains difficult to define their extent unambiguously (FAO 1978-1981; UNEP 1992). Particularly because climatic aridity, the feature which drylands have in common, varies strongly according to rainfall distribution and temperature. A useful criterion for defining limits of dryland regions at the regional scale is the aridity index, calculated as the ratio of rainfall (R) over potential evapotranspiration (PET) (UNEP 1992). A shortcoming in using R/PET is that it ignores site specific moisture conditions, as modified by surface run-off, soil water retention and release properties, and capillary rise. Soil moisture regimes, however, are not considered explicitly in the FAO-Unesco (1974) legend, except for Xerosols and Yermosols.

A practical way of defining the extent of dryland soils would be to use the Agro-Ecological Zones map of FAO (1978-1981), were it not that full digital coverage is not expected before the end of 1995 (Van Velthuizen, *pers. comm.*). Similarly, a digital copy of the Aridity Zones map, presented in the Atlas of Desertification (UNEP 1992), was not available from UNEP-GRID for this study. As a surrogate, the Cool Desert, Hot Desert, Chaparral, Tropical Semi Arid and Tropical Dry Forest life-zones of Holdridge will be used to estimate the lower range of global carbon and nitrogen pools for the dryland regions, while Steppes are also included to get the upper range. Table 2 shows soils of the above life-zones hold 300-369 Pg SOC-C, 473-546 Pg CAC-C and 41-50 Pg N in the first 1.0 m, corresponding respectively with about 20-25, 68-79 and 31-38 % of the world's estimated total reserve. Solomon *et al.* (1993) estimated that soils of 'grasslands/deserts' hold 256 Pg C, while Ojima *et al.* (1993) estimated this to be 417 Pg C to a depth of 1.0 m for 'grassland and drylands'.

Estimates for main dryland soils

Soils of dryland regions are extremely variable. Low rainfall reduces plant growth and build up of organic matter. Typically, long-term low precipitation enables an accumulation of soluble salts, carbonates and silicates with ascending (evaporating) water in the profile which may lead to surficial accumulation (Buringh 1970; Driessen & Dudal 1993).

Dominant soil units conditioned by limited leaching include Yermosols and Xerosols (which have very weak to weakly developed ochric horizons) and Solonchaks and Solonetz (which are characterized by high salt concentrations) (FAO-Unesco 1974). Important associated soils include: (a) Regosols: immature soils developed on unconsolidated materials, (b) Vertisols: deeply cracking and swelling clay soils; (c) Arenosols: deep sandy soils; (d) Cambisols: a range of slightly to moderately weathered soils (mainly calcic and eutric); and (e) a range of shallow soils limited in depth by hard rock (Lithosols, Rendzinas and Rankers). Inclusions of Calcaric Luvisols, Kastanozems and Chernozems may occur towards the more humid climate types where natural vegetation grades to steppes, but these soils have not been considered in Table 3.

Values in Table 3 again are difficult to compare with the findings of other studies. A major constraint is the different types of classification systems used, e.g. FAO-Unesco legend versus Soil Taxonomy, and the way in which various soil types have been regrouped in various studies.

Sombroek *et al.* (1993) estimate carbonate carbon reserves to be 537 Pg CAC-C in Xerosols, Yermosols and petrocalcic phases, while the present study gives 320 Pg CAC-C for Yermosols and Xerosols alone. This difference should reflect the large amounts of carbonate carbon held in other soils with petrocalcic horizons. According to Eswaran *et al.* (1995), 1,044 Pg CAC-C is held in the world's Aridisols. A better correspondence is found for Vertisols, which are classified using similar criteria in all classification systems, viz.: 19 Pg (Sombroek *et al.* 1993), 25 Pg C (Eswaran *et al.* 1995) and 27 Pg C (this study).

