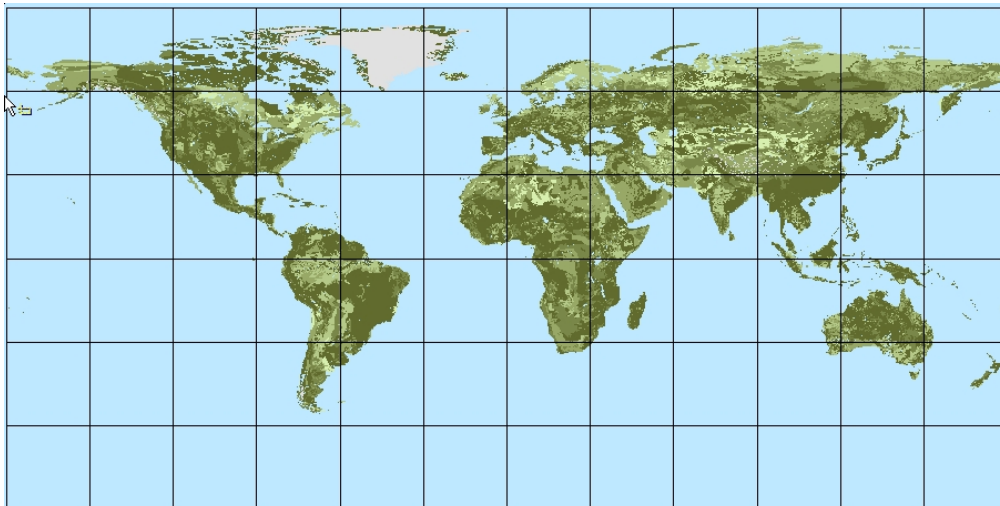


**Inventory of P-Olsen data in the
ISRIC-WISE soil database
for use with QUEFTS
(Version 1.0)**

Niels H. Batjes
(May 2010)



All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying or otherwise, without the prior permission of the copyright owner. Applications for such permission, with a statement of the purpose and extent of the reproduction, should be addressed to the Director, ISRIC - World Soil Information, PO BOX 353, 6700 AJ Wageningen, the Netherlands.

The designations employed and the presentation of materials in electronic forms do not imply the expression of any opinion whatsoever on the part of ISRIC concerning the legal status of any country, territory, city or area or of its author concerning the delimitation of its frontiers or boundaries.

Copyright © 2010, ISRIC - World Soil Information

Disclaimer:

While every effort has been made to ensure that the data are accurate and reliable, ISRIC cannot assume liability for damages caused by inaccuracies in the data or as a result of the failure of the data to function on a particular system. ISRIC provides no warranty, expressed or implied, nor does an authorized distribution of the data set constitute such a warranty. ISRIC reserves the right to modify any information in this document and related data sets without notice.

Correct citation:

Batjes NH 2010. Inventory of P-Olsen data in the ISRIC-WISE soil database for use with QUEFTS (ver. 1.0). Report 2010/06, ISRIC. World Soil Information, Wageningen (24 p. with data file)

(http://www.isric.org/isric/Webdocs/Docs/ISRIC_Report_2010_06.pdf)

Inquiries:

c/o Director, ISRIC – World Soil Information

PO Box 353

6700 AJ Wageningen

The Netherlands

E-mail: soil.isric@wur.nl

Web: www.isric.org

Front cover: Proportion of the world where QUEFTS may be applied based on current boundary conditions for pH_{water}, soil organic carbon content, and soil drainage class; see text for details and Figure 3 for Legend.

Contents

| | |
|---|-----|
| Foreword | iii |
| SUMMARY | iv |
| 1 INTRODUCTION | 1 |
| 2 SOIL PHOSPHORUS | 2 |
| 2.1 Background | 2 |
| 2.2 Soil analytical methods for phosphorus | 3 |
| 2.3 Soil fertility - crop yield response models | 4 |
| 3 MATERIALS AND METHODS | 5 |
| 3.1 Data | 5 |
| 3.2 Methods | 6 |
| 4 RESULTS AND DISCUSSION | 6 |
| 4.1 Summary of P-Olsen data | 6 |
| 4.2 Median P-Olsen values for defined soil classes | 8 |
| 4.3 Current QUEFTS-imposed boundary conditions | 10 |
| 4.4 Other determinants of achievable crop yields | 11 |
| 5 CONCLUSIONS | 12 |
| ACKNOWLEDGEMENTS | 13 |
| REFERENCES | 14 |
| APPENDICES | 18 |
| Appendix 1. Structure and content of P-Olsen data file | 18 |
| Appendix 2. Descriptive statistics for P-Olsen data clustered according to major soil groupings of the Revised FAO Legend (0-20 cm) | 20 |
| Appendix 3. Descriptive statistics for P-Olsen data clustered according to the soil units of the FAO-Unesco 1974 Legend (0-20 cm) | 22 |
| Appendix 4. Descriptive statistics for P-Olsen data clustered according to broad IPCC soil classes (0-20 cm) | 24 |

List of Tables

| | |
|--|---|
| Table 1. Soil properties affecting the selection of the appropriate P-test and recommended methods | 4 |
| Table 2. Summary of analytical methods for determining available P reported in WISE | 7 |

Table 3. Country of origin of profiles having P-Olsen data in WISE (0-20 cm) 8
Table 4. Summary of screened data set (0-20 cm) 9

List of Figures

Figure 1. Schematic representation of P present in soil..... 3
Figure 2. Proportion of the world meeting current QUEFTS boundary conditions for soil drainage class, pH_{water} and soil organic carbon content.....10
Figure 3. Global distribution of soils for which the P-Olsen method is recommended; lighter colours indicate a predominance of acid soils.....11

Foreword

ISRIC – World Soil Information has the mandate to create and increase the awareness and understanding of the role of soils in major global issues. As an international institution, we inform a wide audience about the multiple roles of soils in our daily lives; this requires scientific analysis of sound soil information.

Phosphorus is an essential element for life. Unlike carbon, oxygen, nitrogen, and hydrogen, it does not cycle between plants and soils and the air. It is mined, processed, applied to the soil as fertilizer and some of it is ultimately lost as runoff into lakes, streams and, ultimately, the ocean. Phosphate mines may be exhausted in the near future. In this context, ISRIC has initiated research to understand better the availability and dynamics of soil phosphorus in collaboration with its partners.

This exploratory study presents an inventory of soil phosphorus data, analysed according to the P-Olsen extraction method, as required for broad scale modelling exercises of effects of phosphorus limitation on global food security. It considers selected soil attributes required to run QUEFTS, a model for Quantitative Evaluation of the Fertility of Tropical Soils. The study draws on large soil databases developed at ISRIC, notably the harmonized ISRIC-WISE data set.

Dr Ir Prem Bindraban

Director, ISRIC – World Soil Information

SUMMARY

This exploratory study presents an inventory of P-Olsen, pH_{water} , soil organic carbon, organic nitrogen, and exchangeable K values held in the ISRIC-WISE soil profile database. Such profile data are needed to assess location –rather soil type– specific crop yield responses using QUEFTS, an empirical model for the Quantitative Evaluation of the Fertility of Tropical Soils. Regionally detailed datasets of soil variables considered in QUEFTS are needed for (1) further module development/testing and (2) to create spatial data layers to assess regional effects of phosphorus limitation on food security. The focus of this report is on the latter aspect.

Data for available-P are rarely reported in the source materials that underpin the ISRIC-WISE database; they have been measured according to a range of soil type specific analytical methods. Further, these sources seldom include information on land use management and land use history, drivers that strongly influence soil P-levels.

Out of the over 11,000 soil profiles in WISE, only 1147 have data for P-Olsen (0-20 cm) as presently considered in QUEFTS. In part, the corresponding “point data” may be used to develop/test region-specific modules for QUEFTS; 840 of the point data are for soil profiles with pH_{water} greater than six, corresponding with the pH range for which the P-Olsen method is appropriate. Coefficients of variation for the latter P-Olsen data, clustered according to broad soil classes (FAO, IPCC) as needed for spatial extrapolation, are large (85 to 281%). The present set of median P-Olsen values is not considered representative for any specific geographic area or country, limiting its usefulness for spatial extrapolation based on broad soil classes as defined on e.g. the digital Soil Map of the World.

Selection of the appropriate method to determine so-called plant available-P will vary according to soil type and plant characteristics. In the context of future, global applications that consider the QUEFTS approach, different soil fertility – crop yield response modules/functions (i.e. quantitative relationships between chemical soil properties and potential supply of nutrients) will be needed for acidic soil regions where other extraction methods, such as “P-Bray,” are appropriate as a measure for plant available-P. The validity of using the P-Olsen method for the wide pH range presently considered in QUEFTS (4.7-8.0) may need to be re-assessed, in particular for strongly acid soils.

Keywords: legacy soil data, phosphorus, P-Olsen, QUEFTS, ISRIC-WISE database

1 INTRODUCTION

The Plant Production Systems Group (PPS) of Wageningen UR and the Netherlands Environmental Assessment Agency (PBL) are currently considering QUEFTS, an empirical model for the Quantitative Evaluation of the Fertility of Tropical Soils (Janssen *et al.* 1990; Smaling and Janssen 1993), for use in a study on "Effects of phosphorus limitation on global food security." Although considered relatively undemanding in terms of soil data requirements, the present version of QUEFTS has specific boundary conditions in terms of soil drainage, pH_{water} , P-Olsen values, organic carbon content, and exchangeable potassium. Inherently, this limits the applicability of the present model to a section of the world. Regionally detailed soil datasets are needed for (1) further module development and testing and (2) to create spatial data layers for global assessments.

