Working Paper and Preprint 94/01

WORLD INVENTORY OF SOIL EMISSION POTENTIALS:
Development of a global soil database of process-controlling factors

N.H. Batjes, E.M. Bridges and F.O. Nachtergaele

February 1994

ISRIC
INTERNATIONAL SOIL REFERENCE AND INFORMATION CENTRE

Related Reports and Publications:

World Inventory of Soil Emissions: Report of Working Group Discussions and Recommendations. Proceedings of an international workshop organized in the framework of the Netherlands National Research Programme on Global Air Pollution and Climate Change (24-27 August 1992). WISE Report No. 1, ISRIC, Wageningen, ii + 20 p.

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 (24-27 August 1992). WISE Report No. 2, ISRIC, Wageningen, iv + 122 p. [ISBN 90-6672-049-2].

A Review of Soil Factors and Processes that Control Fluxes of Heat, Moisture and Greenhouse Gases. Technical Paper 23/WISE Report 3, ISRIC, Wageningen, viii + 201 p. [ISBN 90-6672-048-4].

World Inventory of Soil Emission Potentials: Guidelines for soil profile selection and protocol for completing the WISE data entry sheets. Working Paper and Preprint 93/02, International Soil Reference and Information Centre, Wageningen, ii + 32 p.

World Inventory of Soil Emission Potentials: Profile Database User's Manual (Version 1.0 for IBM-PC Compatible Microcomputers). Working Paper and Preprint 93/04, International Soil Reference and Information Centre, Wageningen, ii + 28 p.

....

Paper prepared for: International Symposium on Climate Change and Rice, International Rice Research Institute (IRRI), Los Banos (14-18 March 1994).

WORLD INVENTORY OF SOIL EMISSION POTENTIALS:
Development of a global soil database of process-controlling factors

Niels H. Batjes, E.M. Bridges and F.O. Nachtergaele

ABSTRACT

The subject of global climate change has emerged as an important field of scientific research during the past decades. Following the conference on Soils and the Greenhouse Effect, soil scientists at the International Soil Reference and Information Centre (ISRIC) have been assembling information with the aim of achieving a better understanding of the role of soils in producing, absorbing and emitting natural trace gases, especially methane, nitrous oxide and carbon dioxide. One aim of the project entitled World Inventory of Soil Emission Potentials (WISE) is to develop a soil database for studies of global environmental change. A prototype of the database is now in place at ISRIC for initial testing.

The WISE database is a combination of soil area-data and attribute-data. The area-data are based on a digitized and edited version of the 1:5 M FAO-Unesco Soil Map of the World, which gives the FAO soil unit distribution in each 1/2 by 1/2 degree area of the globe. The attribute-data, which consist of selected site, morphological, physical and chemical properties described for soil profiles, will be used to make a characterisation of each soil unit shown on the grid-map. Representative profiles are obtained from quality controlled digital databases, and complemented with suitable data obtained from manuscript sources.

The WISE database will be used to make an inventory of the world's wetland soils which in turn will give the geographical basis for an improved estimate - in the first place - of methane production potentials. As ISRIC does not possess a field staff, collaboration with scientists at IRRI in the Philippines and Nagoya University in Japan has been initiated to assemble basic data on the measurement of soil methane production potentials and emissions. This information will be used, and simple modelling techniques developed, to provide a refined estimate, which accounts for the effects of soil conditions.

The WISE project is seen as one facet of the broad adoption of data-handling technology applied to soil science in relation to climate change. Many scientists, including those of the IGAC and GCTE foci of the International Geosphere-Biosphere Program (IGBP), have expressed the need for user-friendly and uniform information on soil conditions for their modelling work. It is anticipated that the WISE database will be able to provide the essential background soil data for these calculations upon its release at the end of 1994.

INTRODUCTION

Climatologists, oceanographers and atmospheric scientists have long appreciated the many links between their fields of study (Bolin *et al.*, 1986; Trabalka and Reichle, 1986). The consequent increase in atmospheric concentration of trace-gases, such as CO_2, CH_4, N_2O and the CFC's since the industrial revolution is predicted to change climate and to induce sea level rise (Houghton *et al.*, 1992). This may have critical effects on natural and managed biotic systems, upon which the world food, fuel, fiber and timber supplies depend,

N.H. Batjes and E.M. Bridges, International Soil Reference and Information Centre (ISRIC), P.O. Box 353, 6700 AJ Wageningen, the Netherlands, and F.O.N. Nachtergaele, Land and Water Development Division (AGLS), Food and Agriculture Organization, Viale delle Terme di Caracalla, 00100 Rome, Italy.

and profound environmental and socio-economic repercussions (Parry, 1990; Brouwer *et al.*, 1991; Tinker and Ineson, 1990).

The importance of soils and their biota in the greenhouse effect is becoming better understood (Matson and Ojima, 1990; Bouwman, 1990). Nonetheless, there are still significant areas of uncertainty in current scientific knowledge. This applies, for instance, to the chemical, physical and biological processes which control their production, absorption and emission in different terrestrial ecosystems. Practical difficulties are associated both with the measurement of trace gas fluxes in the field (Mosier, 1990) and subsequent extrapolation or scaling-up of these values to regional and global scales through modelling (Bliss, 1990; Burrough, 1989; Matson and Ojima, 1990; Roswall *et al.*, 1988) .

Geo-referenced databases linked to GIS can provide a geographic framework for scaling-up results of flux measurements and fundamental process studies to ecosystems at the global level (Bliss, 1990; Oldeman and Sombroek, 1990). It is in this context that ISRIC implemented the WISE project, forming a logical sequel to the conference on Soils and the Greenhouse Effect (Bouwman, 1990). The aim of the WISE project, sponsored by the Dutch National Research Programme on Global Air Pollution and Climate Change, is to arrive at a geographic quantification, at the global level, of the soil factors and processes which regulate fluxes of CO_2, CH_4 and N_2O between soils and the atmosphere. There are two main objectives in this project:

a) to compile a global 1:5 M, ½° by ½° degree soil database; and
b) to make a contribution to the understanding and quantification of gaseous emission potentials of soils, with special reference to methane.

METHANE AND CLIMATE CHANGE

Globally, methane is the second most important 'greenhouse gas' (Houghton *et al.*, 1992). The importance of methane in controlling global warming is because it has a strong ability to absorb infrared radiation and a relatively short atmospheric lifetime of ≈ 10 years. Methane plays further an important role in photochemical reactions in the troposphere and stratosphere, and changes in its concentration distinctly affect the chemistry of the atmosphere (Thompson and Cicerone, 1986; Khalil and Rasmussen, 1987).