4. Combatting Land Degradation and Global Warming

4.1 Vulnerability to land degradation

As shown by Jenny (1980) all soils are formed and evolve under the influence of time, climate, parent material, topography, vegetation, fauna and human influences. Although many effects of human influence have been positive — causing an accumulation of C, N and P and improving porosity in ancient agricultural soils (Sombroek 1966; Sandor & Eash 1995) — and increased food production, other activities have lead to extensive soil physical and chemical degradation (Oldeman *et al.* 1991; O'Hara *et al.* 1993). The latter include: industrialization with concomitant release of toxic substances into the atmosphere (e.g., SOx, NOx), producing acid rain; poor agricultural management practices such as 'short cycle' slash-and-burn, excessive fertilizer application of N and P, and poor irrigation and drainage practices leading to salinization.

As the 21st century approaches, it has become increasingly clear that the drylands of the world will be subjected to even greater land use pressures as a result of the continued growth of the population (Beaumont 1989; Biswas 1994). Crucial factors are the wealth of a nation, the political system, and the relative importance of drylands in the economy (Beaumont 1989; Westing 1994). The key issue is that the growing population must be fed and housed, requiring conservation of the natural resources.

Soils of drylands are especially vulnerable to human degradation in view of the slow speed of their recovery after a disturbance. This is mainly due to the limited water supply and associated low rates of *in situ* soil formation and plant growth. Vegetation and soils differ in their resilience to disturbance. Although vegetation communities are easily disturbed or degraded, recovery rates remain fast when compared with soil formation (Arnold *et al.* 1990). Compared to soils of humid areas, dryland soils have a low resilience to human disturbance (UNEP 1992).

Table 3. Estimates of soil C and N pools of main dryland soils of the world. (Pg C respectively N for specified depth zone: A) d= 0-30 cm, B) d= 0-100 cm; corrected for coarse fragments)

A) *d= 0-30 cm*

Soil name	SOC-C	CAC-C	TOT-C	N
Arenosols				
Albic Arenosol	1.4	0.0	1.4	0.1
Cambic Arenosol	2.4	4.4	6.8	0.3
Ferralic Arenosol	3.6	0.0	3.6	0.7
Luvic Arenosol	0.8	1.8	2.5	0.1
Cambisols				
Chromic Cambisol	3.5	1.2	4.7	0.4
Eutric Cambisol	10.8	3.9	14.8	1.6
Calcic Cambisol	2.2	3.7	5.9	0.3
Vertic Cambisol	1.3	0.9	2.2	0.2
Fluvisols				
Calcaric Fluvisol	2.6	5.8	8.3	0.3
Eutric Fluvisol	8.2	2.8	11.1	1.3
Lithosols	38.8	41.8	80.6	4.5
Regosols				
Calcaric Regosol	2.7	6.5	9.2	0.6
Eutric Regosol	8.4	2.1	10.5	1.2
Rendzinas	3.9	2.0	5.9	0.3
Solonchaks				
Gleyic Solonchak	0.8	2.2	3.0	0.1
Mollic Solonchak	0.5	0.6	1.1	0.1
Orthic Solonchak	2.9	8.0	10.9	0.4
Takyric Solonchak	0.4	1.5	2.0	0.1
Solonetz				
Gleyic Solonetz	0.5	0.0	0.5	0.1
Mollic Solonetz	2.7	0.0	2.8	0.4
Orthic Solonetz	3.6	4.5	8.1	0.5
Vertisols				
Chromic Vertisol	6.0	4.7	10.7	0.7
Pellic Vertisol	7.0	2.9	9.9	0.8
Xerosols				
Haplic Xerosol	3.5	10.3	13.9	0.4
Calcic Xerosol	5.6	13.5	19.1	0.7
Luvic Xerosol	1.3	2.5	3.7	0.2
Gypsic Xerosol	0.2	0.4	0.6	0.0
Yermosols				
Haplic Yermosol	4.8	7.5	12.3	1.0
Calcic Yermosol	2.6	13.1	15.7	0.3
Luvic Yermosol	2.6	4.4	7.0	0.3
Takyric Yermosol	0.1	1.6	1.7	0.0
Gypsic Yermosol	0.5	4.1	4.6	0.1
All units	136.4	158.6	295.0	17.9

† Sums may not exactly add up to totals shown due to rounding.