The aim of this exploratory study is to assess whether the necessary (profile) data are available in the ISRIC-WISE database, a compilation of globally accessible soil profile data based on purposive sampling – for details see elsewhere (Batjes 2009a; Batjes and Bridges 1994). Profiles with methodologically suitable data were flagged and subsequently aggregated, according to three systems (FAO-Unesco 1974; FAO 1988; IPCC 1996, p. 3.41), to present median, depth-weighted values (0-20 cm) for P-Olsen for broad soil classes. The aim being to assess in how far these derived data may be linked to global soil databases to permit spatial extrapolation using QUEFTS. Alternatively, the underlying "point data" may be used to develop/test region-specific modules for QUEFTS; the latter, however, is beyond the scope of this study.

Chapter 2 provides some background information on soil phosphorus, analytical measures for determining soil phosphorus, and soil fertility - crop yield response models. Materials and methods are presented in Chapter 3. Results are discussed in Chapter 4, while concluding remarks on the usefulness of the derived data for regional assessments of food security that consider the current version of QUEFTS are drawn in Chapter 5.

The underlying, depth-weighted point-data are presented in an MS-Excel® file, the structure and content of which is presented in Appendix 1. Descriptive statistics for P-Olsen data for the various soil classes considered here, as required for spatial extrapolation, are given in Appendix 2 to 4.

2 SOIL PHOSPHORUS

2.1 Background

Worldwide, phosphorus deficiency in plants is second only to N as the major soil fertility problem (Lindsay and Vlek 1977). Conversely, P lost from P-saturated soils that reaches water commonly is the main cause of eutrophication (Bouwman *et al.* 2009; Smil 2000). Phosphorus in the global environment, including transfers, cycles, and management obstacles to efficient P management for improved global food security have been discussed in detail elsewhere (ICSU-SCOPE 2001; Smit *et al.* 2009).

Global reserves of phosphate rock, a non-renewable natural resource and the main source of phosphorus used in fertilizers, are finite with severe implications foreseen for agricultural development and the world's food supply in the coming 50-100 years (Cordell *et al.* 2009; Smit *et al.* 2009). Human activities have intensified releases of P; by the year 2000 the global mobilization of the nutrient has roughly tripled compared to its natural flows (Smil 2000).

Phosphorus is a key component of fertilizers needed to sustain production on numerous soils with inherently low levels of available-P (Dabin 1980; Fairhurst *et al.* 1999; Sanchez 1976). Of all the major plant nutrients, phosphorus possibly has the most complicated chemistry in the soil, at least as far as assessments of P-levels and P-fertiliser requirements are concerned (Dabin 1980; Landon 1991; Ryan and Rashid 2006).

Amounts, forms (organic and inorganic), and distribution of P in the soil vary with different processes: natural processes that determine soil mineralogy and P-sorption characteristics, as well as human-controlled processes such as the application and timing of P-containing fertilizers, lime and organic material. Under natural conditions, the weathering and dissolution of rocks and relatively insoluble P-containing minerals is a slow process; it is only capable of supporting slow-growing vegetation and crops adapted to low P-availability. In acid soils, various forms of iron (Fe), aluminum (Al) and manganese (Mn) oxides that strongly bind P dominate, while in calcareous soils P is mainly found in the form of Ca-compounds of varying solubility (Dabin 1980; Fairhurst *et al.* 1999; Ryan and Rashid 2006); volcanic soils rich in allophane strongly fix phosphorus. Ultimately, the form of P in the soil will influence P-availability to the plant; actual uptake will be determined by soil water conditions, crop type and growth rate, root morphology and plant-specific characteristics to extract soil-P through excretion of exudates (Hoffland *et al.* 1992); fungi may also be important in this respect (Hoffland *et al.* 2004). Reactions between soils and fertilizer phosphorus have been discussed in detail elsewhere (Ryan and Rashid 2006; Sanchez 1976). Alternatively, in regions over-supplied with phosphorus, P-loadings may exceed the natural capacity of soils to

retain P leading to runoff and water quality problems such as eutrophication (Bouwman *et al.* 2009; Harrison *et al.* 2010).

2.2 Soil analytical methods for phosphorus

Phosphorus in the soil is only partly soluble and not very mobile (Figure 1); exchange reactions involving adsorbed-P are very slow compared to that of other nutrients. Soil phosphorus tests provide important information for estimating the P nutrient status of the soil. Generally, plants only can utilise a small fraction of the total P in soil, the so-called "available-P." This amount is strictly correlated to the so-called labile soil P, sometimes referred to as the "intensity" of the nutrient in the profile.

Routine soil tests for P do not consider the total P content because the amount of soil P in plant-available forms is always much less than the total P; they form a proxy for available P. Similarly, most routine soil tests do not measure the P soluble in water because this amount is usually very low and does not properly represent the P plants can potentially absorb during a growing season. Therefore, soil tests for P are designed to predict only the plant-available P fraction (USDA-NRCS 2004; van Reeuwijk 2002). Strictly speaking, however, such tests can only provide an accurate "relative index" of the quantity that plants may utilize from a soil; rarely, if ever, they can provide an absolute measure of it (Thomas and Peaslee 1973). Therefore, it would be better to speak of "extractable" (by a given method) rather than "plant available" soil P.

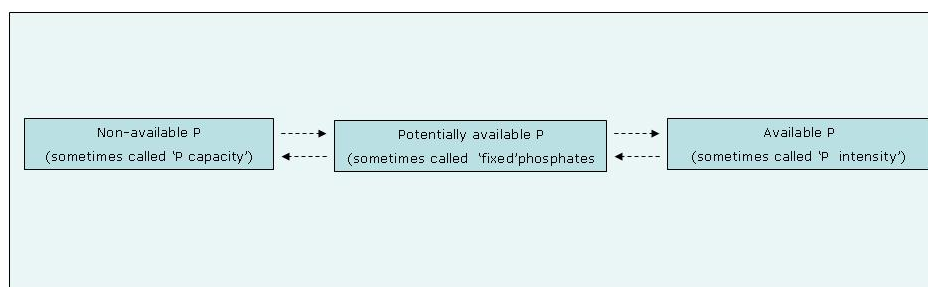


Figure 1. Schematic representation of P present in soil (After: Landon 1991)

As discussed by Dabin (1980) and others, different methods give variable results according to the type and concentration of the extractant, the soil-solution ratio, time of shaking, and temperature. Results obtained with different P-methods are seldom comparable. Therefore, analyses of P in soil must always be provided with the name of the analytical method used. For a given method to be useful, the laboratory data must also be correlated with crop production data from field experiments. Typically, the laboratory tests that give the greatest correlation with plant growth and yields – under defined conditions of soils and climate – are selected; this

will vary with crop type and density of planting. As a result, a wide range of analytical methods is used for determining “available P” in soil throughout the world (Table 1).

Table 1. Soil properties affecting the selection of the appropriate P-test and recommended methods (Source: Elrashidi 2010)

| Soil | pH | Minerals | Methods |
|------------------------------------|------------|---------------------------------|---|
| Acidic | < 6.0 | Al-P, Fe-P and Mn-P | Bray-1, Mehlich-1, Mehlich-3, Water, Fe-oxide impregnated paper (IIP), Anion Exchange Resin (AER) |
| Slightly acid to slightly alkaline | 6.0 to 7.2 | Al-P, Fe-P, Mn-P, Mg-P and Ca-P | Bray-1, Mehlich-1, Mehlich-3, <i>Olsen</i> , Water, IIP and AER |
| Alkaline, calcareous | > 7.2 | Ca-P and Mg-P | <i>Olsen</i> , Water, IIP and AER |

In acidic soils, defined here as $\text{pH}_{\text{water}} < 6.0$, phosphate ions combine with iron and aluminium to form compounds that are not readily available to plants; in the presence of calcium, phosphate tends to be converted to calcium phosphate whereby P-availability to plants is reduced. By implication, the various methods may fail to extract “plant available-P” if they are used on soil types for which they are inappropriate.

2.3 Soil fertility - crop yield response models

Specific soil fertility – crop yield response curves will have to be developed depending on the soil types, soil analytical methods, crops and climates under consideration. Using field test data, recommendations can be made concerning the amounts of phosphate and other fertilizers that will most likely give optimum yields.

A detailed consideration of P-fertilizer application and timing, *vis a vis* that of N and K-fertilizers, in relation to crop production and yield is beyond the scope of this study. For example, by adding lime to a naturally acid soil the pH may be increased to a level where P-fertilizer application becomes meaningful (e.g. Sanchez 1976).

The most widely applicable method for determining “available” soil P is probably the Olsen Sodium-Bicarbonate Extraction (USDA-NRCS 2004, p. 242). This analytical method has been considered when developing QUEFTS, the Quantitative Evaluation of the Fertility of Tropical Soils (Janssen *et al.* 1990; Smaling and Janssen 1993). Using four steps, the empirical model describes relations between (1) chemical soil test values, (2) potential NPK supply from soils and fertilizer, (3) actual NPK uptake, and (4) maize grain yield. Empirical relationships used in Steps 1 and 3 are

derived from field experimental data; they can be fine-tuned using region-specific soil nutrient and crop yield data (Janssen *et al.* 1990).

QUEFTS was developed to calculate maize yield as a function of N, P_{Olsen} and K supply from soil and fertilizer, while accounting for interactions among the macronutrients (N, P and K). It was largely developed using soil nutrient and crop-response data from field trials in Suriname and Kenya; other equations were mainly based on theoretical considerations. Strict boundary conditions have been defined for application of this empirical model (Smaling and Janssen 1993): well-drained, deep soils; pH_{water} between 4.7 and 8.0¹; organic carbon content below 70 g kg⁻¹; P-Olsen values below 30 mg P kg⁻¹; and, exchangeable potassium below 30 mmol kg⁻¹ in the topsoil (0-20 cm).

3 MATERIALS AND METHODS

3.1 Data

Soil profile data were derived from the harmonized ISRIC-WISE soil data base (Batjes 2009a), complemented with recent additions collated in the framework of various ongoing ISRIC projects. This database holds selected site and horizon data for over 11,000 soil profiles from over 150 countries. Profile data for inclusion in WISE were extracted from a wide range of sources, screened, and harmonized with respect to the original (1974) and revised (1988) Legend of the FAO-Unesco Soil Map of the World.