The major sources and sinks of atmospheric methane are well known (Houghton et *al.*, 1992). Natural wetlands and irrigated rice lands account for about one third of the total estimated source strength of 515 Tg (10^{15}g) CH_4 yr^{-1} (Houghton *et al.*, 1992). The ranges listed in a review of 19 calculated global emissions of methane from rice cultivation vary widely, from 59 to 200 Tg CH_4 yr^{-1} (Minami, 1993). This reflects the problems encountered in the extrapolation of local emission rates to a global scale, and the figures remain fraught with uncertainty. The current best estimate is 60 Tg CH_4 yr^{-1}, with a range of 20 to 150 Tg CH_4 yr^{-1} (Houghton *et al.*, 1992). The reported differences in global emissions are the consequence of: a) the large hourly, daily and seasonal variation in measured CH_4 fluxes; b) uncertainty about the relative importance of the process-controlling factors, such as water management, organic matter applications, fertilizer treatment and soil type; and c) the extrapolation of a limited number of flux measurement data, often obtained for short-term periods only, to areas and time-spans for which they need not necessarily be representative.

According to data of IRRI, annual rice production must increase by about 65% by the year 2020 to meet the demand of the growing world population (see Braatz and Hogan, 1990). Consequently, the level of methane emission from irrigated rice lands is likely to increase unless mitigation options to reduce methane emissions are introduced.

A comprehensive discussion of the methane literature is beyond the scope of this paper as many reviews have been published recently (Cicerone and Oremland, 1988; Bouwman 1990; Neue and Roger, 1992; Batjes, 1992a). The balance between the microbial processes of methanogenesis and methane consumption controls to a great extent whether a certain terrestrial ecosystem will function as a sink or source of atmospheric methane. Methanogenesis occurs in all anaerobic environments in which organic matter undergoes decomposition, for instance natural wetlands, rice paddies, as well as the digestive tracts of ruminants and termites. In general, processes of methane oxidation in soils, and their controls, remain less well understood than those of methanogenesis (e.g. Oremland, 1988; Oremland and Culbertson, 1992).

The main transfer processes of methane to the atmosphere are ebullition, diffusion, and transport through the aerenchyma of vascular plants. Many uncertainties remain in assessing the relative importance of soil factors, plant or rice cultivars, and other environmental and agricultural controls, on methane production, consumption and emission (see reviews of Bouwman, 1990; Batjes, 1992a). Laboratory and field experiments are needed to refine the current understanding of the perceived controls, and to provide a better basis for their quantification through modelling work.

Various studies have shown that soil type influences CH_4-emission levels from rice fields (Neue *et al.*, 1990; Inubushi *et al.*, 1990a; Yagi and Minami, 1990; Kimura 1992; Denier van der Gon *et al.*, 1992; Neue and Roger, 1992). However, the effects of soil type may be overruled by other factors, including water regime, soil temperature, fertilizers, type of organic matter applications, and rice cultivars through their differing capacity to transport CH_4 via vascular transport and differing root exudation rates.

The minimum set of soil properties required for reliable modelling of methane production in soils is still open to debate. Nevertheless, a basic data set will include certainly: hydrologic regime; measures of the E_h/pH-buffer capacity; organic carbon content; C/N ratio; per cent clay; mineralogy; free-Fe content; sulphate content and salinity (Neue *et al.*, 1990; Denier van der Gon, 1992; Kimura, 1992; Batjes, 1992a). Whereas a large number of these soil factors - in principle - can be taken directly from profile descriptions, others, such as E_h/pH-buffer relationships, will have to be derived from pedo-transfer functions. These considerations point to the usefulness of developing a global soil database that can show: a) where potential areas of methane-producing soils occur, and b) provide the basic quantitative data necessary for deriving transfer functions.

THE WISE SOIL DATABASE

Rationale

The basic data layers for a Global Environmental GIS to calculate net methane production and emissions include climate, seasonality of water regime/inundation, vegetation or land use, agricultural practices, and soil type (Bouwman, 1990; Sombroek, 1990; Matthews, 1993). During a workshop held at ISRIC (Batjes and Bridges, 1992), it was concluded that the Soil Map of the World (FAO-Unesco, 1971-1981), published at a scale of 1:5 M, is the only viable geographic base map on soil resources. Although known to be partly out of date, it will remain the sole uniform map available for compiling the area-data on world soils pending completion of the 1:1 M World Soils and Terrain Database (Oldeman and Van Engelen, 1993). Unlike Zobler (1986), who used the original printed Soil Map of the World to compile a 1° x 1° latitute-longitude database for global modelling purposes, the WISE project makes use of an edited, digital-version of the Soil Map of the World, on which errors have been corrected, some boundary changes included and use is made of the complete information on the composition of the soil mapping units (FAO, 1991 and 1994). As indicated in Figure 1, the area-data of the WISE database can be updated gradually as sections of the Soil Map of the World are being updated by FAO in the context of its SOTER activities.

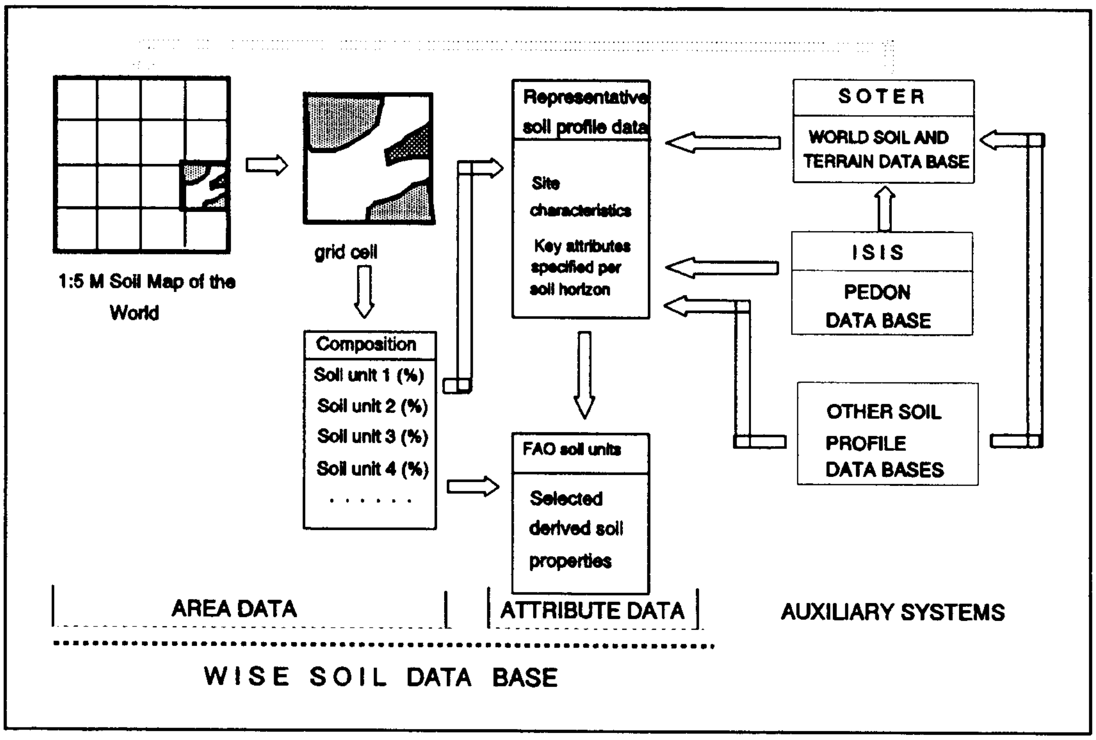

Fig. 1. Schematic representation of the WISE database, with its area-data and attribute-data (Batjes, 1992b).