Table 3 (continued)

B) *d= 0-100 cm*

Soil name	SOC-C	CAC-C	TOT-C	N
Arenosols				
Albic Arenosol	1.9	4.1	6.0	0.2
Cambic Arenosol	5.8	14.9	20.7	0.8
Ferralic Arenosol	8.4	0.0	8.4	1.4
Luvic Arenosol	2.0	5.9	7.9	0.4
Cambisols				
Chromic Cambisol	6.6	3.0	9.6	0.7
Eutric Cambisol	21.6	12.5	34.1	2.9
Calcic Cambisol	5.2	12.6	17.8	0.7
Vertic Cambisol	2.7	2.6	5.3	0.4
Fluvisols				
Calcaric Fluvisol	6.8	19.3	26.1	0.9
Eutric Fluvisol	21.4	8.8	30.2	3.2
Lithosols	38.8	41.8	80.6	4.5
Regosols				
Calcaric Regosol	7.7	16.0	23.7	1.5
Eutric Regosol	13.8	2.5	16.3	2.3
Rendzinas	3.9	3.5	7.4	0.3
Solonetz				
Gleyic Solonetz	1.0	0.2	1.2	0.1
Mollic Solonetz	5.3	0.6	5.8	0.4
Orthic Solonetz	7.4	17.0	24.4	2.6
Solonchaks				
Gleyic Solonchak	1.9	8.1	10.0	0.4
Mollic Solonchak	1.0	3.0	4.0	0.1
Orthic Solonchak	6.9	27.5	34.3	1.0
Takyric Solonchak	1.2	6.4	7.6	0.1
Vertisols				
Chromic Vertisol	15.1	16.4	31.5	1.6
Pellic Vertisol	16.8	10.1	26.9	1.7
Xerosols				
Haplic Xerosol	7.5	34.8	42.2	0.9
Calcic Xerosol	10.5	76.9	87.4	1.4
Luvic Xerosol	3.3	11.5	14.8	0.3
Gypsic Xerosol	0.5	1.3	1.8	0.0
Yermosols				
Haplic Yermosol	12.5	30.9	43.4	3.6
Calcic Yermosol	7.7	86.4	94.1	0.5
Luvic Yermosol	4.7	19.3	23.9	0.5
Takyric Yermosol	0.4	5.7	6.1	0.1
Gypsic Yermosol	1.2	5.4	6.6	0.1
All units	251.1	508.9	760.0	35.4

† Sums may not exactly add up to totals shown due to rounding.

4.2 *Main causes of soil degradation*

In many countries, external social, economic and technological influences have contributed significantly to social and ecological imbalances in land use systems, leading to land degradation (Biswas 1994). Five main causes of human-induced land degradation are deforestation and removal of natural vegetation, over-cultivation, over-grazing, mismanagement of water resources, and industrial development (Grainger 1985; Kotschi & Adeljhelm 1986; Thomas & Middleton 1994; UNEP 1992). The adverse effects of intensive tourism in uplands and national parks are also well known.

Local-scale variability in organic matter oxidation, N-mineralization and soil loss through cultivation are strongly dependent on management practices (Veldkamp 1993; Herrmann *et al.* 1994; Ihori *et al.* 1995) and seasonal rainfall distribution. Climate-induced changes, causing major differences in ground cover, could degrade structure and decrease porosity in most soils, leading to increased runoff and erosion in sloping land. Associated, adverse off-site effects are sedimentation and flooding in low lying areas, and increased wind erosion in dry areas.

Since the beginning of the 20th century, there has been an overall tendency for increased aridification in the Sudano-Sahelian zone (Grainger 1985; Carbonnel & Hubert 1992). These changes should not be seen in isolation from human-induced processes of global change. Atmospheric circulation patterns over deforested tropical regions, for example, have been shown to prompt climate changes distant from the disturbance, both in tropical, middle and high latitudes (McGuffie *et al.* 1995). Soil erosion from arid and semiarid systems influences nutrient status in the rest of the earth's ecosystems (Simonson 1995) and may alter global climatic patterns (Schlesinger *et al.* 1990).