Profiles have been described, sampled, and analyzed according to methods and standards in use in the originating countries. Analytical results for the same property cannot always be compared directly due to differences in the methods and standards used. By implication, the amount of measured data available for modelling is sometimes much less than expected (Batjes 2009a).

WISE was specifically developed for land-related applications at continental and global level (Batjes and Bridges 1994). At these broad scales, the soil classification code is generally the primary attribute for clustering data (Batjes *et al.* 2007; FAO/IIASA/ISRIC/ISSCAS/JRC 2009). The soil classes used here (FAO-Unesco 1974; FAO 1988; IPCC 1996) provide a coarse indicator for soil mineralogy and organic matter content, important determinants of P-availability for plants in soil (Table 1). Alternatively, they do not take into account possible effects of land use and soil management practices, such as P-fertilizer application and mulching, on available P-levels. More detailed, digital soil mapping

¹ The original boundary conditions for pH_{water} were set at 4.5-7.0 (Janssen *et al.* 1990).

approaches that consider effects of co-variables such as land cover or land use on soil properties are being developed (e.g., Hartemink *et al.* 2008; Hengl 2009), but often these approaches are still limited by the availability of comparable, measured soil data.

3.2 Methods

Profile horizon data in WISE were screened on the comparability of soil analytical methods for determining P, as further discussed in Chapter 4. The resulting dataset with P-Olsen values, and other input variables required to run QUEFTS, was stored in a working file. Subsequently, depth-weighted values for P-Olsen, organic carbon, total nitrogen, pH_{water}, and exchangeable-K were computed for fixed-depth layers.

For this study, medians and other descriptive statistics for the above properties (0-20 cm), for defined soil classes as required for spatial extrapolation purposes, were calculated next using Statistix 7 (Analytical Software 2000). Alternatively, the data set described in Appendix 1 may be used to develop region-specific, empirical modules for QUEFTS, but this is beyond the scope of the present inventory.

4 RESULTS AND DISCUSSION

4.1 Summary of P-Olsen data

There are few data for “available P” in most historic sources, both analogue and digital, that underpin the ISRIC-WISE database. They have been determined according to 18 different laboratory methods (Table 2). As indicated earlier, the selection of a method for measuring P depends on the concentration of solution P; concentration of interfering substances in the solution to be analyzed; and the particular acid system involved in the analytical procedure (USDA-NRCS 2004; van Reeuwijk 2002).

As indicated in Section 3.2, the available data for available-P were first screened according to soil analytical methods. Seen the scope of this exploratory study, only profiles/horizons having P-Olsen values were retained. Sometimes, however, the analytical procedure for determining available-P was described in rather broad terms in the source materials, for instance “Bray-I for acid soils resp. Olsen for other soils.” In such cases, the data for available-P were allocated to the “P-Olsen method” when pH_{water} ≥ 6.0, in accordance with Table 1. The resulting, “raw” dataset

(Appendix 1) includes 1147 different soil profiles from 15 countries (Table 3).

Evaluation of the above dataset, however, showed that various laboratories have applied the P-Olsen method to acidic soils, with pH_{water} values ranging from 3.8 to 6.0, for which this extraction procedure is not recommended (Table 1). The corresponding point data were flagged and excluded from further analysis here: the Olsen extraction method will give unreliable estimates for acid soils. Similarly, for some profiles there were no pH_{water} data in the source materials; these figures were also excluded from further analysis. However, the corresponding point data have been flagged and preserved for reference purposes and possible QUEFTS model testing (see Appendix I).

Table 2. Summary of analytical methods for determining “available P” reported in WISE

| Method code ^a | Description |
|--------------------------|--|
| PA02 | Bray I (dilute HCl/NH ₄ F) |
| <i>PA03</i> | Olsen (0.5 M NaHCO ₃ at pH 8.5) |
| PA04 | Truog (dilute H ₂ SO ₄) |
| PA05 | Morgan (Na-acetate/acetic acid) |
| PA06 | Saunders and Metelkamp (anion-exch. resin) |
| PA07 | Bray II (dilute HCl/NH ₄ F) |
| PA08 | Modified after ISFEI method, A.H. Hunter (1975) |
| PA09 | Nelson (dilute HCl/H ₂ SO ₄) |
| PA10 | ADAS method (NH ₄ acetate/acetic acid) |
| PA11 | Spectrometer method (Brasil) |
| PA12 | North Carolina or Mehlich (0.05 M HCl, 0.025 N H ₂ SO ₄) |
| PA13 | Colorimetric in 0.02 N H ₂ SO ₄ extract, molybdenum blue method |
| PA14 | Dabin (ORSTOM), modified Olsen method for tropical soils (0.5 N NaHCO ₃ + 0.5 N NH ₄ F buffered to pH 8.5 by NaOH) |
| PA15 | Kurtz-Bray I (0.025 M HCl + 0.03 M NH ₄ F) |
| PA16 | Complexation with citric acid (van Renwick) |
| PA17 | NH ₄ -lactate extraction method (KU-Leuven) |
| <i>PA18</i> | Bray-I (acid soils) resp. Olsen (other soils) |
| PA99 | P-method, not defined |

^a Soil horizon data analysed using methods shown in italics have been considered in this study; see text for details

Subsequent to this second screening on soil pH, 840 sets of depth-weighted P-Olsen data (0-20 cm) remained for statistical analysis. This corresponds with some 8% of the original number of profiles in WISE. The remaining data originate from 14 different countries, in particular Botswana and Yemen where FAO carried out extensive soil survey programs (Table 3).

Table 3. Country of origin of profiles having P-Olsen data in WISE (0-20 cm)

| ISO Country | Screening | |
|---------------------------------|---------------------|---------------------|
| | Step 1 ^a | Step 2 ^b |
| AL Albania | 4 | 4 |
| BW Botswana | 831 | 612 |
| CN China, mainland | 18 | 14 |
| CO Colombia | 3 | 3 |
| EC Ecuador | 12 | 2 |
| GA Gabon | 2 | 0 |
| FJ Fiji | 4 | 1 |
| GH Ghana | 2 | 2 |
| IQ Iraq | 10 | 10 |
| NE Niger | 3 | 3 |
| PE Peru | 15 | 7 |
| TZ Tanzania, United Republic of | 78 | 23 |
| US United States | 21 | 21 |
| VE Venezuela | 8 | 2 |
| YE Yemen | 136 | 136 |
| — Total | 1147 | 840 |

^a Total number of points with P-Olsen data after first screening on analytical methods; in part, these may be considered for further QUEFTS model development; see Appendix 1 for descriptive statistics.

^b Total after second screening for $\text{pH}_{\text{water}} > 6.0$, the pH range considered appropriate for applying the P-Olsen method (see Table 1).

4.2 Median P-Olsen values for defined soil classes

Median or mean soil property values, for defined soil classes and depth ranges, are needed when spatial extrapolation based on conventional mapping approaches is the objective (see Batjes 2006; FAO/IIASA/ISRIC/ISSCAS/JRC 2009). Descriptive statistics for the various soil properties considered in QUEFTS are presented in Table 4, showing great coefficients of variation for P-Olsen, organic carbon, total nitrogen, and exchangeable-K. Further, it should be noted that the range reported for pH_{water} , from 6.0 to 10.6, extends beyond the upper boundary condition for pH_{water} of 8.0 as defined for QUEFTS in Smaling and Janssen (1993).

Table 4. Summary of screened data set (0-20 cm) ^a

| | PHWATER | POLSY | ORGC | TOTN | EXK |
|------------|---------|--------|--------|--------|--------|
| N | 840 | 840 | 789 | 156 | 790 |
| MEAN | 7.2996 | 12.046 | 6.0354 | 1.4506 | 0.6411 |
| SE MEAN | 0.0311 | 0.6545 | 0.2247 | 0.0989 | 0.0212 |
| C.V. | 12.359 | 157.46 | 104.59 | 85.149 | 93.089 |
| MINIMUM | 6.0000 | 0.6000 | 0.6700 | 0.1000 | 0.0400 |
| 1ST QUARTI | 6.5050 | 4.5000 | 2.4500 | 0.5400 | 0.2500 |
| MEDIAN | 7.1200 | 7.0000 | 4.0000 | 1.1500 | 0.4850 |
| 3RD QUARTI | 8.0000 | 14.000 | 7.0000 | 1.9875 | 0.8000 |
| MAXIMUM | 10.600 | 399.36 | 60.000 | 7.8000 | 6.1600 |

^a Corresponds with step 2 in Table 3, i.e. profiles in WISE having P-Olsen values reported for soils with $\text{pH}_{\text{water}} \geq 6.0$; see text for details. P-Olsen is given in $\text{mg P}_2\text{O}_5 \text{ kg}^{-1}$, organic C in g kg^{-1} , total nitrogen in g N kg^{-1} , and exchangeable K in $\text{cmol}_c \text{ kg}^{-1}$. Decimal places are shown as generated by Statistix 7 (Analytical Software 2000) and may suggest false accuracy; this also applies to results shown in Appendix 2 to 4.

Individual data populations for the defined soil classes are often considered too small ($n < 30$) to present meaningful values for median P-Olsen values (see Snedecor and Cochran 1980). Consequently, descriptive statistics per major soil class (FAO 1988, FAO-Unesco 1974 and IPCC 1996) are only presented here when $n > 30$ for P-Olsen, see Appendix 2 to 4. Further, seen the still limited number of observations, no descriptive statistics for P-Olsen values are provided here at the FAO soil unit level. By implication, linkage of the median P-Olsen data presented here to a global soil map for possible QUEFTS model application is not realistic. As a first approximation, however, a possible solution could be to define proxy values for P-Olsen that take into account broad soil classes and regional differences in land use and management history (e.g., using historic P-fertilizer application data for broad land use types) in order to differentiate between "unfertilized" and "fertilized" areas. Such an approach should also take into account that the Olsen extraction method is only appropriate for mineral soil types with pH_{water} greater than 6 (Table). Therefore, new or adapted modules for QUEFTS will be needed for those regions where other analytical methods for determining available P in soil are recommended/used (see Section 4.3).