The ultimate WISE database will consist of:

(1) A GIS-file with information on the component FAO soil units of each ½ x ½ degree grid cell, corresponding with the area-data.
(2) A suite of soil profile data for the respective FAO soil units, with associated a subfile listing the analytical methods and source of the primary data.
(3) A file of derived characteristics for the topsoil and subsoil of the respective FAO soil units, which is to provide a uniform basis for subsequent modelling activities.

Area-data

In the context of the WISE project, the predictive use of the digitized Soil Map of the World becomes of significant importance. The areas of soil units depicted on this digital map are being used as a cartographic basis for the computerized preparation of a ½° x ½° lat.-lon. digital base map. This grid-cell size is commonly used in global change research, and has been requested by the sponsors of the WISE project.

First, the type and relative area of the component soil units occurring at the centre-point of each 5' x 5' grid-cell of the digitized Soil Map of the World have been identified and characterized by computer, using composition rules developed by FAO (1991). Next, the information for the 36 component 5' x 5' cells of a particular ½° x ½° grid-cell have been computed, providing the definitive area data (Nachtergaele, 1992). The software for this part of the work has been prepared by staff of the Land and Water Development Division (AGLS) of FAO, with whom WISE staff is closely cooperating.

Prototypes of the ½° x ½° area-data files for Africa and the Near East are currently being tested for possible inconsistencies, after which FAO will generate similar files for the remaining sections of the world. The information held in individual files of area-data (e.g. Africa, Asia, Near East) will be off-loaded to one central dBASE-file at ISRIC, providing the basis for a global file of area-data. To each area on the grid-map will be attached, through the FAO-Unesco legend descriptors, a suite of profile data from representative soil profiles. This forms the soil point data (Figure 1). The linkage of ½° x ½° area-data with actual profile data in WISE, is a significant improvement on the information held by Zobler's (1986) world soil file.

Soil profile data

The attributes that would be needed to develop the 1:5 M WISE soil database were identified in a survey of the literature (Batjes, 1992a) and discussed during an international workshop (Batjes and Bridges, 1992). This work provided the basis for developing Guidelines for the selection of representative soil profiles, and a protocol for coding the various site and profile data (Batjes, 1993a). They are based on elements of the methodologies of ISIS (Van Waveren and Bos, 1988) and SOTER (Van Engelen and Tiang, 1993), with simplifications necessary to accommodate the broader scope of the WISE database. The Guidelines allow a systematic collection of profile data as well as a systematic documentation of: a) the methods by which the analytical results were obtained in various laboratories worldwide, and b) the sources from which the individual profiles are derived (Fig. 2).

A database management system, capable of storing and retrieving the profile attributes specified in the Guidelines, was developed next (Batjes, 1993b). Version 2.0 of this data handling system runs under dBASE IV. Thereby, all soil databases developed by ISRIC (ISIS, SOTER and WISE) use the same commercial software package, enhancing data-compatibility, both within the Institute and internationally (e.g. SDB of FAO).

The attributes that can be accommodated in the profile component of the WISE database can be divided into site and horizon data (Fig. 2; Annex). In general, there seems to be a good agreement that such a list of attributes will go a long way to meet the needs of terrestrial and atmospheric modellers, including those of IGBP-DIS working group (Ingram, 1993). However, it will not always be possible to obtain complete data sets for each profile as all attributes are not necessarily collected on a routine basis (Msanya, 1987). Therefore, a pragmatic approach to data collection has had to be adopted.

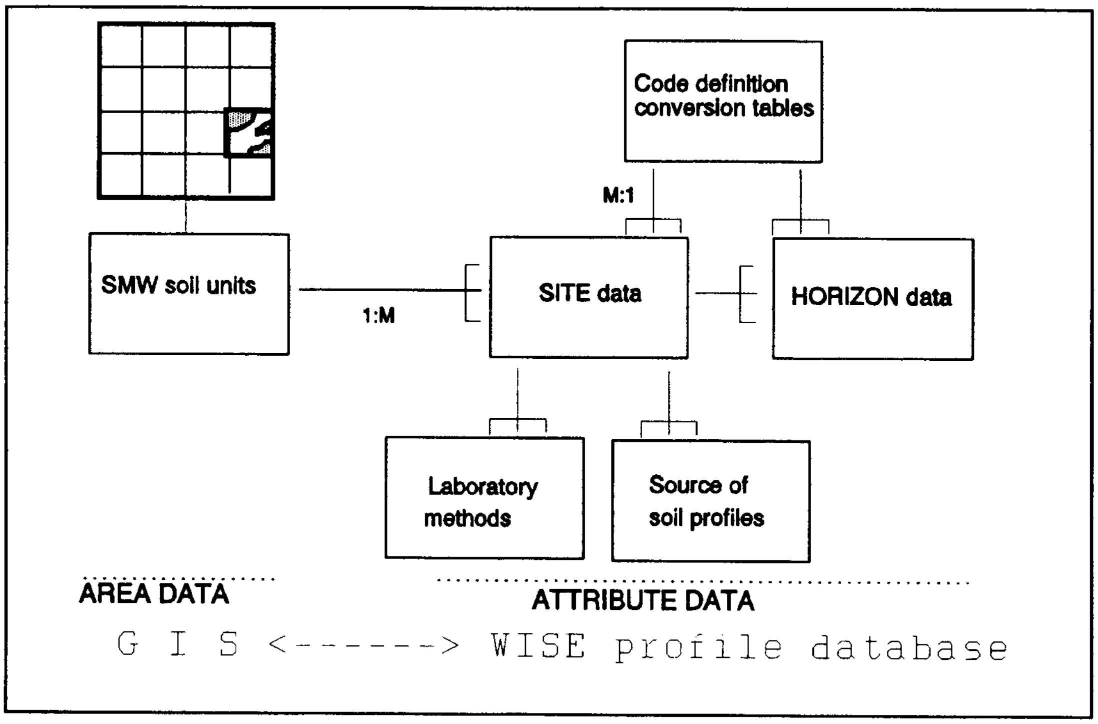

Fig. 2. Schematic representation of the SITE and HORIZON data files, and related key-attribute files (Batjes, 1993b). (M:1 stands for many to one relations, and 1:M for one to many relations)