4.3 *Main processes of land degradation*

Main processes of soil degradation associated with desertification may be summarized as follows:

(a) increased land pressure leads to local loss of vegetation cover and increased area of bare patches (increase in patchiness (Schlesinger *et al.* 1990)). Removal of crop (residues) for fuel or fodder reinforces this trend.

(b) direct exposure of topsoil to solar radiation increases soil temperature and the rate of organic matter decomposition (Jenkinson & Ayanaba 1977), where soil moisture is not limiting.

(c) loss of organic matter causes soil structural degradation (e.g., porosity, aggregate stability), reduces water holding capacity, causes compaction with decreased infiltration and increased runoff, thereby reducing the system's resilience against erosion.

(d) decline in organic matter content decreases nutrient storage properties. Nutrients are lost by percolation and the efficiency of chemical fertilizers is reduced.

(e) impact of rain and sun on bare topsoil results in crusting, water infiltration is further reduced, and percentage of runoff increases.

(f) sediments, with enclosed nutrients, are carried away by erosion. Effective soil depth accessible to plant roots decreases, leaving exposed restrictive soil layers or bare rock.

(g) exposed soil is eroded by wind, crops are destroyed by dust bearing winds (off-site effects), and dunes may encroach on arable land. An important off-site effect is the silting-up of dams and river beds, and increased flooding risk in low lying areas. Additionally, airborne dust from dryland regions can form an important source of nutrients (Simonson 1995) and alkalinity (Rodá *et al.* 1993) in areas where it is deposited on soils.
(h) in the worst-case scenario, gradually degraded patches link up to form extended areas of bare and degraded land. At this stage, reclamation becomes virtually impossible.

4.4 Combatting land degradation

Controlling desertification involves all aspects of environmental management, including water and soil management. In most cases, changes in soil properties by direct human influence, whether intentional or not, are far greater than effects induced by direct climate change (see Scharpenseel *et al.* 1990). Soil management measures designed to optimize the soil's sustained productivity should therefore be adequate to counteract degradation of agricultural land by climate change (FAO 1993). When new land is to be developed, or land use is to be changed, it is important to survey the resources and to make an assessment of their suitability for specific uses (FAO 1979b, 1985; Kassam *et al.* 1993). Thereby, expansion of cropping onto marginal land can be reduced. Better range management and development of new livestock breeds will improve productivity and reduce pressures on the land, particularly if critical dry-season fallows are re-introduced (Grainger 1985). Restoring tree and woodland cover will stabilise cropping and pastoralism by reducing soil erosion and providing improved supplementary fodder (Grainger 1985).

Erosion control measures vary considerably according to ecological and socio-economic conditions. Traditional strategies which are generally well suited to the physical environment, are partly becoming obsolete because of population growth. The use of modern farm equipment in contemporary agricultural systems has often failed because of lack of compatibility with populations concerned. Roose (1992) proposes a rural development strategy (water and soil fertility conservation) based on the requirements, traditions and economic capability of farmers.

Sustainable irrigated agriculture is possible in arid zones, even when water quality is mediocre, provided site conditions are properly evaluated, adequate drainage facilities installed, and monitoring systems are put in place (Szabolcs 1991). However, these measures are costly.

Linkages between drought, food production, famine and migration make monitoring of dryland degradation an important issue. Improved monitoring systems are being developed particularly in the field of remote sensing (Millington *et al.* 1994). Harrison & Carg (1991) demonstrate the problems of classifying the vegetation of complex semi-arid landscapes using satellite data, showing that ground observations of changes remain critical for 'ground-truthing'. Important indicators of soil quality that should be monitored include soil structure, soil permeability, soil organic matter content, base saturation, pH and changes in available nutrients or salts in relation to water management.

Studies of land degradation processes have resulted in various qualitative and quantitative models (see De Jong 1994). These models are useful to test scenarios and to explore alternatives to current land uses, provided they have been validated for regional conditions. Uniform databases of the main environmental factors are critical in order to develop, to test and to run these models (Van den Berg 1992). Although models are effective tools for understanding complex interactions among various system components and for visualizing different scenario's to decision makers, many remain poorly suited to the highly site-specific needs of farmers (see Powell *et al.* 1994).