Expansion of available P-data in the new ISRIC core soil database, for example using soil profile data collated during international projects² such as e-SOTER and AfSIS, is an ongoing, albeit inherently time consuming, activity that is largely driven by project specific demands. Inherently, the amount, quality and type of soil profile information that may be obtained

² See <http://www.isric.org/UK/About+ISRIC/Projects/Current+Projects/default.htm> for details

from such exercises will vary widely within and between countries; access to some data sources can be restricted.

4.3 Current QUEFTS-imposed boundary conditions

Clear boundary conditions have been defined for QUEFTS (Janssen *et al.* 1990; Smaling and Janssen 1993); so far, the procedure for determining plant available-P has been limited to the Olsen Sodium-Bicarbonate extraction method. As indicated earlier, the revised model (Smaling and Janssen 1993) may be applied to freely drained, deep soils that have a pH_{water} of 4.7 to 8.0, organic carbon content $< 70 \text{ g kg}^{-1}$, $\text{P-Olsen}^3 \leq 30 \text{ mg kg}^{-1}$, and exchangeable potassium $< 30 \text{ mmol K kg}^{-1}$ in the topsoil (0-20 cm).

According to the *current* boundary conditions for soil drainage, pH_{water} and organic matter content, QUEFTS may only be applied to a section of the world (subject to regional validation). The corresponding region (Figure 2) was derived from a 5 by 5 arc minutes map of derived soil properties (see Batjes 2006), taking into account the full FAO soil unit composition of each terrestrial grid cell. The proportion of each grid cell that meets the above boundary conditions was computed next; boundary conditions for exchangeable K were not considered here as such derived data are not available for the world. Alternatively, it should be noted again that, from a soil analytical point of view, the P-Olsen extraction method is recommended when $\text{pH}_{\text{water}} \geq 6.0$ (Elrashidi 2010). The corresponding section of the world is shown in Figure 3, using proportional classes.

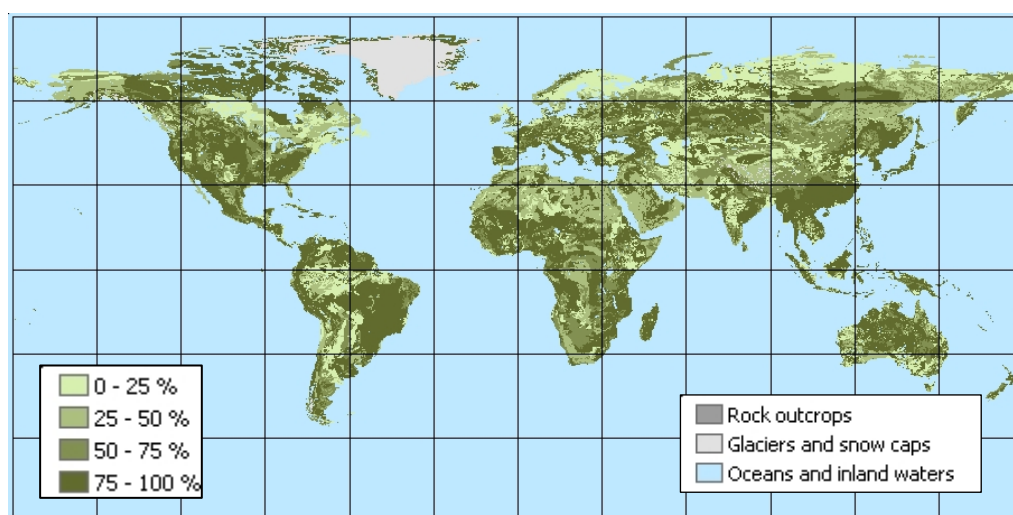


Figure 2. Proportion of the world meeting current QUEFTS boundary conditions for soil drainage class, pH_{water} and soil organic carbon content (0-20 cm)

³ In this study, P-Olsen values are given as $\text{mg P}_2\text{O}_5 \text{ kg}^{-1}$ (i.e. $2.29 * \text{P}$)

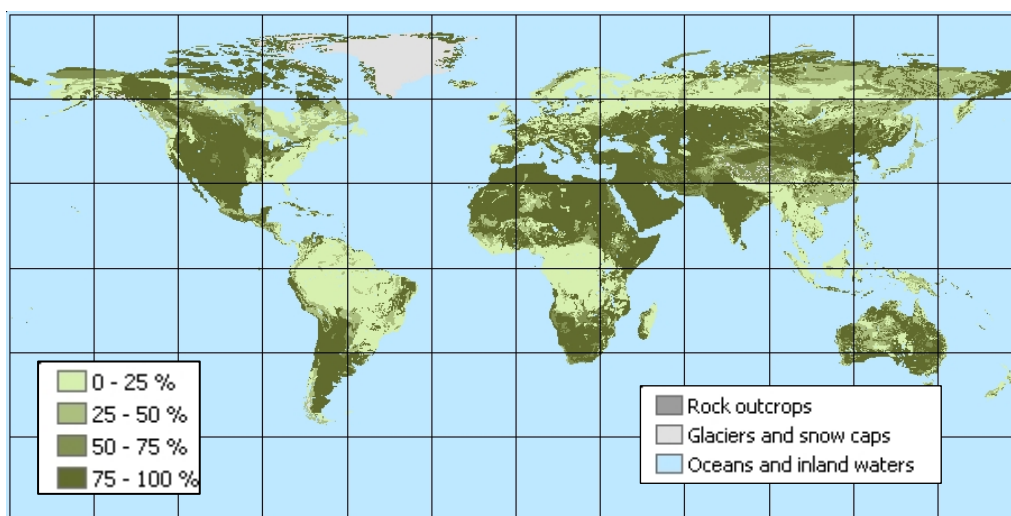


Figure 3. Global distribution of soils for which the P-Olsen method is recommended ($\text{pH}_{\text{water}} \geq 6.0$, for 0-20 cm); lighter colours indicate a predominance of acid soils.

For the future, new modules for QUEFTS will need to be developed and tested for other regions of the world. These should take into account soil type-specific analytical procedures for determining “plant available-P”, or rather “extractable P” as discussed by Thomas and Peaslee (1973), for example the widely used P-Bray method for acid soils. This would require the generation of new sets of model input variables.

4.4 Other determinants of achievable crop yields

The principles that underlie QUEFTS may be applied to other crops, soils, nutrients and agro-ecological regions than those considered in the original studies. The system has been applied in a wide range of studies involving both rainfed and irrigated systems and range of crops including maize (Janssen *et al.* 1990; Liu *et al.* 2006; Smaling and Janssen 1993), rice (Das *et al.* 2009; Haefele *et al.* 2003; Wade *et al.* 1998; Witt *et al.* 1999), wheat (Liu *et al.* 2006; Maiti *et al.* 2006) and even banana (Nyombi *et al.* 2010), for different soils and climates. Often this included critical field validation studies; various levels of success have been reported. Tabi *et al.* (2008), for example, indicated that to apply the model to predict maize yields under different levels of soil fertility management in Northern Nigeria validation using representative field data from the area was required. They also raised the question whether the empirical equations used for estimating the potential supply of N, P and K (QUEFTS, step 1) from soil analysis data can be used in regions with different soils or climates.

Yield-determining factors other than topsoil N, P and K levels, such as climate and management practices, are not yet accounted for in QUEFTS. So far, the model only considers the top 20 cm whereas subsoil properties are often important determinants of achievable crop yields. For example, a high aluminum saturation in strongly acid soils may affect crop rootability and hence potential access to water held at greater depth (Bouma *et al.* 1998), thereby hampering crop growth unless remedied through lime application. Assessing how limiting soil fertility is at the field, or mapping unit level, would require the development of a more comprehensive modelling approach that also considers these other controlling variables. This may be done, for example, using quantitative land evaluation (FAO 1976, 1983) procedures that take into consideration different land use management/input systems or land utilization types.

5 CONCLUSIONS

- Selection of the appropriate method for determining plant available-P will vary according to soil type; at present, QUEFTS specifically considers the P-Olsen extraction and maize as a nutrient-demanding reference crop.
- The point data set presented in Appendix 1 may be used for further QUEFTS module development and testing; typically, however, the Olsen extraction method is only recommended for soils with pH_{water} greater than 6.
- The present set of median values for P-Olsen (0-20 cm), for defined soil classes (e.g. FAO 1988), is not considered to be representative for any specific geographic area or country having been derived from a small number and limited range of globally distributed soil profiles. This precludes their linkage to global soil databases for QUEFTS-based studies at a broad scale; proxy based approaches that also take into account soil fertilizer use history for broadly defined land use types may need to be developed as a first approximation.
- Tailored soil fertility – crop yield response functions are needed for soil regions where use of the P-Olsen method is not recommended, for example, for the large extent of acidic soils in the tropics. In principle, such modules can be based on the general principles that underpin QUEFTS using field-validated equations that consider the relationship between say P-Bray content in the soil and reference crop yield.
- Focussed collection of soil phosphorus data for inclusion in the ISRIC soil database is hampered by the fact that available P is seldom measured in conventional soil surveys. Further, a wide range of analytical methods is used internationally, largely depending on the pH of the prevailing soil types. In addition, the source materials seldom provide information on land use management and land use history, important determinants of available P-levels in soil.

ACKNOWLEDGEMENTS

This work was funded by the Netherlands Environmental Assessment Agency (PBL contract number E/555057/02/ES) in the context of a study on "Effects of phosphorus limitation on global food security" by the Plant Production Systems Group (PPS) of Wageningen UR and the Netherlands Environmental Assessment Agency (PBL).