Collection of profile data

Collection and processing of soil profiles is proceeding according to the Guidelines developed for the WISE database. Responses to an international data collection activity, requesting descriptions of regionally representative profiles for the various countries of the world on tape or in manuscript form, have been limited. Staff at ISRIC have developed software to mechanically transfer data held by the major database holders from one system to another (Tempel, 1993). In this exercise, problems of data compatibility and comparability between disparate databases have had to be overcome, for instance where different criteria are used to describe similar features (e.g. physiography; organic carbon content). Vogel (1993) reviewed the possibility of correlating attributes, such as organic matter content or pH, obtained according to different analytical procedures, which can vary widely internationally (Driessen, 1986; Pleijsier, 1989). A module for transferring ISIS-data to WISE is being tested, and a similar procedure for the transfer of data from the USDA-Lincoln database to the WISE profile database is nearing completion. After final checks, these modules will be used to transfer about 390 ISIS-profiles and 1,300 SCS profiles to the WISE profile database.

In situations where digital files where unavailable for inclusion in the WISE database, for instance where unresolved copyright issues prevented their release, profile data had to be entered manually into the WISE database. In such situations, greater reliance than had been expected fell upon the collection of data held in the ISRIC library. To date, data from some 1,650 profiles have been manually transcribed to WISE Data

Entry forms, and entered in the computer. In this activity, much attention is being paid to the necessity for global distribution of soil profiles in the WISE database.

All profiles in the WISE database are given an indication of their inferred quality, ranging from good to poor. Data quality is further ensured by a computerized screening of the data-files for possible inconsistencies in selected numerical data (e.g. texture, pH, C/N), and all coded-data. This computerized data-checking procedure supplements the compulsory visual checks of manually-entered data sets.

As the number of similar, regionally representative soil profiles (e.g. stratified by climate and parent material) increases, it will become possible to improve the knowledge about soil attributes for each FAO-Unesco soil unit by providing statistically reliable information on data shown within the ½° x ½° grid cells. Inherently, the collection of representative profiles for the WISE database is seen as an open-ended activity that should be continued beyond the official termination of the WISE project at the end of 1994.

Pedo-transfer functions

Certain physical soil attributes are seldom collected on a routine basis, particularly water retention versus tension relationships and the unsaturated hydraulic conductivity. The solution then is to estimate these relationships from available soil data held in the profile database, such as particle-size distribution, organic-C content and bulk density, through pedo-transfer functions (Tietje and Tapkenhinrichs, 1993). Examples of information that can be derived from soil parameters held in the WISE database are listed in Table 1.

Table 1. Examples of information that can be derived from soil parameters held in the WISE database (After Ingram, 1993).

Soil parameters	Derived data
Soil surface colour	albedo
Organic C, Total N, and bulk density per horizon	C and N pools (e.g as kg/m^2 to 1 m depth)
θ(h), bulk density and rooting depth	water holding capacity
Heat capacity of soil constituents	heat conductance
CEC, OM content, clay content and θ(h)	mineralogy
CEC and exchangeable bases	soil nutrient status
pH	soil acidity
Particle size distribution, bulk density and θ(h)	K_{sat}, K(θ)

Abbreviations: θ is volumetric water content; h is soil water pressure head; ρ is bulk density; K is hydraulic conductivity.

APPLICATIONS

General

Several applications, each of which corresponds to a well-defined scenario, can be compiled from the same base map and set of soil attributes (Table 2). As each attribute will have a different effect on a particular process it will need to be weighted in a different manner depending on the processes, be it studies of crop production, soil gaseous emission potentials or soil pollution.

Table 2. Selected examples of soil attributes needed for different types of environmental studies*

Topics	Soil Processes	Relevant Soil Factors
- Crop production	water release, weathering, cation exchange, ...	Fertility status, salinity, soil moisture characteristics, rootable depth, ...
- Pollution by heavy metals	adsorption, solubility	Organic matter content, pH, $CaCO_3$ content, water balance, salinity, ...
- Acidification	weathering, base exchange	$CaCO_3$, exchangeable bases, cation exchange capacity, mineralogy, ...
- CH_4 production	methanogenesis	Organic matter content/quality, pH, sulphate content, texture, N-content, nutrient status, drainage class (redox-potential), soil porosity, ...
- N_2O emissions	via denitrification:	- Org. matter, texture, pH, soil moisture characteristics, soil drainage (anaerobiosis), nutrient status, soil porosity, ...
	via nitrification:	- Org. matter, N-content, texture, pH, soil moisture characteristics, soil drainage, nutrient status, soil porosity, ...

* Also needed from auxiliary sources are e.g.: climate, land use/vegetation, management practices (e.g. fertilizer application; organic matter amendments; irrigation/drainage practices; loading with pollutants)

Methane

Now that the dBASE area and profile data files can be linked for a test-area (Africa), the framework is in place for handling the spatial and soil attribute data required to make a (refined) assessment of potential methane production from wetland soils. First, the WISE database will be used to make an inventory of the world's wetland soils, and to present refined estimates of methane production potentials of wetland soils using an expert-system (Fig. 3). This will require refinement of a qualitative scheme to describe the different aspects of methane production.

The WISE workshop agreed ISRIC and IRRI should make best use of past and current field measurements of methane production and emission from rice paddies, and natural wetlands, for model development and verification. In this context, it was recommended that a questionnaire should be sent to research groups involved in field measurements of methane emissions. One aim of the questionnaire was to obtain data for deriving expert-systems on methane production/emission, so as to permit a geographic extrapolation using a Geographical Information System linked to WISE and auxiliary databases. Responses to the questionnaire, unfortunately, gave less information useful for developing a modelling approach than had been anticipated by the WISE workshop.

