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THE EFFICIENCY OF DIFFERENT ESTIMATION METHODS OF HYDRO-PHYSICAL LIMITS[1]

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SUMMARY

The soil water available to crops is defined by specific values of water potential limits. Underlying the estimation of hydro-physical limits, identified as permanent wilting point (PWP) and field capacity (FC), is the selection of a suitable method based on a multi-criteria analysis that is not always clear and defined. In this kind of analysis, the time required for measurements must be taken into consideration as well as other external measurement factors, e.g., the reliability and suitability of the study area, measurement uncertainty, cost, effort and labour invested. In this paper, the efficiency of different methods for determining hydro-physical limits is evaluated by using indices that allow for the calculation of efficiency in terms of effort and cost. The analysis evaluates both direct determination methods (pressure plate - PP and water activity meter - WAM) and indirect estimation methods (pedotransfer functions - PTFs). The PTFs must be validated for the area of interest before use, but the time and cost associated with this validation are not included in the cost of analysis. Compared to the other methods, the combined use of PP and WAM to determine hydro-physical limits differs significantly in time and cost required and quality of information. For direct methods, increasing sample size significantly reduces cost and time. This paper assesses the effectiveness of combining a general analysis based on efficiency indices and more specific analyses based on the different influencing factors, which were considered separately so as not to mask potential benefits or drawbacks that are not evidenced in efficiency estimation.

Index terms: field capacity, permanent wilting point, pedotransfer functions, water activity meter.

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RESUMO: *EFICIÊNCIA DE DIFERENTES MÉTODOS NA ESTIMATIVA DOS LIMITES FÍSICO-HÍDRICOS*

A quantidade de água no solo está disponível para as culturas de acordo com os limites de valores específicos do potencial da água. A determinação dos limites hidrofísicos, identificada como ponto de murcha permanente (permanent wilting point - PWP) e capacidade de campo (field capacity - FC), envolve a escolha de um método adequado com base numa análise multicritérios que nem sempre é bem clara e definida. Essa análise deve considerar o tempo necessário para realizar as medições, bem como outros fatores externos à prática da medição, entre os quais a confiabilidade e adequação da área de estudo, incerteza da medição, custo, esforço e trabalho necessários. Neste ensaio, a eficiência dos diversos métodos de determinação dos limites hidrofísicos (pontos da curva de retenção da água no solo) é avaliada com base em índices que permitem o cálculo da eficiência em termos de esforço e custo. Avaliaram-se métodos de determinação diretos (câmaras de pressão - PP e psicrômetro modelo WP4) e também métodos de estimativa indireta (funções de pedotransferência - PTFs). As PTFs devem ser validadas para cada área em estudo antes da sua aplicação, porém o tempo e o custo associados com essa validação não estão incluídos no custo da análise. Quando comparada com os demais métodos, a utilização combinada dos métodos de PP e WAM para determinação dos limites hidrofísicos resulta em diferenças significativas em termos de tempo, custo e qualidade da informação. No que concerne aos métodos diretos, o aumento do tamanho da amostra reduz significativamente o custo e o tempo. O presente ensaio avaliou a eficácia na combinação de uma análise geral com base em índices de eficiência e análises mais específicas baseadas em diferentes fatores de influência, que foram considerados separadamente com o intuito de não ocultar eventuais benefícios ou desvantagens não evidenciadas na eficiência da determinação.

Termos de indexação: capacidade de campo, ponto de murcha permanente, funções de pedotransferência, psicrômetro WP4.

INTRODUCTION

In the context of water resource management, various methods have been used to obtain or determine soil hydraulic properties, particularly hydrolimits (Štekauerová et al., 2002) or hydro-physical limits (Oliveira et al., 2004; Gontijo et al., 2008) from properties that can be easily measured and quantified. Such methods facilitate and shorten the measurement process. Hydro-physical limits are defined as the upper and lower limits of water available to plants, understood as the water content between field capacity (FC) and permanent wilting point (PWP) (Orfanus & Mikulec, 2005). A variety of methods can be used to determine soil hydraulic properties based on approaches such as the determination of water content or water potential. The available methods have been classified by a number of authors (Tarjuelo, 1995; Fuentes, 1998; Villar & Ferrer, 2005; Martínez, 2008). Some methods directly measure soil hydraulic properties using gravimetric analysis, the instantaneous profile method, time domain reflectometry (TDR), frequency domain reflectometry (FDR), lysimeters, tensiometers, heat dissipation sensors, pressure plates (PP) or water activity meters (WAM), among others (Watson, 1966; Cancela et al., 2006a; Souto et al., 2008). In contrast, other methods are based on the estimation of hydro-physical limits from other parameters. Such methods are termed indirect estimation methods (pedotransfer functions - PTF) (Mualem, 1976; Vereecken, 1988; Wösten et al., 1995; Minasny et al., 1999; Tomasella et al., 2003).

Because the hydro-physical properties of the soil vary in space (Nielsen et al., 1973; Greco & Vieira, 2005), a large number of samples are required to represent the reality, and the associated measurement processes are time-consuming, difficult and expensive.

