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Inventory of P-Olsen data in the ISRIC-WISE soil database for use with QUEFTS

(Version 1.0)

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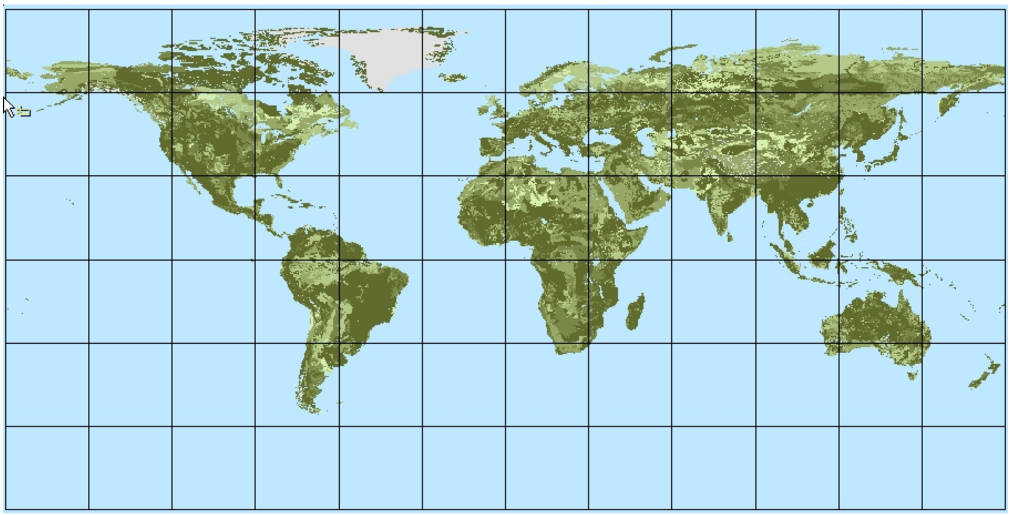
(May 2010)



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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.

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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.

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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-sorbtion 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.

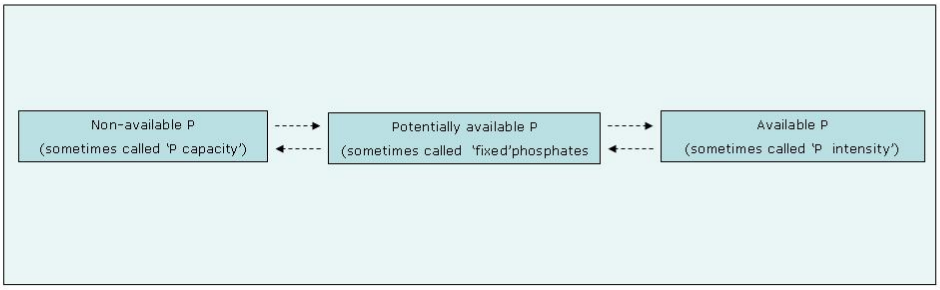

Figure 1. Schematic representation of P present in soil (After: Landon 1991)

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, *Olsen*, Water, IIP and AER
Alkaline, calcareous	> 7.2	Ca-P and Mg-P	*Olsen*, Water, IIP and AER

In acidic soils, defined here as pH_{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 8.0[1]; 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-variates 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 $pH_{water} \geq 6.0$, 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_4F)
PA03	Olsen (0.5 M $NaHCO_3$ at pH 8.5)
PA04	Truog (dilute H_2SO_4)
PA05	Morgan (Na-acetate/acetic acid)
PA06	Saunders and Metelerkamp (anion-exch. resin)
PA07	Bray II (dilute HCl/NH_4F)
PA08	Modified after ISFEI method, A.H. Hunter (1975)
PA09	Nelson (dilute HCl/H_2SO_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_2SO_4)
PA13	Colorimetric in 0.02 N H_2SO_4 extract, molybdenum blue method
PA14	Dabin (ORSTOM), modified Olsen method for tropical soils (0.5 N $NaHCO_3$ + 0.5 N NH_4F buffered to pH 8.5 by NaOH)
PA15	Kurtz-Bray I (0.025 M HCl + 0.03 M NH_4F)
PA16	Complexation with citric acid (van Renwick)
PA17	NH_4-lactate extraction method (KU-Leuven)
PA18	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 pH_{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 pH_{water} ≥ 6.0; see text for details. P-Olsen is given in mg P_2O_5 kg^{-1}, organic C in g kg^{-1}, total nitrogen in g N kg^{-1}, and exchangeable K in $cmol_c$ kg^{-1}. Decimal places are shown as generated by Statistix 7 (Analytical Software 2000) and may suggest false accuracy; this is 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 projects[2] 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 g kg^{-1}, P-Olsen[3] ≤ 30 mg kg^{-1}, and exchangeable potassium < 30 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 pH_{water} ≥ 6.0 (Elrashidi 2010). The corresponding section of the world is shown in Figure 3, using proportional classes.