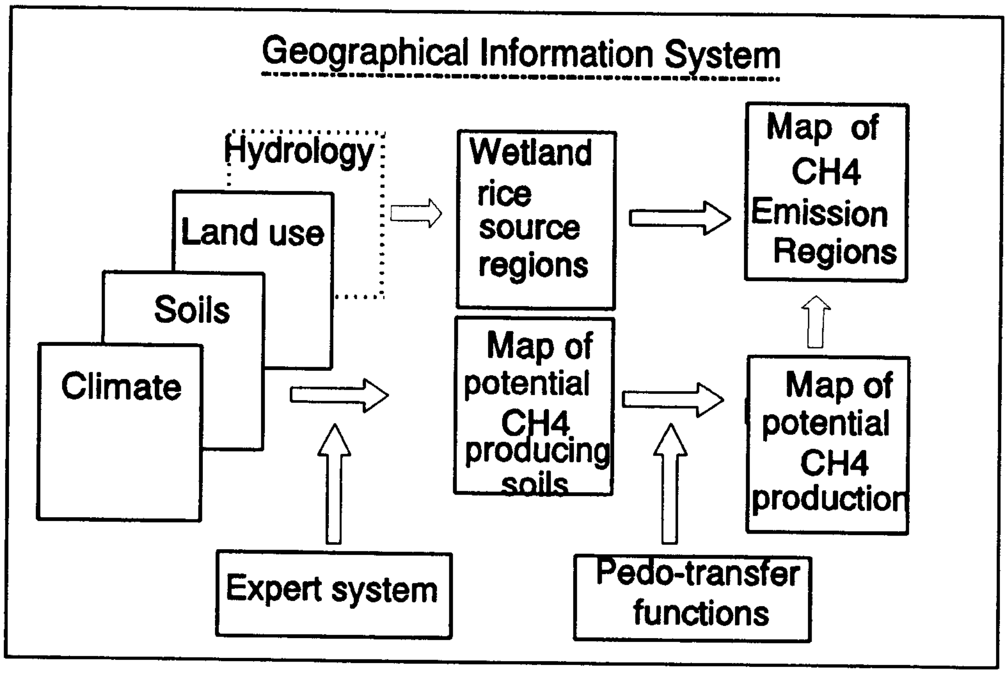

Fig. 3. Schematic representation of projected use of WISE and auxiliary databases in identifying potential methane producing soils and, ultimately, making refined calculations of methane emissions from wetland rice soils.

A collaborative activity with colleagues from the Soil Science and Geology Department of the Wageningen Agricultural University has been initiated in the framework of another NOP-sponsored project on the Influence of Soil Parameters on the Production and Emission of Methane in/by Wetland Rice Soils. In this effort, which is scheduled to start in March 1994, it is proposed to implement a series of incubation experiments with paddy soils to assess potential methane production. These are to provide the basic data necessary for developing pedo-transfer functions that relate soil characteristics (held in the WISE database) with potential methane production rates of the main methane producing FAO-Unesco soil units (e.g. Fluvisols, Gleysols and gleyic subunits, and Histosols) in a quantified way.

Contacts with specialist rice/methane research institutes, established in the framework of a joint ISRIC-IRRI Methane Questionnaire activity, will prove useful to identify research-groups that could contribute the topsoil samples necessary for the incubation experiments. IRRI further cooperates in the inter-regional Research Programme on Methane Emissions from Rice Fields in China, Indonesia, Thailand and the Philippines, a UNDP-funded project which started in 1993. Future activities should relate to the use of WISE and other auxiliary databases (e.g. land use, climate) to propose refined global estimates of methane emissions for wetland rice soils.

Global digital databases

Databases are needed at scales that reflect their effect on regional and global processes which are relevant to modelling goals (Wessman, 1992). Reviews of common data sets for global emission inventories have been prepared by Bouwman (1990), Sombroek (1990) and Matthews (1993). Uncertainty in the databases can arise from different sources, including errors in the original materials used in database compilation or in translation of the classification systems used to record data. These uncertainties are difficult to evaluate, and will vary amongst the data sets.

Matthews (1993) discusses the design and development of global digital databases and their integration in studies of terrestrial sources and sinks on 'greenhouse gases', proposing a sequential approach. First, primary databases on major surface characteristics are prepared. These databases are subsequently integrated to produce secondary sets of source categories (e.g., soils, vegetation, hydrology). Finally, these secondary databases are combined with measured flux data to produce tertiary data sets on emissions.

The factors having the greatest effect on methane emissions probably are: 1) water level and its seasonality during the growing season; 2) soil temperature; 3) fertilizer applications; 4) soil type; 5) cultivar (or vegetation type); 6) agricultural practices, including direct seeding or transplanting (Khalil, 1993; Matthews, 1993). At present there are insufficient data to incorporate all the above factors in a global budget-study. For instance, there still is no global information on the application of organic matter to rice paddies, while the importance of organic matter quality and quantity on methane emissions is well known (Minami, 1993). Similarly, the nature of regional pre-planting activities (e.g. puddling, direct-seeding/transplanting), and drainage and water percolation, which through their effect on soil redox potentials and crop growth (and gas transport properties) have a significant effect on methane emissions, will remain difficult to quantify in a global model. Nonetheless, global estimates of CH_4 emissions can be improved substantially by incorporating the current knowledge on water levels and temperature (Khalil, 1993; Minami, 1993). Bachelet and Neue (1993) proposed an expert-classification of rice soils to group rice growing regions according to their methane production potentials, for which additional experimental, scientific-backing is now being sought. An important contribution of the WISE project to this work will be in providing quantitative data on the geographic and attribute data of the world soils, using currently available knowledge.

Modelling approaches

Most global modelling approaches for methane from natural wetlands (Matthews and Fung, 1987; Aselmann and Crützen, 1990) and irrigated rice (Matthews *et al.*, 1991; Bachelet and Neue, 1993) are empirical and based on (fairly) simple assumptions. Most of these studies of necessity rely on limited available information on the type, location and extent of wetlands/rice-lands, and measurements of the CH_4 flux from a number of so-called representative sites. An inventory approach that includes the spatial distribution and characteristics of the wetlands is preferred in these studies (Roulet and Matthews, 1993). Bachelet and Neue (1993), for instance, showed the importance of considering soil characteristics in global studies of methane emissions from irrigated rice lands. An alternative approach to constraining the global methane budget is through inverse modelling (Fung *et al.*, 1991).

There seems to be a fairly wide agreement that the present understanding of the perceived controlling factors and processes is not yet adequate for implementing process based models of methane emission from rice cultivation (Van Breemen and Feijtel, 1990; Matson and Ojima, 1990; JEA-EPA, 1990). Studies of mechanisms that regulate CH_4 fluxes in a rice plant and in rice ecosystems call for fundamental research that is beyond the activities of ISRIC. Work related to model development therefore must take place in close cooperation with scientists from field-research institutes. Since a model based on processes is (still) not realistic on a global scale, the task of WISE can be seen in identifying sensitivity factors of soils that play a crucial role in determining the magnitude of CH_4 emission. Links have been established with researchers at IRRI, Nagoya University and Wageningen Agricultural University, for these aspects of the work.