The methods used to quantify soil hydraulic properties can be divided into: i) determination with pressure plate (PP) (Richards & Fireman, 1943; Tormena et al., 1998) or WP4 water activity meters (WAMs) (Gee et al., 1992; Albuquerque et al., 2005; Martínez, 2008) and ii) estimation with pedotransfer functions (PTF) (Bouma, 1989; McBratney et al., 2002) or software applications (Donatelli et al., 1996; Acutis & Donatelli, 2003).

Minasny & McBratney (2002) defined a concept of efficiency and developed it in later research (Minasny et al., 2003). They related efficiency to the greatest certainty in order to minimise cost and effort. The key features of the concept are the inputs required and the economic interest of measuring efficiency.

A number of authors, e.g., Gee et al. (1992), Vereecken et al. (1992), Marion et al. (1994), Minasny et al. (1999) and, more recently, Turner et al. (2000), Christiaens & Feyen (2001) and Rajkai et al. (2004), compared different methods to measure efficiency. However, only a few authors have quantitatively assessed the efficiency of these methods in detail

(Minasny, 2000; Minasny & McBratney, 2002; Rubio, 2005; Rubio et al., 2008). Consequently, only a few methods have been analysed and compared in terms of efficiency.

The selection of a particular method is based on a multi-criteria analysis that considers ease of use, amount of time required to perform measurements (Rodriguez, 2004) and other external measurement conditions (Cancela et al., 2006a; Martínez & Cancela, 2011), reliability of results and suitability for the study area, measurement uncertainty, cost, effort and labour needed (Martínez et al., 2010b). Accordingly, an assessment of the efficiency of the methods used is essential.

The objective of this research was to compare the efficiencies of the methods used to estimate soil hydraulic properties of an irrigated area of the region of Terra Cha (Galicia, Spain). The evaluated methods comprise the most commonly cited methods for the study area: direct determination methods based on laboratory measurements using PP and WAM, and indirect estimation methods such as the PTF developed by Soto et al. (2001), PTFs specific to the study area, and a PTF available from software SOILPAR 2.00 (Acutis & Donatelli, 2003). This comparison addresses the suitability of these methods to determine or estimate hydro-physical limits based on effort and cost required. Specifically, the objectives of this research are: to analyse and assess the methods in terms of effort, cost and quality of information and to analyse the effects of the sample size considered in the analysis.

MATERIAL AND METHODS

Description of the area

Soil samples were collected from an irrigated area in the region of Terra Cha, Galicia, northwestern Spain (Cancela et al., 2004; Cancela et al., 2006b) (Figure 1a). The Terra Cha region, with an average elevation of 420 m asl, is an area with little topographic contrast and the headwater catchment of the Miño River. The study of the soils and geomorphology of the area is based on earlier studies (Castelao, 1989).

The parent materials are tertiary sediments and recent alluvial sediments. According to the FAO classification, three soil types can be distinguished: Fluvisols, Gleysols and Cambisols. Fluvisols are mostly found near riverbeds, in contrast to the hydromorphic features of Cambisols, characterised by steeper slopes. Compared to the other soil types, Gleysols are located in areas with steeper slopes. In the study area, soils have a limited depth with an impermeable layer at 40 cm depth and are distributed as follows: 68 % Cambisols, 22 % Gleysols and 10 % Fluvisols (Castelao & Díaz-Fierros, 1992; Álvarez et al., 2005).

Sampling design

Given the spatial variability, the soil properties were analysed based on a systematic random sampling, which was considered the most suitable method for sample collection. A 500 m square mesh that covered the study area and comprised 83 nodes was generated. From among these nodes, 24 mesh points were initially selected (Figure 1b). Field sampling points were determined by a global positioning system device in two periods in 2002 and 2003, under similar climatic conditions.

Laboratory analysis techniques

The values of bulk density and texture at each mesh point were determined, and the type of soil and crop was recorded (Tables 1 and 2). In keeping with studies by Cancela (2004), the bulk density test for gravelly and rocky soils proposed by USDA (2004) was used to determine bulk density because the soil was stony; the coarse fraction was high and it was impossible to use a method with soil samples that would preserve the soil structure. Soil particle-size distribution (sand, silt and clay) was determined by standard methods (MAPA, 1995). Organic matter and organic carbon contents were determined by a modified Sauerlandt method (Guitián & Carballás, 1976).

Undisturbed samples collected from the upper 20 cm of soil with a 4 cm diameter core sampler were used (Cancela, 2004). The samples were homogenised and sieved (2 mm), and the fine fraction of the samples was used for the analyses and for measurements with PP and WAM.

The selection of disturbed or undisturbed samples is not a defining characteristic of either method (PP or WAM) (Wraith & Or, 2001). Using disturbed samples minimises the difficulties of establishing optimum contact between the plate and the sample, thus eliminating measurement variations caused by structural differences in the samples and allowing for the extrapolation of results to samples with similar textures (Lal, 1979). Richards & Fireman (1943) dissented from this approach in tests of dry and wet samples whose structure was disturbed either manually or by sieving. Yet, in our research disturbed samples were used, based on previous studies for the same area (Cancela, 2004; Martínez, 2008).