Special thanks go to Ad van Oostrum (ISRIC) for useful discussions on the comparability and applicability of extraction methods for soil phosphorus. Further, Prem Bindraban (ISRIC), Lex Bouwman (PBL) and Sheida Sattari (PPS-WUR) are thanked for their constructive comments on an earlier version of this report.

REFERENCES

- Analytical Software 2000. *Statistix for Windows (ver. 7.0)*. Analytical Software, Talahasee, 333 p
- Batjes NH 2006. *ISRIC-WISE derived soil properties on a 5 by 5 arc-minutes global grid (ver. 1.0)*. Report 2006/02, ISRIC - World Soil Information, Wageningen [Available at: http://www.isric.org/isric/webdocs/Docs/ISRIC_Report_2006_02.pdf; last accessed March 2009]
- Batjes NH 2009a. Harmonized soil profile data for applications at global and continental scales: updates to the WISE database. *Soil Use and Management* 25, 124-127 (<http://dx.doi.org/10.1111/j.1475-2743.2009.00202.x>)
- Batjes NH 2009b. *IPCC default soil classes derived from the Harmonized World Soil Data Base (Ver. 1.0)*, Carbon Benefits Project (CBP) and ISRIC - World Soil Information, Wageningen (available at: http://www.isric.org/isric/Webdocs/Docs/ISRIC_Report_2009_02.pdf)
- Batjes NH and Bridges EM 1994. Potential emissions of radiatively active gases from soil to atmosphere with special reference to methane: development of a global database (WISE). *Journal of Geophysical Research* 99(D8), 16479-16489
- Batjes NH, Al-Adamat R, Bhattacharyya T, Bernoux M, Cerri CEP, Gicheru P, Kamoni P, Milne E, Pal DK and Rawajfih Z 2007. Preparation of consistent soil data sets for SOC modelling purposes: secondary SOTER data sets for four case study areas. *Agriculture, Ecosystems and Environment* 122, 26-34
- Bouma J, Batjes NH and Groot JJR 1998. Exploring land quality effects on world food supply. *Geoderma* 86, 43-59
- Bouwman AF, Beusen AHW and Billen G 2009. Human alteration of the global nitrogen and phosphorus soil balances for the period 1970 - 2050. *Global Biogeochem. Cycles* 23, GB0A04, doi:10.1029/2009GB003576
- Cordell D, Drangert J-O and White S 2009. The story of phosphorus: Global food security and food for thought. *Global Environmental Change* 19, 292-305
- Dabin P 1980. Phosphorus deficiency in tropical soils as a constraint on agricultural output, *Priorities for alleviating soil-related constraints to food production in the tropics*. IRRI, Los Banos (Philippines), pp 217-233
- Das D, Maiti D and Pathak H 2009. Site-specific nutrient management in rice in Eastern India using a modeling approach. *Nutrient Cycling in Agroecosystems* 83, 85-94
- Elrashidi MA 2010. *Selection of an appropriate phosphorus test for soils*, Soil Survey Laboratory, USDA, Lincoln (NE) (available at ftp://ftp-fc.sc.egov.usda.gov/NSSC/Analytical_Soils/phosphor.pdf; last accessed 04 May 2010)

- Fairhurst T, Lefroy R, Mutert E and Batjes NH 1999. The importance, distribution and causes of P deficiency as a constraint to crop production in the tropics. *Agroforestry Forum* 9, 2-8
- FAO-Unesco 1974. *Soil Map of the World, 1:5,000,000. Vol. 1 - Legend*, United Nations Educational, Scientific, and Cultural Organization, Paris
- FAO 1976. *A framework for land evaluation*. Soils Bulletin No. 32, Food and Agriculture Organization of the United Nations, Rome
- FAO 1983. *Guidelines: land evaluation for rainfed agriculture*. FAO Soils Bulletin 52, Food and Agriculture Organization of the United Nations, Rome
- FAO 1988. *FAO-Unesco Soil Map of the World, Revised Legend, with corrections and updates*. World Soil Resources Report 60, FAO, Rome; reprinted with updates as Technical Paper 20 by ISRIC, Wageningen, 1997
- FAO/IIASA/ISRIC/ISSCAS/JRC 2009. *Harmonized World Soil Database (version 1.1)*, Food and Agriculture Organization of the United Nations, International Institute for Applied Systems Analysis, ISRIC - World Soil Information, Institute of Soil Science - Chinese Academy of Sciences, Joint Research Centre of the European Commission, Laxenburg. Available at <http://www.iiasa.ac.at/Research/LUC/luc07/External-World-soil-database/HTML/index.html?sb=1>; last accessed 10/2009
- Haefele SM, Wopereis MCS, Ndiaye MK, Barro SE and Ould Isselmou M 2003. Internal nutrient efficiencies, fertilizer recovery rates and indigenous nutrient supply of irrigated lowland rice in Sahelian West Africa. *Field Crops Research* 80, 19-32
- Harrison JA, Bouwman AF, Mayorga E and Seitzinger S 2010. Magnitudes and sources of dissolved inorganic phosphorus inputs to surface fresh waters and the coastal zone: A new global model. *Global Biogeochem. Cycles* 24
- Hartemink AE, McBratney A and Mendoca-Santos ML (editors) 2008. *Digital soil mapping with limited data*. Springer, 445 p
- Hengl T 2009. *A practical guide to geostatistical mapping*. Published by www.lulu.com (ISBN: 978-90-9024981-0)
- Hoffland E, Boogaard R, Nelemans J and Findenegg G 1992. Biosynthesis and root exudation of citric and malic acids in phosphate-starved rape plants. *New Phytologist* 122, 675-680
- Hoffland E, Kuyper TW, Wallander Hk, Plassard C, Gorbushina AA, Haselwandter K, Holmström S, Landeweert R, Lundström US, Rosling A, Sen R, Smits MM, van Hees PA and van Breemen N 2004. The role of fungi in weathering. *Frontiers in Ecology and the Environment* 2, 258-264
- ICSU-SCOPE 2001. *Phosphorus in the Global Environment - Transfers, Cycles and Management*. ICSU-SCOPE, Paris, 459 (available at: <http://www.icsu-scope.org/downloadpubs/scope54/TOC.htm>) p
- IPCC 1996. *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories*, Institute for Global Environmental Strategies (IGES) for the IPCC, Hayama (JP)

- Janssen BH, Guiking FCT, van der Eijk D, Smaling EMA, Wolf J and van Reuler H 1990. A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). *Geoderma* 46, 299-318
- Landon JR 1991. *Booker Tropical Soil Manual*. Longman Scientific & Technical, New York, 474 p
- Lindsay WL and Vlek PLG 1977. Phosphate minerals. In: Dixon, Weed, Kittrick, Milford and White (editors), *Minerals in soil environments*. Soil Science Society of America, Madison (WI), pp 639-672
- Liu M, Yu Z, Liu Y and Konijn N 2006. Fertilizer requirements for wheat and maize in China: the QUEFTS approach. *Nutrient Cycling in Agroecosystems* 74, 245-258
- Maiti D, Das DK and Pathak H 2006. Simulation of fertilizer requirement for irrigated wheat in eastern India using the QUEFTS model. *Archives of Agronomy and Soil Science* 52, 403 - 418
- Nyombi Kva, P. J. A., Corbeels M, Taulya G, Leffelaar PA and Giller KE 2010. Mineral fertilizer response and nutrient use efficiencies of East African highland banana (*Musa* spp., AAA-EAHB, cv. Kisansa). *Field Crops Research* 117, 38-50
- Ryan J and Rashid A 2006. Phosphorus. In: Lal (editor), *Encyclopedia of Soil Science, Vol. 2*. Taylor & Francis, New York, pp 1275-1279
- Sanchez PA 1976. *Properties and management of soils in the tropics*. Wiley, New York
- Smaling EMA and Janssen BH 1993. Calibration of quefts, a model predicting nutrient uptake and yields from chemical soil fertility indices. *Geoderma* 59, 21-44
- Smil V 2000. Phosphorus in the environment: Natural flows and human interferences. *Annu. Rev. Energy Environ.* 25, 53-88
- Smit AL, Bindraban PS, Schröder JJ, Conijn JG and van der Meer HG 2009. *Phosphorus in agriculture: global resources, trends and developments : report to the Steering Committee Technology Assessment of the Ministry of Agriculture, Nature and Food Quality, The Netherlands*. Report / Plant Research International;282. Plant Research International, Wageningen
- Snedecor GW and Cochran WG 1980. *Statistical Methods (7th. ed.)*. The Iowa State University Press, Iowa, 507 p
- Tabi F, Diels J, Ogunkunle A, Iwuafor E, Vanlauwe B and Sanginga N 2008. Potential nutrient supply, nutrient utilization efficiencies, fertilizer recovery rates and maize yield in northern Nigeria. *Nutrient Cycling in Agroecosystems* 80, 161-172
- Thomas GW and Peaslee DE 1973. Testing soils for phosphorus. In: Walsh and Beaton (editors), *Soil testing and plant analysis (rev. ed.)*. Soil Science Society of America, Madison (WI), pp 115-132
- USDA-NRCS 2004. *Soil Survey Laboratory Manual Soil Survey Investigations Report 42 (ver. 4.0)*, USDA-National Resources Conservation Service, Washington (Available through: [ftp://ftp-fc.sc.egov.usda.gov/NSSC/Lab Methods Manual/SSIR42 2004 view.pdf](ftp://ftp-fc.sc.egov.usda.gov/NSSC/Lab%20Methods%20Manual/SSIR42%202004.view.pdf); Accessed: 25 June 2008)