Research priorities for developing process-based models of methane emission, as identified by JEA-EPA (1990), include studies on:

a) The biogeochemistry of methane production, both in wetland rice fields and natural wetlands, including methanogenesis, methanotrophs, and regulating factors;

b) The effects of climate, soil, water management, cultivars, fertilizer applications and cultural practices on CH_4 fluxes;

c) Temporal variation in CH_4 fluxes between sites;

d) Field-level measurements to assess spatial variability, and simulation models to synthesize the process-level and field-level data.

e) Effects of mitigation techniques for CH_4 emissions, and their effects on emissions of N_2O, another important 'greenhouse gas'.

Braatz and Hogan (1991) formulated an approach for developing process-related models for methane emission by rice paddies. They propose to develop three major, interactive modules describing: a) the soil redox processes; b) the development of the rice plant; and c) and the dynamics of the physical and microbial processes. Only a limited number of the soil data requirements listed by Braatz and Hogan (1991) are collected on a routine basis during routine soil surveys (see Msanya, 1987; WISE data collection activity), precluding their inclusion in a global soil database. A coordinated effort is needed to collect the basic data sets at regionally representative sites, and according to uniform procedures, in order to develop, test and validate process-based CH_4 models. These deterministic models, by definition, will produce results pertaining to single events. The environmental and land use factors, however, will always be subject to spatial and temporal variability so that there will be a degree of stochastic uncertainty in the results of deterministic process-models. Future developments should consider the possibility of combining a stochastic and deterministic approach in one single CH_4-model; this should be seen as a long-term objective.

DISCUSSION AND CONCLUSIONS

Although attempts have been made in the past to use the printed FAO-Unesco Soil Map of the World as a basis for determining the nature of the soil cover for modelling purposes (Zobler, 1986), the resolution used was coarse and the potential of the map as a source of information was only partially exploited. Algorithms developed by FAO staff as part of the WISE project have greatly expanded the amount of information on the world soil pattern which can be utilised for modelling purposes. Nonetheless, the spatial and temporal variability and quality of soil profile data internationally remain controversial issues (Mausbach and Wilding, 1991; Driessen, 1986; Pleijsier, 1989). A full-scale update of information on world soil resources using SOTER is a separate and much longer-term project. As sections of the Soil Map of the World are being updated in the framework of the SOTER project, new spatial information can readily be incorporated in the WISE database. Similarly, newly obtained profiles, considered representative for these areas, can be incorporated into the profile component of the WISE database, enhancing its usefulness.

The gathering in a uniform manner of soil profile data in WISE represents a major task in soil science which should help understand something of the variability of the soils represented by the soil units of the FAO-Unesco Soil Map of the World. At the time of writing, the WISE project is nearing completion and already requests for the database are being received. Some immediate applications are being investigated but many of the opportunities provided by the existence of such a database remain to be exploited in the future by the international modelling fraternity. A range of auxiliary databases, for instance on climate and land use, of a similar resolution are needed also for these GIS-based studies; several of these global databases still need to be developed or to be released in the public domain.

Likely applications of the WISE database in the context of trace gas studies include (Batjes and Bridges, 1994):

a) simple extrapolation of process studies for similar soils to estimate regional or zonal fluxes of a trace gas;
b) process model studies for regional and global flux estimates;
c) interpretation of inverse-modelling estimates of terrestrial source and sink terms.

Currently, it still proves difficult to establish to what degree the respective process-controlling factors will quantitatively affect the production and emission of CH_4 in a certain terrestrial ecosystem at a particular moment in time. This is why proposals for developing process-related CH_4-models have only recently been formulated, initially with respect to rice paddy-fields. The preliminary data requirements of these models in terms of soil conditions, as formulated by Braatz and Hogan (1991), already exceed the level of information held in most existing high resolution soil survey reports, so that new data collection activities should be initiated at the level of the experimental site.

Refined estimates of global CH_4 emission from wetlands can already be obtained by extrapolating seasonally averaged, field measured CH_4 emission rates considered representative for well described natural wetlands or irrigated rice ecosystems to the corresponding global ecosystem. Such a refined extrapolation will not only require additional CH_4-flux data but also knowledge of the geographic and seasonal distribution of the various types of natural and man-made wetlands (Matthews *et al.*, 1991) as well as more detailed and up to date information about the distribution and main characteristics of potential methane producing soils. The WISE database will be useful in the context of these activities. It can be used also in other studies on global change, such as revised estimates of N_2O-emissions from soils (see Bouwman *et al.*, 1993), climate-vegetation succession models, and to assess the vulnerability of soils to chemical pollution.

Acknowledgements:

Niels Batjes acknowledges sponsorship by the Netherlands National Research Programme on Global Air Pollution and Climate Change (NOP-project No. 851039) to attend the International Symposium on Climate Change and Rice at IRRI.

REFERENCES

Asselmann, I., and P.J. Crützen, 1990. A global inventory of wetland distribution and seasonality, net primary productivity, and estimated methane emissions, in *Soils and the Greenhouse Effect*, edited by A.F. Bouwman, pp. 441-449, John Wiley & Sons, Chichester.

Bachelet, D., and H.U. Neue, 1993. Methane emissions from wetland rice areas of Asia, *Chemosphere* 26, 219-237.

Batjes, N.H., 1992a. Methane, in *A review of soil factors and processes that control fluxes of heat, moisture and greenhouse gases*, prepared by N.H. Batjes and E.M. Bridges, pp. 37-66, Technical Paper 23, ISRIC, Wageningen.

Batjes, N.H., 1992b. The WISE database: General considerations on a possible structure and attribute data, in *A review of soil factors and processes that control fluxes of heat, moisture and greenhouse gases*, prepared by N.H. Batjes and E.M. Bridges, pp. 149-158, Technical Paper 23, ISRIC, Wageningen.

Batjes, N.H., 1993a. World Inventory of Soil Emission Potentials: Guidelines for soil profile selection and protocol for completing the WISE data entry sheets, 32 pp., Working Paper and Preprint 93/02, ISRIC, Wageningen.

Batjes, N.H., 1993b. World Inventory of Soil Emission Potentials: Profile database user's manual (version 1.0 in dBASE III$^+$ for IBM-PC compatible microcomputers), 28 pp., Working Paper and Preprint 93/04, ISRIC, Wageningen.

Batjes, N.H., and E.M. Bridges (Eds), 1992. World inventory of soil emission potentials, *Proceedings of an International Workshop Organized in the Framework of the Dutch National Research Programme on Global Air Pollution and Climate Change (Wageningen, 24-27 August 1992)*, 122 pp., WISE Report 2, ISRIC, Wageningen.

Batjes, N.H., and E.M. Bridges, 1994. *Potential Emissions of Radiatively Active Gases from Soil to Atmosphere with Special Reference to Methane: Development of a Global Database (WISE)*. Accepted in *Journal of Geophysical Research - Atmospheres*.