Land users and planners should protect soil resources from global change (e.g., climate, atmospheric pollution, drought, erosion) by:

(a) managing soils with a view to ensuring maximum physical resilience is retained by preserving a heterogenous system of macropores, by conserving soil (micro)biological diversity (Beese *et al.* 1994; Steinberger 1995), and by maintaining a closed ground cover (FAO 1993; Lal & Kimble 1994; Sauerbeck 1994). This can be done with soil management practices already available, including conservation or minimum tillage, water management and erosion control (Kovda 1980; Kern & Johnson 1993; Lal 1995a) and the planting of hedgerows (Kiepe 1995). Tillage methods that minimize depth and extent of soil disturbances will have the least impact on soil gaseous emissions (Reicoksy & Lindstron 1995).

(b) using integrated plant nutrient management systems to balance the input and removal of nutrients over time (FAO 1993; Smaling 1993; Sauerbeck 1994). Fertiliser costs for farming systems with an inherently low biological production potential, however, are likely to exceed the benefits in terms of increased crop and livestock output (Powell *et al.* 1994). Reducing nutrient losses via runoff, leaching, volatilization etc. can enhance the profitability of using external nutrient sources.

(c) restoration of degraded and eroded lands by proven methods, such as afforestation, agro-forestry, improved pastures with low stocking rates, use of chemical fertilizers, ecologically compatible farming systems, conservation tillage, mulch farming techniques, fertility maintenance, and integrated pest management (Kovda 1980; Lal & Kimble 1994).

(d) developing and promoting viable, science-based alternatives to subsistence and resource-based agriculture (Lal & Kimble 1994). More research is required in areas related to vegetation dynamics and feed availability from natural pastures (Grainger 1985; Powell *et al.* 1994). This research should take into consideration the needs and wishes of the rural population and their cultural and societal values. These solutions should, for example, take into account the spatial variability of rainfall and the risk-minimizing behaviour of rural families.

(e) taking into consideration socio-economic issues which limit the land users ability to remedy land degradation (e.g., lack of secure tenure/ownership of the land, limited access to inputs, and possible lack of knowledge and technology to effectively use these inputs).

4.5 Possible effects of climate change

Understanding how soil organic matter and nutrient status change in dryland soils in response to climate change requires knowledge of several biogeochemical input and output processes. The effect of global climate change on soil organic matter content, soil organic matter quality and nutrient pools depends on the relative sensitivity of photosynthesis, autotrophic and heterotrophic respiration to climatic changes. There is increasing evidence that water or temperature stressed plants are more responsive to CO_2 increase — because higher CO_2 reduces transpiration — than unstressed plants. According to a review of mainly short duration experiments (Idso & Idso 1994), it appears that the relative growth-enhancing effects of atmospheric CO_2 enrichment is greatest when resource limitations and environmental stresses are most severe. Idso & Idso (1994) therefore argue that it could well be that the percentage growth response of natural ecosystems to atmospheric CO_2 enrichment will be greater than that of managed agricultural systems. In how far these experimental trends apply also to longer-term periods in ecosystems remains to be assessed (Smith *et al.* 1993). In general, it seems that global systems without effective management intervention will become much stronger C sources under doubled CO_2 climate (Sampson *et al.* 1993).

Ecosystem models discussed by Schimel (1995) suggest that plant growth, under increased atmospheric CO_2 concentrations, may eventually become nutrient-limited; sequestration of C resulting from CO_2-enhanced growth will store nitrogen and other nutrients in wood or unreactive soil organic matter. In the long-term, this can cause these elements to become limiting for plant growth. In principle, this problem can be addressed by larger applications of chemical fertilizers and promotion of integrated plant-nutrition measures in agro-ecosystems (Sombroek *et al.* 1993). Effectiveness of the CO_2 fertilization effect could also be modified by atmospheric N deposition and increased levels of UV-B radiation. Indirect changes caused by increased UV-B — such as changes in plant form, biomass allocation to different parts of the plant, timing of developmental phases and secondary metabolism — may be equally or more important than direct damaging effects of UV-B (Caldwell *et al.* 1995).