- van Reeuwijk LP 2002. *Procedures for soil analysis (6th ed.)*. Technical Paper 9, ISRIC, Wageningen (http://www.isric.org/Isric/Webdocs/Docs/ISRIC_TechPap09_2002.pdf)
- Wade LJ, George T, Ladha JK, Singh U, Bhuiyan SI and Pandey S 1998. Opportunities to manipulate nutrient-by-water interactions in rainfed lowland rice systems. *Field Crops Research* 56, 93-112
- Witt C, Dobermann A, Abdulrachman S, Gines HC, Guanghuo W, Nagarajan R, Satawatananont S, Thuc Son T, Sy Tan P, Van Tiem L, Simbahan GC and Olk DC 1999. Internal nutrient efficiencies of irrigated lowland rice in tropical and subtropical Asia. *Field Crops Research* 63, 113-138

APPENDICES

Appendix 1. Structure and content of P-Olsen data file

1) Database structure (file: *ISRIC_WISE_P_Olsen_data_June2010.xls*)

| Name | Type | Size | Properties |
|----------------------------|---------|------|---|
| WISE_Polsen_ID | Text | 20 | Identifier for profile (with P_Olsen data) in WISE |
| ISO | Text | 2 | Country ISO code |
| Layer_code ^b | Text | 2 | Code for layer (D1= 0-20 cm; D2= 20-40 cm)) |
| pHwater | Single | 4 | pH measured in water (depth-weighted for given layer) |
| ORGC | Single | 4 | Organic carbon (g/kg; depth-weighted) |
| TotN | Single | 4 | Total nitrogen (g/kg; depth-weighted) |
| POLSy | Single | 4 | P-Olsen (mg P ₂ O ₅ /kg; depth-weighted) |
| ExK | Single | 4 | Exchangeable-K (cmol/kg; depth-weighted) |
| IPCCsoilclass ⁴ | Text | 5 | IPCC soil class |
| mFAO90 | Text | 2 | Major FAO 1990 Revised Legend code |
| FAO90 | Text | 3 | FAO 1990 Revised Legend code |
| mFAO74 | Text | 1 | Major FAO 1974 Legend code |
| FAO74 | Text | 2 | FAO 1975 Legend code |
| TXT_Layer | Text | 1 | FAO texture class of layer ^a |
| DRAIN | Text | 1 | FAO soil drainage class ^a |
| LATIT | Text | 1 | Latitude (WGS_1984) |
| LATDEG ⁵ | Integer | 2 | Latitude, degrees |
| LATMIN | Integer | 2 | Latitude, minutes |
| LATSEC | Integer | 2 | Latitude, seconds |
| LONGI | Text | 1 | Longitude |
| LONDEG | Integer | 2 | Longitude, degrees |
| LONMIN | Integer | 2 | Longitude, minutes |
| LONSEC | Integer | 2 | Longitude, seconds |
| POLSY_method | Text | 50 | Brief description for P-Olsen method/reference |
| pHwaterGT6 | Text | 3 | Flag for pH _{water} : 'GT6', 'lt6' or 'x' if no values are available. The P-Olsen method is only recommended where pH _{water} >6.0 (Table 1); the corresponding data are considered in the analyses described in this report. |

^a Point data are attached as file *ISRIC_WISE_P_Olsen_data_June2010.xls*; see file *WISE3_coding_conventions_short.xls* for coding conventions.

^b At present, QUEFTS only considers the first 20 cm of soil ($n= 1147$). However, for some mineral soil types with deep organic layers, such as Chernozems, soil data for 0-40 cm may be required to calibrate/refine QUEFTS (Sheida Sattari, *pers. comm.*). Hence the inclusion of data for 20-40 cm in this table ($n= 1041$); these data, however, are not discussed in detail in the report which focuses on data flagged with 'GT6' as needed for spatial extrapolation purposes.

⁴ See http://www.isric.org/isric/Webdocs/Docs/ISRIC_Report_2009_02.pdf for details

⁵ See http://www.isric.org/isric/webdocs/Docs/ISRIC_Report_2008_02.pdf for additional information on possible accuracy

2) Range in characteristics for "full" data set

Descriptive statistics for all depth-weighted data considered in table *ISRIC_WISE_P_Olsen_data_June2010* are given below to show the range in soil properties; in part, these point data may be used for QUEFTS module development/testing purposes. This corresponds with *Step 1* as described in the report. For example, pH_{water} for 0-20 cm ranges from 3.8 to 10.6 in the "full" data set. However, as indicated in the text (Table 1) use of the P-Olsen method is only recommended when $\text{pH}_{\text{water}} \geq 6.0$. Alternatively, boundary conditions for pH_{water} in QUEFTS are given as 4.7 to 8.0 in Smaling and Janssen (1993) *versus* 4.5 to 7.0 in an earlier version (Janssen et al. 1990). Data discussed in the body of the report and Appendix 2 to 4 are limited to point-data having $\text{pH}_{\text{water}} \geq 6.0$ (i.e., flag '*pHwaterGT6*' is 'GT6').

Range of properties for full data set for two soil depths (0-20 cm and 20-40 cm) ^a

| <i>D1 (0-20 cm)</i> | PHWATER | POLSY | ORGC | TOTN | EXK |
|----------------------|---------|--------|--------|--------|--------|
| N | 1109 | 1147 | 1084 | 244 | 1088 |
| MEAN | 6.8398 | 12.764 | 7.6337 | 1.4991 | 0.6878 |
| SE MEAN | 0.0346 | 0.6521 | 0.2901 | 0.0818 | 0.0247 |
| C.V. | 16.829 | 173.01 | 125.10 | 85.183 | 118.61 |
| MINIMUM | 3.7800 | 0.6000 | 0.6700 | 0.1000 | 0.0400 |
| 1ST QUARTI | 6.0000 | 5.0000 | 2.4250 | 0.6000 | 0.2000 |
| MEDIAN | 6.7700 | 7.0000 | 4.0500 | 1.2300 | 0.4000 |
| 3RD QUARTI | 7.6950 | 14.000 | 8.5000 | 1.9000 | 0.8000 |
| MAXIMUM | 10.600 | 399.36 | 102.21 | 8.9800 | 10.820 |
| <i>D2 (20-40 cm)</i> | PHWATER | POLSY | ORGC | TOTN | EXK |
| N | 1005 | 1041 | 953 | 207 | 968 |
| MEAN | 6.9101 | 8.3196 | 4.9325 | 0.9263 | 0.5734 |
| SE MEAN | 0.0405 | 0.3860 | 0.1933 | 0.0490 | 0.0209 |
| C.V. | 18.581 | 149.71 | 121.00 | 76.116 | 113.32 |
| MINIMUM | 3.5800 | 0.5000 | 0.6000 | 0.1000 | 0.0600 |
| 1ST QUARTI | 6.0000 | 2.0000 | 2.0000 | 0.4500 | 0.2000 |
| MEDIAN | 6.8200 | 5.0000 | 3.0000 | 0.7500 | 0.4000 |
| 3RD QUARTI | 7.8650 | 8.0000 | 5.2000 | 1.2100 | 0.7000 |
| MAXIMUM | 10.800 | 172.50 | 60.000 | 4.5000 | 6.3000 |

Appendix 2. Descriptive statistics for P-Olsen data clustered according to major soil groupings of the Revised FAO Legend (0-20 cm) ⁶

| Soil type ⁷ | PHWATER | POLSY | ORGC | TOTN | EXK |
|------------------------|---------|--------|--------|--------|--------|
| AR - Arenosols | | | | | |
| N | 190 | 190 | 174 | 7 | 185 |
| MEAN | 6.9183 | 7.2474 | 2.7425 | 0.4114 | 0.2854 |
| SE MEAN | 0.0543 | 0.6912 | 0.1298 | 0.1522 | 0.0182 |
| C.V. | 10.810 | 131.45 | 62.440 | 97.903 | 86.549 |
| MINIMUM | 6.0000 | 2.0000 | 1.0000 | 0.1000 | 0.1000 |
| 1ST QUARTI | 6.3425 | 2.0000 | 1.7500 | 0.2000 | 0.1000 |
| MEDIAN | 6.7000 | 5.0000 | 2.0000 | 0.3000 | 0.2000 |
| 3RD QUARTI | 7.2625 | 7.0625 | 3.2500 | 0.4000 | 0.3100 |
| MAXIMUM | 9.1000 | 67.000 | 14.000 | 1.3000 | 2.4000 |
| CL - Calcisols | | | | | |
| N | 51 | 51 | 49 | 8 | 38 |
| MEAN | 8.0784 | 19.528 | 6.1143 | 1.2413 | 0.8587 |
| SE MEAN | 0.0752 | 7.6858 | 0.4902 | 0.3817 | 0.1114 |
| C.V. | 6.6495 | 281.07 | 56.119 | 86.968 | 79.985 |
| MINIMUM | 6.9300 | 2.0000 | 1.1000 | 0.1500 | 0.1000 |
| 1ST QUARTI | 7.6500 | 5.9500 | 3.5000 | 0.4500 | 0.3875 |
| MEDIAN | 8.1000 | 9.0000 | 5.0000 | 0.7050 | 0.6850 |
| 3RD QUARTI | 8.5500 | 18.000 | 8.8500 | 2.4775 | 1.1000 |
| MAXIMUM | 9.0000 | 399.36 | 17.040 | 2.9000 | 3.2800 |
| CM - Cambisols | | | | | |
| N | 61 | 61 | 60 | 46 | 54 |
| MEAN | 7.9485 | 12.078 | 7.5033 | 1.9959 | 0.9030 |
| SE MEAN | 0.1045 | 1.9047 | 0.7532 | 0.2362 | 0.0850 |
| C.V. | 10.268 | 123.16 | 77.751 | 80.252 | 69.215 |
| MINIMUM | 6.0000 | 2.0000 | 1.5000 | 0.2000 | 0.1000 |
| 1ST QUARTI | 7.4350 | 2.5000 | 3.7475 | 0.7500 | 0.4875 |
| MEDIAN | 8.1000 | 7.0000 | 6.3250 | 1.3050 | 0.7000 |
| 3RD QUARTI | 8.4750 | 14.040 | 9.0625 | 2.9000 | 1.1775 |
| MAXIMUM | 9.7000 | 80.000 | 35.900 | 7.8000 | 3.4200 |
| FL - Fluvisols | | | | | |
| N | 47 | 47 | 45 | 22 | 39 |
| MEAN | 7.9306 | 13.061 | 7.7798 | 1.3277 | 0.7333 |
| SE MEAN | 0.1376 | 1.6206 | 1.5003 | 0.1918 | 0.0745 |
| C.V. | 11.896 | 85.062 | 129.36 | 67.742 | 63.422 |
| MINIMUM | 6.0000 | 2.0000 | 1.6000 | 0.1000 | 0.1000 |
| 1ST QUARTI | 7.1900 | 5.0000 | 3.1400 | 0.5100 | 0.4000 |
| MEDIAN | 8.3000 | 9.0000 | 4.8000 | 1.4500 | 0.7000 |
| 3RD QUARTI | 8.7000 | 18.000 | 7.3750 | 1.9500 | 0.9000 |
| MAXIMUM | 9.3000 | 46.000 | 60.000 | 3.1000 | 2.0000 |

⁶ Limited to point-data for which $\text{pH}_{\text{water}} \geq 6.0$, see text for details (Step 2).