Bliss, N.B., 1990. A hierarchy of soil databases for calibrating models of global climate change, in *Soils and the Greenhouse Effect*, edited by A.F. Bouwman, pp. 523-529, John Wiley and Sons, Chichester.

Bolin, B., B.R. Böös, J. Jäger, and R.A. Warrick (Eds), 1986. *The Greenhouse Effect, Climatic Change and Ecosystems*, SCOPE 29, John Wiley and Sons, Chichester.

Bouwman, A.F. (ed.), 1990. *Soils and the Greenhouse Effect*, 575 pp., John Wiley and Sons, Chichester.

Bouwman, A.F., I. Fung, E. Matthews and J. John, 1993. Global analysis of the potential for N_2O production in natural soils. *Global Biogeochemical Cycles* 7(3), 557-597

Braatz, B.V., and K.B. Hogan, 1990. *Sustainable rice productivity and methane reduction research plan*, US Environmental Protection Agency, Office of Air and Radiation, Washington DC.

Brouwer, F.M., A.J. Thomas and M.J. Chadwick (eds), 1991. *Land use changes in Europe: Processes of change, environmental transformations and future trends*. Volume 18, The GeoJournal Library, Kluwer Academic Publishers, Dordrecht.

Burrough, P.A., 1989. Modelling land qualities in space and time: The role of geographical information systems, in *Land Qualities in Space and Time*, edited by J. Bouma and A.K. Bregt, pp. 45-59, Pudoc, Wageningen.

Cicerone, R.J., and R.S. Oremland, 1988. Biogeochemical aspects of atmospheric methane. *Global Biogeochemical Cycles* 2, 299-327.

Denier van der Gon, H.A.C., H.U. Neue, R.S. Lantin, R. Wassmann, M.C.R. Alberto, J.B. Aduna, and M.J.P. Tan, 1992. Controlling factors of methane emission from rice fields, in *Proceedings of an International Workshop organized in the framework of the Dutch National Research Programme on Global Air Pollution and Climate Change (Wageningen, 24-27 August 1992)*, edited by N.H. Batjes and E.M. Bridges, pp. 81-92, WISE Report No. 2, ISRIC, Wageningen.

Driessen, P.M., 1986. Soil data, a matter of concern, in *Annual Report*, pp. 43-47, International Soil Museum (now ISRIC), Wageningen.

FAO, 1991. *The Digitized Soil Map of the World. Notes - Volume 1: Africa* (release 1.0), World Soil Resources Report No. 67/1, Food and Agricultural Organization, Rome.

FAO, 1994. *Digitized Soil Map of the World, 5' x 5' raster version, with estimates of soil properties and soil qualities.* World Soil Resources Report (in preparation).

FAO-Unesco, 1971-1981. *Soil Map of the World, 1:5 M.* Volumes 1 to 10, United Nations Educational, Scientific and Cultural Organization, Paris.

Fung, I, J. John, J. Lerner, E. Matthews, M. Prather, L.P. Steele and P.J. Fraser, 1991. Three-dimensional model synthesis of the global methane cycle. *Journal of Geophysical Research* 96, 13,033-13,065.

Houghton, J.T., B.A. Callander, and S.K. Varney (Eds), 1992. *Climate Change, 1992: The Supplementary Report to the IPCC Scientific Assessment*, 200 pp., Supplementary Report, Cambridge University Press, Cambridge.

Ingram, J.S.I. (ed.), 1993. Report of the IGBP-DIS/GCTE Global Soils Database Workshop, 8-9 October 1992, Silsoe.

Inubushi, K., M. Umebayashi, and H. Wada, 1990. Methane emission from paddy fields, in *Transactions of 14th International Congress of Soil Science (Kyoto)*, Vol. 2, pp. 249-254.

JEA-EPA, 1990. *Methane emissions and opportunities for control.* Workshop results of Intergovernmental Panel on Climate Change, 64 pp. plus appendices, coordinated by Japan Environmental Agency and United States Environmental Protection Agency.

Khalil, M.A.K., 1993. Methane emissions from rice fields. In *Proceedings of International IPCC workshop on Methane and Nitrous Oxide: Methods in national emission inventories and options for control* (Amersfoort, 3-5 February 1993), edited by A.R. Van Amstel, pp. 239-244, National Institute of Public Health and Environmental Protection (RIVM), Bilthoven.

Khalil, M.A.K., and R.A. Rasmussen, 1987. Atmospheric methane: Trends over the last 10,000 years. *Atmospheric Environment 21*, 2445-2452, 1987.

Kimura, M., 1992. Methane emissions from paddy soils in Japan and Thailand, in *Proceedings of an international workshop organized in the framework of the Dutch National Research Programme on Global Air Pollution and Climate Change (Wageningen, 24-27 August 1992)*, edited by N.H. Batjes and E.M. Bridges, pp. 43-79, WISE Report No. 2, ISRIC, Wageningen.

Matson, P.A., and D.S. Ojima (Eds), 1990. *Terrestrial biosphere exchange with global atmospheric chemistry*, 103 pp., Global Change Report No. 13, International Geosphere-Biosphere Programme, Stockholm.

Matthews, E., 1993.Global geographical databases for modelling trace gas fluxes. *Int. J. Geographical Information Systems* 7, 124-142.

Matthews,E., and I. Fung, 1991. Methane emissions from natural wetlands: Global distribution, area, and environmental characteristics, *Global Biogeochemical Cycles 1*, 61-86.

Matthews, E., I. Fung, and J. Lerner, 1991. Methane emissions form rice cultivation: Geographic and seasonal distribution of cultivated areas and emission, *Global Biogeochemical Cycles 9*, 251-256.

Mausbach, M.J., and L.P. Wilding (Eds), 1991. *Spatial Variability of Soils and Landforms*, SSSA Special Publication No. 28, Soil Science Society of America, Inc., Madison, Wisconsin.

Minami, K., 1993. Methane from rice production. In *Proceedings of International IPCC workshop on Methane and Nitrous Oxide: Methods in national emission inventories and options for control* (Amersfoort, 3-5 February 1993), edited by A.R. Van Amstel, p. 143-162, National Institute of Public Health and Environmental Protection (RIVM), Bilthoven.

Mosier, A.R., 1990. Gas flux measurement techniques with special reference to techniques suitable for measurements over large ecologically uniform areas, in *Soils and the Greenhouse Effect*, edited by A.F. Bouwman, pp. 289-301, John Wiley and Sons, London.

Msanya, B.M., 1987. Soil resources inventories: Characterization, quality and evaluation of their adequacy for specific land use, PhD. Thesis, Faculty of Sciences, State University of Ghent.

Nachtergaele, F., 1992. Testing of 30' x 30' grid database for the Soil Map of the World. Internal Working Document, FAO-AGLS, Rome (unpublished).