Changes in plant communities associated with changes in climate will affect litter quality, which will lead to either positive or negative feedbacks depending on whether lignaceous perennials or non lignaceous annuals take over. With respect to drylands, West *et al.* (1994) expect a decrease in shrub abundance, an increase in half-shrubs and herbaceous species, an increase in C_4 plants, an increase in C/N ratio in plant tissues, and a decrease in succulents under all scenarios of climate change. Climatic shifts may be accompanied by increases in temperature, seasonal rainfall distribution, atmospheric N deposition, burning and so on, making it difficult to make predictions as other factors are included. Different microbial responses to these changes are reasonably well known, but complex interactions such as effects on N-fixation, N-mineralisation, denitrification, cation leaching and ratios of trace gas emissions remain difficult to predict (Davidson 1994). Climatic change may further affect the population dynamics and status of insect pests of crops, affecting possibilities for C storage (Cammel & Knight 1992). Since the Q_{10} for litter decomposition is greater (1.3-4.0) than the Q_{10} for primary production (1.0-1.5), litter decomposition is projected to proceed relatively more rapidly under scenarios with increased temperature (Kohlmaier *et al.* 1990), provided the water and nutrient supply do not become limiting. Jenny (1980) has also shown that soil organic matter content decreases as temperature increases along precipitation transects. One way to proceed in understanding these complex interrelationships is to use computer simulation (Goldewijk *et al.* 1994; Schimel 1995). Sampson *et al.* (1993) estimate the current C flux from grasslands, savannas and deserts at between 0 to +0.6 Pg C yr^{-1} (+ = sink), which would change to -0.3 to +0.1 Pg C yr^{-1} under 'doubled CO_2 climate', and to a sink of +0.1 to +0.5 Pg C yr^{-1} with 'doubled CO_2 climate and optimum vegetation management'.

Soil salinity and salinization are affected by both precipitation and temperature changes, because of the direct link between leaching, evapo-transpiration and salinity (Szabolcs 1991; Varallyay 1994). Even without climatic change, there would be an increase in dryland salinisation in the near future (West *et al.* 1994).

Wind and water erosion in drylands are expected to increase over the next decades, but it remains difficult to say how the rate will respond to different scenarios of climatic change (West *et al.* 1994). While water-driven erosion is likely to decrease as rainfall decreases, total erosion could increase as wind-driven erosion increases. Increased occurrence of extreme weather events such as storms, however, could increase the erosive impact of scarce rainfall showers. Thereby, the overall effect of water erosion can still be high.

5. Discussion and Conclusions

This paper estimates the present mass of carbon and nitrogen in the soils of the world, with special attention to dryland areas. Although current estimates of SOC mass in the 1.0 m depth range (un-corrected for coarse-fragments) are similar to those computed by Eswaran *et al.* (1995), large differences in estimates can be observed when individual soil units are compared. With respect to estimates of carbonate-carbon and soil nitrogen, the uncertainty is even higher. The estimates presented in this paper are average values suitable for global assessments. They are considered unreliable for presenting national statistics, which require regionally explicit data sets. Revisions will be made as new data for under-represented soil units are added to the WISE database.

The C and N data presented, were compiled from field samples collected during the last 20-30 years. As such the information does not represent the carbon content of the soils of the world at any single moment in time. As a consequence these carbon data cannot be used directly to assess changes in soil C during this period, for which paired studies are needed (Mann 1986; Veldkamp 1993; Ihori *et al.* 1995). The soil carbon data held in the WISE database, however, can provide primary input for process-based models to predict changes in carbon content resulting from land degradation, climate change and management practices (Goldewijk *et al.* 1994; Schimel *et al.* 1995). A data set, with a first selection of profiles derived from WISE has been released to the scientific community for such purposes (Batjes 1995). It has been proposed to serve as the basis for a global soil database to be developed by IGBP-DIS (Scholes *et al.* 1994).