⁷ For details see FAO (1988); results are only shown where n for P-Olsen >30, see text.

GL - Gleysols

| | | | | | |
|------------|--------|--------|--------|--------|--------|
| N | 33 | 33 | 33 | 1 | 33 |
| MEAN | 7.0000 | 10.638 | 15.858 | 0.4100 | 1.3130 |
| SE MEAN | 0.1136 | 1.8078 | 2.0723 | M | 0.1069 |
| C.V. | 9.3250 | 97.624 | 75.069 | M | 46.782 |
| MINIMUM | 6.0300 | 2.0000 | 3.3000 | 0.4100 | 0.1000 |
| 1ST QUARTI | 6.5900 | 5.0000 | 7.7500 | M | 0.9000 |
| MEDIAN | 6.9000 | 8.0000 | 14.000 | 0.4100 | 1.3200 |
| 3RD QUARTI | 7.5200 | 12.375 | 18.500 | M | 1.5000 |
| MAXIMUM | 8.8000 | 50.250 | 59.000 | 0.4100 | 3.1000 |

LV - Luvisols

| | | | | | |
|------------|--------|--------|--------|--------|--------|
| N | 218 | 218 | 195 | 11 | 213 |
| MEAN | 7.0114 | 13.381 | 5.0595 | 1.6009 | 0.5905 |
| SE MEAN | 0.0467 | 0.9681 | 0.3142 | 0.2800 | 0.0332 |
| C.V. | 9.8385 | 106.83 | 86.730 | 57.999 | 82.075 |
| MINIMUM | 6.0000 | 0.6000 | 1.0000 | 0.5000 | 0.1000 |
| 1ST QUARTI | 6.4500 | 5.0000 | 2.7000 | 0.7700 | 0.3000 |
| MEDIAN | 6.8800 | 7.0000 | 4.0000 | 1.3200 | 0.5000 |
| 3RD QUARTI | 7.5000 | 16.000 | 6.0000 | 2.6000 | 0.7000 |
| MAXIMUM | 9.2500 | 89.000 | 30.000 | 3.3100 | 3.1200 |

RG - Regosols

| | | | | | |
|------------|--------|--------|--------|--------|--------|
| N | 53 | 53 | 50 | 20 | 49 |
| MEAN | 7.5408 | 16.739 | 4.3386 | 0.8795 | 0.5788 |
| SE MEAN | 0.1205 | 2.0203 | 0.5699 | 0.2010 | 0.0511 |
| C.V. | 11.633 | 87.870 | 92.886 | 102.21 | 61.862 |
| MINIMUM | 6.0000 | 1.5000 | 0.6700 | 0.1000 | 0.1000 |
| 1ST QUARTI | 6.8250 | 5.9250 | 2.0000 | 0.2000 | 0.3000 |
| MEDIAN | 7.9000 | 14.000 | 2.9250 | 0.4500 | 0.5000 |
| 3RD QUARTI | 8.2000 | 22.875 | 4.7750 | 1.5625 | 0.7000 |
| MAXIMUM | 8.9400 | 76.000 | 16.600 | 3.2000 | 1.6700 |

VR - Vertisols

| | | | | | |
|------------|--------|--------|--------|--------|--------|
| N | 58 | 58 | 58 | 9 | 58 |
| MEAN | 7.2343 | 8.5943 | 6.5474 | 0.9522 | 0.8991 |
| SE MEAN | 0.0966 | 1.3062 | 0.4679 | 0.1590 | 0.0844 |
| C.V. | 10.170 | 115.75 | 54.421 | 50.092 | 71.452 |
| MINIMUM | 6.0500 | 1.0000 | 1.7000 | 0.3800 | 0.0400 |
| 1ST QUARTI | 6.6750 | 3.5000 | 4.0000 | 0.5500 | 0.3000 |
| MEDIAN | 7.2000 | 5.0000 | 5.5000 | 0.9000 | 0.7500 |
| 3RD QUARTI | 7.7000 | 7.9000 | 9.0250 | 1.4150 | 1.4000 |
| MAXIMUM | 9.1200 | 46.000 | 16.560 | 1.7100 | 2.9600 |

Appendix 3. Descriptive statistics for P-Olsen data clustered according to soil units of the FAO-Unesco 1974 Legend (0-20 cm) ⁸

| Soil type ⁹ | PHWATER | POLSY | ORGC | TOTN | EXK |
|------------------------|---------|--------|--------|--------|--------|
| B - Cambisols | | | | | |
| N | 50 | 50 | 49 | 35 | 43 |
| MEAN | 7.9066 | 22.316 | 8.7194 | 1.6674 | 0.9802 |
| SE MEAN | 0.1170 | 8.0038 | 0.8801 | 0.2647 | 0.1092 |
| C.V. | 10.468 | 253.61 | 70.659 | 93.903 | 73.074 |
| MINIMUM | 6.0000 | 2.0000 | 1.7000 | 0.2000 | 0.1000 |
| 1ST QUARTI | 7.4625 | 4.8125 | 5.0000 | 0.7300 | 0.5000 |
| MEDIAN | 8.0650 | 9.0000 | 7.4500 | 1.1000 | 0.7000 |
| 3RD QUARTI | 8.4075 | 18.990 | 10.300 | 2.1200 | 1.2000 |
| MAXIMUM | 9.7000 | 399.36 | 35.900 | 7.8000 | 3.4200 |
| G - Gleysols | | | | | |
| N | 34 | 34 | 34 | 3 | 34 |
| MEAN | 7.0109 | 11.131 | 16.417 | 1.4067 | 1.2521 |
| SE MEAN | 0.1123 | 1.8325 | 2.0648 | 0.5196 | 0.1088 |
| C.V. | 9.3405 | 95.995 | 73.336 | 63.982 | 50.656 |
| MINIMUM | 6.0300 | 2.0000 | 3.0000 | 0.4100 | 0.1000 |
| 1ST QUARTI | 6.6350 | 5.0000 | 7.8750 | 0.4100 | 0.8900 |
| MEDIAN | 6.9000 | 8.0750 | 14.875 | 1.6500 | 1.3000 |
| 3RD QUARTI | 7.5100 | 13.063 | 19.938 | 2.1600 | 1.4850 |
| MAXIMUM | 8.8000 | 50.250 | 59.000 | 2.1600 | 3.1000 |
| J - Fluvisols | | | | | |
| N | 52 | 52 | 50 | 22 | 42 |
| MEAN | 7.8383 | 13.695 | 8.2008 | 1.3277 | 0.7457 |
| SE MEAN | 0.1332 | 1.5493 | 1.3787 | 0.1918 | 0.0744 |
| C.V. | 12.255 | 81.578 | 118.88 | 67.742 | 64.634 |
| MINIMUM | 6.0000 | 2.0000 | 1.6000 | 0.1000 | 0.1000 |
| 1ST QUARTI | 7.0000 | 5.0000 | 3.3450 | 0.5100 | 0.4000 |
| MEDIAN | 8.0000 | 12.000 | 4.9200 | 1.4500 | 0.6850 |
| 3RD QUARTI | 8.6750 | 20.450 | 9.7250 | 1.9500 | 0.9000 |
| MAXIMUM | 9.3000 | 46.000 | 60.000 | 3.1000 | 2.0000 |
| L - Luvisols | | | | | |
| N | 189 | 189 | 180 | 12 | 184 |
| MEAN | 6.9847 | 11.333 | 5.1802 | 1.4858 | 0.6088 |
| SE MEAN | 0.0527 | 0.9509 | 0.3244 | 0.2803 | 0.0393 |
| C.V. | 10.366 | 115.36 | 84.027 | 65.344 | 87.676 |
| MINIMUM | 6.0000 | 0.6000 | 1.0000 | 0.2200 | 0.1000 |
| 1ST QUARTI | 6.4150 | 4.3750 | 3.0000 | 0.7550 | 0.3000 |
| MEDIAN | 6.8300 | 7.0000 | 4.0000 | 1.1850 | 0.4500 |
| 3RD QUARTI | 7.4650 | 13.625 | 6.1875 | 2.4250 | 0.7000 |
| MAXIMUM | 9.2500 | 89.000 | 30.000 | 3.3100 | 3.1200 |

⁸ Limited to point-data for which $\text{pH}_{\text{water}} \geq 6.0$, see text for details (Step 2).

⁹ For details see FAO-Unesco (1974); results are only shown where n for P-Olsen >30, see text.