Neue, H.U., and P.A. Roger, 1992. *Rice Agriculture: Factors Controlling Emissions*, in NATO Scientific Series (in press).

Neue, H.U., P. Becker-Heidmann, and H.W. Scharpenseel, 1990. Organic matter dynamics, soil properties, and cultural practices in rice lands and their relationships to methane production, in *Soils and the Greenhouse Effect*, edited by A.F. Bouwman, pp. 457-466, John Wiley and Sons, Chichester.

Oldeman, L.R., and V.W.P. van Engelen, 1993. A world soils and terrain digital database (SOTER) - An improved assessment of land resources. *Geoderma* 60, 309-325.

Oldeman, L.R., and W.G. Sombroek, 1990. Use of the SOTER database to model global change, in *Transactions 14th International Congress of Soil Science (Kyoto)*, Vol. 5, pp. 136-141.

Oremland, R.M., 1988. Biogeochemistry of methanogenic bacteria, in *Biology of Anaerobic Microorganisms*, edited by A.J.B. Zehnder, pp. 641-706, John Wiley and Sons, New York.

Oremland, R.S., and C.W. Culbertson, 1992. Importance of methane-oxidizing bacteria in the methane budget as revealed by the use of a specific inhibitor, *Nature 356*, 421-423.

Parry, M.L., 1990. *Climate change and world agriculture*. Earthscan Publications Limited (in association with International Institute for Applied Systems Analysis and United Nations Environment Programme), London.

Pleijsier, K., 1989. Variability in soil data, in *Land Qualities in Space and Time*, edited by J. Bouma and A.K. Bregt, pp. 89-99, Pudoc, Wageningen.

Rosswall, T., R.G. Woodmansee, and P.G. Risser (Eds), 1988. *Scales and Global Change: Spatial and Temporal Variability in Biospheric and Geospheric Processes*, SCOPE 35, John Wiley and Sons, Chichester, 1988.

Roulet, N.T. and E. Matthews, 1993. Methane emissions from natural wetlands. In *Proceedings of International IPCC workshop on Methane and Nitrous Oxide: Methods in national emission inventories and options for control* (Amersfoort, 3-5 February 1993), edited by A.R. Van Amstel, p. 163-170, National Institute of Public Health and Environmental Protection (RIVM), Bilthoven.

Sombroek, W.G., 1990. Geographic quantification of soils and changes in their properties, in *Soils and the Greenhouse Effect*, edited by A.F. Bouwman, pp. 225-244, John Wiley and Sons, Chichester.

Tempel, P., 1993. *Automated soil data transfer facility between disparate soil databases.* Working Paper and Preprint (First draft), ISRIC, Wageningen.

Thompson, A.M. and R.J. Cicerone, 1986. Possible perturbations to atmospheric CO, CH_4 and OH. *Journal of Geophysical Research*, 9(D), 10858-10864.

Tietje, O., and M. Tapkenhinrichs, 1993. Evaluation of pedo-transfer functions, *Soil Science of America Journal 57*, 1088-1095.

Tinker, P.B., and P. Ineson, 1990. Soil organic matter and biology in relation to climatic change, in *Soils on a Warmer Earth*, edited by H.W. Scharpenseel, H.W., M. Schomaker, and A. Ayoub, pp. 71-87, Developments in Soil Science 20, Elsevier, Amsterdam.

Trabalka, J.R., and D.E. Reichle (Eds), 1986. *The Changing Carbon Cycle: A Global Analysis*, 592 pp., Springer-Verlag, New York.

Van Breemen, N., and T.C.J. Feijtel, 1990. Soil processes and properties involved in the production of greenhouse gases, with special relevance to soil taxonomic systems, in *Soils and the Greenhouse Effect*, edited by A.F. Bouwman, pp. 195-223, John Wiley and Sons, Chichester.

Van Engelen, V.W.P. and Wen Ting Tiang, 1993. *Global and national soil and terrain digital databases (SOTER): procedures manual*, 103 pp. A joint publication of FAO, ISSS, UNEP and ISRIC, Wageningen.

Van Waveren, E.J. and A.B. Bos, 1988. *ISRIC Soil Information System: User Manual and Technical manual (Revised edition)*. Technical Paper 15, ISRIC, Wageningen.

Vogel, A.W., 1993. A comparison of analytical data determined by different methods. Working Paper and Preprint (For Discussion), ISRIC, Wageningen.

Wessman, C.A., 1992. Spatial scales and global change: Bridging the gap from plots to GCM grid cells. *Annu. Re. Ecol. Syst.* 23, 175-200.

Yagi, K., and K. Minami, 1990. Effects of organic matter application on CH_4 emissions from Japanese paddy fields, in *Soils and the Greenhouse Effect*, edited by A.F. Bouwman, pp. 467-473, John Wiley and Sons, New York.

Zobler, L., A world soil file for global climate, *NASA Technical Memorandum 87802*, 1986.

Appendix: List of attribute data for the SITE and HORIZON data files of the WISE profile database (Batjes, 1993a).

SITE data	HORIZON data
WISE_ID (unique identifier of profile)	WISE_ID + HORIZON_NO (unique reference number for horizon within a profile)
Soil classification and source	*General attributes*
FAO-Unesco classification (1974 Legend)	Horizon designation
Phase	Depth, top
Topsoil texture class	Depth, bottom
FAO-Unesco classification (1990 Revised Legend)	Matrix colour (dry and moist)
Phase	Mottling
USDA subgroup level classification	Presence of roots
Edition (year) of Soil Taxonomy	
Local classification	*Chemical attributes**
Source of data	Organic Carbon
Name of laboratory where analyses were made	Total N
Soil profile description status	Available P
Date of description	pH-H_2O
	pH-KCl
Location	pH-$CaCl_2$
Country	Electrical conductivity (EC)
Location of soil profile, descriptive	Free $CaCO_3$
Latitude (deg/min/sec)	$CaSO_4$
Longitude (deg/min/sec)	Exchangeable Ca^{2+}
Altitude	Exch. Mg^{2+}
	Exch. Na^+
General site data	Exch. K^+
Major landform	Exch. Al^{3+} + H^+ (exchangeable acidity)
Landscape position	Exch. Al^{3+} (exchangeable aluminum)
Aspect	Cation Exchange capacity (CEC)
Slope	Effective CEC (at field pH)
Drainage class	Base saturation (as % of CEC)
Groundwater depth	
Effective soil depth	*Physical attributes**
Parent material	Structure type
Köppen climate classification	Particle size distribution:
Land use	weight % sand
Natural Vegetation	weight % silt
	weight % clay
	Stone and gravel content
	Bulk density
	Volume per cent water held at specified suctions
	Hydraulic conductivity at specified suctions

*: Analytical methods are specified in a separate key-attribute file.