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. Several spatial data sets (e.g., soil pH, organic carbon, soil water retention properties), with a resolution of ½° latitude by ½° longitude, have been prepared using the format of the Global Ecosystems Database (Kineman 1992). On the longer-term it is envisaged that the WISE database could be used to refine studies of crop production potentials (e.g., Luyten 1995) and soil gaseous emission potentials (e.g., Bouwman *et al.* 1994; Bachelet

& Neue 1993) which of necessity used the 1° by 1° resolution data file which Zobler (1986) derived from the original, printed Soil Map of the World (FAO-Unesco 1974).

The need remains for additional information on the world's soil resources. This is critical as parts of the Soil Map of the World (FAO-Unesco 1971-1981; FAO 1991) are outdated (Sombroek, 1990; Oldeman & Van Engelen, 1993). An internationally endorsed 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 several soil survey organizations to update the South and Central American section of the Soil Map of the World, 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 current update for the Southeast Asian Soil Degradation Assessment (UNEP, FAO, ISRIC) may be used as a physiographic template for a Southeast Asian SOTER.

A full update of the information on the world's soil resources in a 1:5 M scale SOTER would provide the IGBP community with much of the primary soil data it would require for its global studies of terrestrial agro-ecosystems. Also these databases can be used with dynamic models and GIS techniques to identify areas vulnerable to specific types of land degradation and land use change scenarios (Batjes *et al.* 1993)

Human activities have led to about 1964×10^6 ha of degraded lands in the world (Oldeman *et al.* 1991), many of which occur in dryland areas (UNEP 1992). In these soils, organic matter content is decreasing and as a result cation exchange capacity, water holding properties and structural stability decrease also, seriously reducing the possibility for sustainable agriculture. Nonetheless, much can be done by human beings to manage ecosystems, to adapt farming systems and to reduce the impacts of land degradation and climate change. It is likely that vegetation-based C-management or mitigation measures (e.g., afforestation, limited tillage) cannot fully offset the existing anthropogenic disturbances of the global C cycle. The potential for the terrestrial biosphere to store carbon will also be limited by degradation of natural vegetation and soils in response to human population growth and agricultural expansion, notably in the tropics. As the population continues to increase, the potential for vegetation shifts and CO_2 fertilization (Bazzaz & Fajer 1992; Idso & Idso 1994) to create a carbon sink on land (Sombroek *et al.* 1993) may become largely academic (Schlesinger 1990) since large sections of originally fertile land may become too degraded to be reclaimed. Also, it has been argued that under increased atmospheric CO_2 concentrations and higher temperatures, nutrients may become limiting for net primary production and thereby ultimately reduce soil C stocks. Process-based models are needed to provide possible answers to the above questions (e.g., Solomon *et al.* 1993; Goldewijk *et al.* 1994; Schimel 1995). While the amounts of carbon that can be sequestered in vegetation and soils in semiarid regions is severely limited by low rainfall and generally high temperature, small changes in total amounts will be important for global warming in view of the large extent of semiarid lands. This would require excellent conservation and management of the land under consideration.

Improving the science base for soil and ecosystem management, with attention to the C, N and P cycle impacts of managements practices, is needed for all agro-ecosystems to help managers understand and incorporate C-related management factors into land use decisions

(Sampson *et al.* 1993; Campbell & Zetner 1993). Several priority issues need to be addressed as reviewed by Beaumont (1989) and Lal & Kimble (1994).

Policies must be developed to reduce the fundamental causes of land degradation and greenhouse gas increases: non-sustainable land use practices and increasing fossil fuel use, both of which are driven by growing human population and economic development, must be curtailed. In assessing prospects and time scales for combatting land degradation in dryland regions, it must be kept in mind that the strategies formulated by scientists and planners can only be effective with the willing participation of the rural people directly concerned. Many projects have failed because planners did not find out the local communities affected what their views and needs are. Hence the need for a holistic design and a participatory approach that directly involves the local community in the planning and implementation process (Kotschi & Adelhelm 1986; Westing 1994; Catizzone & Muchena 1994). The administrative and logistical challenges of implementing a truly participatory approach, however, are considerable requiring a concentrated effort.

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