Q - Arenosols

| | | | | | |
|------------|--------|--------|--------|--------|--------|
| N | 189 | 189 | 173 | 7 | 184 |
| MEAN | 6.9326 | 7.2116 | 2.7035 | 0.4114 | 0.2856 |
| SE MEAN | 0.0544 | 0.6939 | 0.1248 | 0.1522 | 0.0183 |
| C.V. | 10.778 | 132.28 | 60.713 | 97.903 | 86.760 |
| MINIMUM | 6.0000 | 2.0000 | 1.0000 | 0.1000 | 0.1000 |
| 1ST QUARTI | 6.4000 | 2.0000 | 1.7500 | 0.2000 | 0.1000 |
| MEDIAN | 6.7300 | 5.0000 | 2.0000 | 0.3000 | 0.2000 |
| 3RD QUARTI | 7.3000 | 7.0000 | 3.2500 | 0.4000 | 0.3150 |
| MAXIMUM | 9.1000 | 67.000 | 14.000 | 1.3000 | 2.4000 |

R - Regosols

| | | | | | |
|------------|--------|--------|--------|--------|--------|
| N | 65 | 65 | 62 | 22 | 56 |
| MEAN | 7.6946 | 15.304 | 5.3708 | 0.8405 | 0.6407 |
| SE MEAN | 0.1017 | 1.7027 | 0.5272 | 0.1850 | 0.0523 |
| C.V. | 10.656 | 89.701 | 77.295 | 103.25 | 61.054 |
| MINIMUM | 6.0000 | 1.5000 | 0.6700 | 0.1000 | 0.1000 |
| 1ST QUARTI | 7.1500 | 5.9250 | 2.2750 | 0.2000 | 0.3050 |
| MEDIAN | 8.0000 | 12.000 | 3.7300 | 0.4500 | 0.5950 |
| 3RD QUARTI | 8.3000 | 21.000 | 7.6250 | 1.3875 | 0.8000 |
| MAXIMUM | 8.9400 | 76.000 | 16.600 | 3.2000 | 1.6700 |

V - Vertisols

| | | | | | |
|------------|--------|--------|--------|--------|--------|
| N | 58 | 58 | 58 | 9 | 58 |
| MEAN | 7.2343 | 8.5943 | 6.5474 | 0.9522 | 0.8991 |
| SE MEAN | 0.0966 | 1.3062 | 0.4679 | 0.1590 | 0.0844 |
| C.V. | 10.170 | 115.75 | 54.421 | 50.092 | 71.452 |
| MINIMUM | 6.0500 | 1.0000 | 1.7000 | 0.3800 | 0.0400 |
| 1ST QUARTI | 6.6750 | 3.5000 | 4.0000 | 0.5500 | 0.3000 |
| MEDIAN | 7.2000 | 5.0000 | 5.5000 | 0.9000 | 0.7500 |
| 3RD QUARTI | 7.7000 | 7.9000 | 9.0250 | 1.4150 | 1.4000 |
| MAXIMUM | 9.1200 | 46.000 | 16.560 | 1.7100 | 2.9600 |

X - Xerosols

| | | | | | |
|------------|--------|--------|--------|--------|--------|
| N | 63 | 63 | 49 | 12 | 58 |
| MEAN | 7.6603 | 16.060 | 5.0692 | 2.8792 | 0.6347 |
| SE MEAN | 0.1000 | 1.8076 | 0.2560 | 0.3994 | 0.0475 |
| C.V. | 10.364 | 89.336 | 35.349 | 48.053 | 56.954 |
| MINIMUM | 6.0000 | 2.0000 | 3.0000 | 0.6000 | 0.1000 |
| 1ST QUARTI | 6.9300 | 5.0000 | 3.6000 | 2.2650 | 0.3950 |
| MEDIAN | 7.6900 | 11.000 | 4.4000 | 2.8000 | 0.6000 |
| 3RD QUARTI | 8.4000 | 21.750 | 6.0000 | 4.2250 | 0.8000 |
| MAXIMUM | 9.0000 | 53.000 | 10.000 | 4.9000 | 1.8000 |

Y - Yermosols

| | | | | | |
|------------|--------|--------|--------|--------|--------|
| N | 38 | 38 | 38 | 9 | 35 |
| MEAN | 7.3742 | 11.850 | 2.3421 | 1.0900 | 0.5037 |
| SE MEAN | 0.1361 | 1.8238 | 0.1389 | 0.3347 | 0.0511 |
| C.V. | 11.381 | 94.878 | 36.556 | 92.130 | 60.052 |
| MINIMUM | 6.1000 | 2.0000 | 1.0000 | 0.1000 | 0.1000 |
| 1ST QUARTI | 6.7800 | 4.8750 | 1.9500 | 0.2850 | 0.3000 |
| MEDIAN | 7.3000 | 7.4450 | 2.0000 | 0.6000 | 0.4500 |
| 3RD QUARTI | 8.0600 | 14.500 | 3.0000 | 1.8500 | 0.6000 |
| MAXIMUM | 8.9000 | 52.000 | 4.0000 | 3.1000 | 1.3000 |

Appendix 4. Descriptive statistics for P-Olsen data clustered according to broad IPCC soil classes (0-20 cm) ¹⁰

| Soil type ^a | PHWATER | POLSY | ORGC | TOTN | EXK |
|---------------------------------------|---------|--------|--------|--------|--------|
| HAC - High activity clay soils | | | | | |
| N | 579 | 579 | 544 | 139 | 534 |
| MEAN | 7.4893 | 13.835 | 6.4813 | 1.5026 | 0.7314 |
| SE MEAN | 0.0380 | 0.9000 | 0.2593 | 0.1062 | 0.0273 |
| C.V. | 12.217 | 156.53 | 93.322 | 83.315 | 86.094 |
| MINIMUM | 6.0000 | 0.6000 | 0.6700 | 0.1000 | 0.0400 |
| 1ST QUARTI | 6.7700 | 5.0000 | 3.0000 | 0.6000 | 0.3000 |
| MEDIAN | 7.5000 | 7.0000 | 4.7000 | 1.2000 | 0.5500 |
| 3RD QUARTI | 8.2000 | 16.500 | 8.0000 | 2.1000 | 0.9150 |
| MAXIMUM | 10.600 | 399.36 | 60.000 | 7.8000 | 6.1600 |
| LAC - Low activity clay soils | | | | | |
| N | 38 | 38 | 38 | 9 | 38 |
| MEAN | 6.5747 | 10.002 | 6.2003 | 1.5711 | 0.5197 |
| SE MEAN | 0.0765 | 1.6322 | 0.9659 | 0.3740 | 0.0471 |
| C.V. | 7.1757 | 100.60 | 96.027 | 71.415 | 55.912 |
| MINIMUM | 6.0000 | 2.0000 | 2.0000 | 0.2200 | 0.1000 |
| 1ST QUARTI | 6.2200 | 5.0000 | 3.0000 | 0.8750 | 0.3000 |
| MEDIAN | 6.5000 | 7.0000 | 4.0000 | 1.1000 | 0.4750 |
| 3RD QUARTI | 6.7075 | 12.000 | 6.2500 | 2.6500 | 0.7000 |
| MAXIMUM | 8.4000 | 50.000 | 28.420 | 3.5000 | 1.3000 |
| SAN - Sandy soils | | | | | |
| N | 190 | 190 | 174 | 7 | 185 |
| MEAN | 6.9183 | 7.2474 | 2.7425 | 0.4114 | 0.2854 |
| SE MEAN | 0.0543 | 0.6912 | 0.1298 | 0.1522 | 0.0182 |
| C.V. | 10.810 | 131.45 | 62.440 | 97.903 | 86.549 |
| MINIMUM | 6.0000 | 2.0000 | 1.0000 | 0.1000 | 0.1000 |
| 1ST QUARTI | 6.3425 | 2.0000 | 1.7500 | 0.2000 | 0.1000 |
| MEDIAN | 6.7000 | 5.0000 | 2.0000 | 0.3000 | 0.2000 |
| 3RD QUARTI | 7.2625 | 7.0625 | 3.2500 | 0.4000 | 0.3100 |
| MAXIMUM | 9.1000 | 67.000 | 14.000 | 1.3000 | 2.4000 |
| WET - Wetland soils | | | | | |
| N | 33 | 33 | 33 | 1 | 33 |
| MEAN | 7.0000 | 10.638 | 15.858 | 0.4100 | 1.3130 |
| SE MEAN | 0.1136 | 1.8078 | 2.0723 | M | 0.1069 |
| C.V. | 9.3250 | 97.624 | 75.069 | M | 46.782 |
| MINIMUM | 6.0300 | 2.0000 | 3.3000 | 0.4100 | 0.1000 |
| 1ST QUARTI | 6.5900 | 5.0000 | 7.7500 | M | 0.9000 |
| MEDIAN | 6.9000 | 8.0000 | 14.000 | 0.4100 | 1.3200 |
| 3RD QUARTI | 7.5200 | 12.375 | 18.500 | M | 1.5000 |
| MAXIMUM | 8.8000 | 50.250 | 59.000 | 0.4100 | 3.1000 |

^a Criteria for defining broad IPCC soil classes may be found in IPCC (1996, p. 3.41), see also Batjes (2009b). In this study, Sandy soils have been assumed to correspond with Arenosols. The Spodic, Volcanic and Organic class are not represented in the present soil data set, partly due to limited data availability resp. pH boundary conditions for applying the Olsen method not being met.

¹⁰ Limited to point-data for which pH_{water} ≥ 6.0, see text for details (Step 2).



World Soil Information

ISRIC - World Soil Information is an independent foundation with a global mandate, funded by the Netherlands Government, and with a strategic association with Wageningen University and Research Centre.

Our aims:

- To inform and educate - through the World Soil Museum, public information, discussion and publication*
- As ICSU World Data Centre for Soils, to serve the scientific community as custodian of global soil information*
- To undertake applied research on land and water resources*