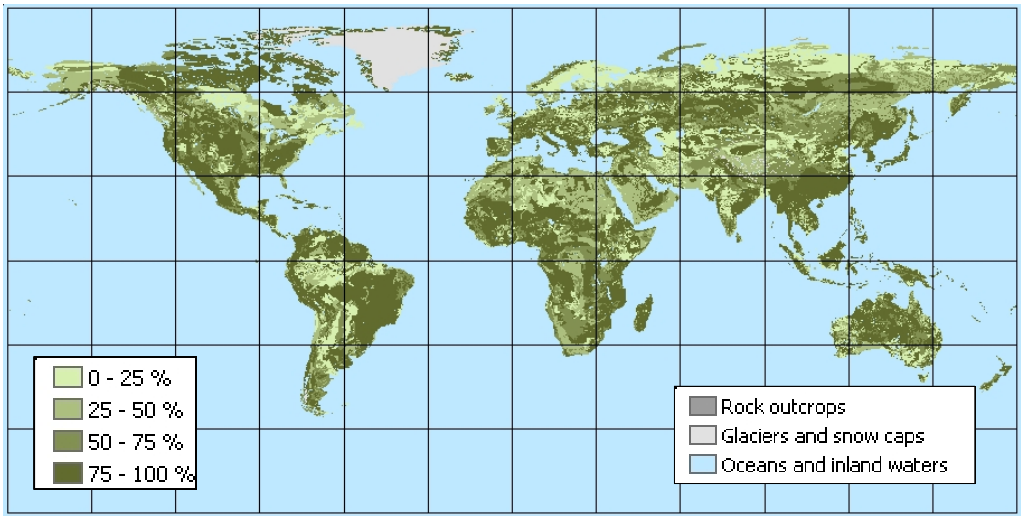

Figure 2. Proportion of the world meeting current QUEFTS boundary conditions for soil drainage class, pH_{water} and soil organic carbon content (0-20 cm)

[3] In this study, P-Olsen values are given as mg P_2O_5 kg^{-1} (i.e. 2.29 * P)

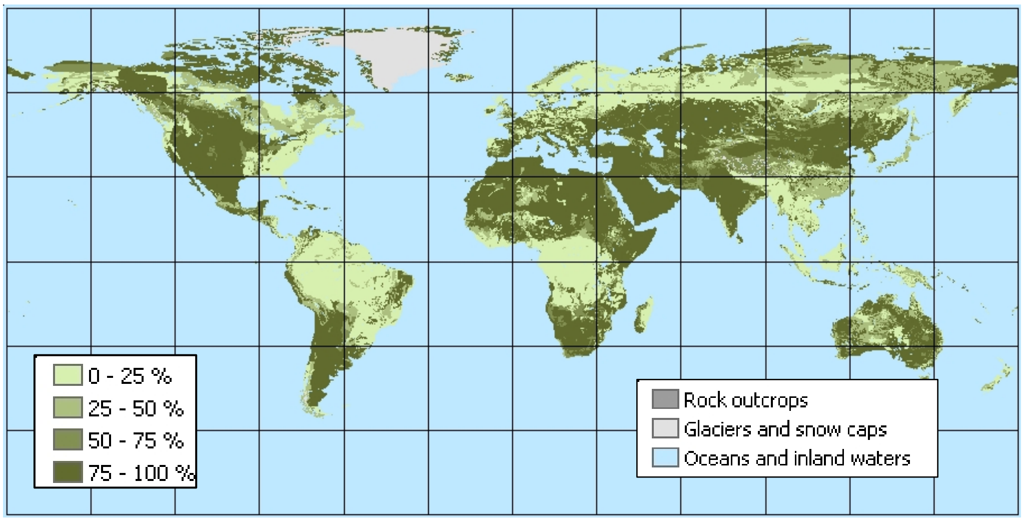

Figure 3. Global distribution of soils for which the P-Olsen method is recommended ($pH_{water} \geq 6.0$, for 0-20 cm); lighter colours indicate a predominance of acid soils.

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.

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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_2O_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.

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[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 $pH_{water} \geq 6.0$. 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 $pH_{water} \geq 6.0$ (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]

D1 (0-20 cm)	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

D2 (20-40 cm)	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 $pH_{water} \geq 6.0$, 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 $pH_{water} \geq 6.0$, 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 $pH_{water} \geq 6.0$, see text for details (Step 2).