Methods used to determine soil hydraulic properties

To determine soil hydraulic properties, PP (Soil Moisture Equipment Corp, Santa Barbara CA) and WAM (WP4 Dewpoint Potentia Meter, Decagon Device, Inc) were used for direct laboratory measurements, whereas PTF and the SOILPAR 2.0 software application were used for indirect estimations (Acutis & Donatelli, 2003).

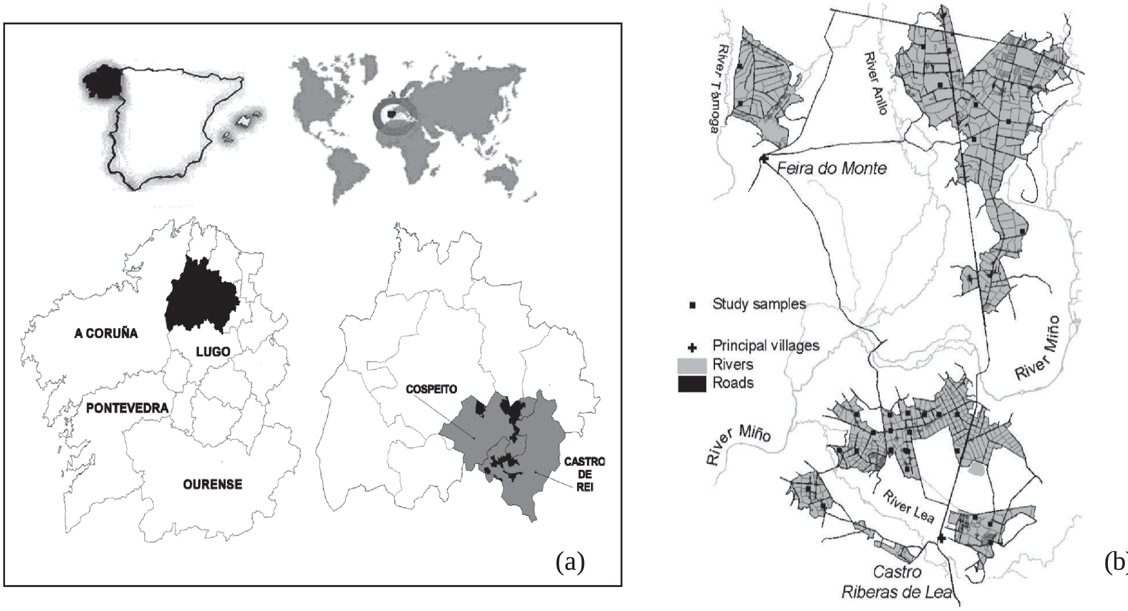

Figure 1. a) Location of "Terra Cha" in Galicia and b) Network of soil sampling.

Table 1. Statistical summary of soil variables

Descriptive statistic	BD	Sand	Silt	Clay	pH (H_2O)	pH (KCl)	OC	OM
	kg dm^{-3}	——	%	——			—— %	——
Minimum	0.7	29.5	15.1	13.5	4.3	3.8	1.9	3.3
Maximum	1.3	71.4	32.8	54.5	6.5	6.1	5.5	9.5
Arithmetic mean	1.0	53.3	23.5	23.1	5.4	4.8	3.7	6.4
Standard deviation	0.2	0.6	4.4	8.5	0.5	0.0	0.9	1.6
n	24	24	24	24	24	24	24	24

BD: Bulk density; pH (H_2O): pH in water; pH KCl: pH in 1 mol L^{-1} potassium chloride; OC: Organic carbon content; OM: Organic matter content.

Table 2. Distribution of crops per soil type

Soil type	Number of samples per crop		
	Corn	Grassland	Total
Cambisol	2 (66.6 %)	11 (52.4 %)	13 (54.2 %)
Gleysol	-	6 (28.6 %)	6 (25.0 %)
Fluvisol	1 (33.3 %)	4 (19.0 %)	5 (20.8 %)
Total	3	21	24

The WP4 is based on the chilled mirror dew-point technique (Gee et al., 1992; Scanlon et al., 1997, Martínez et al., 2011) and is used to determine PWP. With this instrument and assuming that the osmotic potential due to dissolved salts in the soil solution is negligible as compared with matric forces, the tension of soil water potential can be determined using the Kelvin equation (Rawlins & Campbell, 1986). The method of analysis followed to obtain the relationship between water potential and water content involved the use of samples sieved through a 2-mm sieve and wetted with increasing amounts of water, so that four treatments per sample were applied with the following moisture contents by weight: 5, 10, 15 and 20 %. To measure the moisture series that corresponded to each sample, the samples were transferred to cylindrical cups whose characteristics made them suitable for use with the water activity meter. Four consecutive readings of soil water tension were taken for each moisture content by weighing. To analyse the results, the arithmetic mean of the readings was calculated. For each sample, 16 readings were taken. After each moisture percent was measured, the cup was taken out of the water activity meter and weighed.

Complementary soil water content determinations were carried out with the PP according to the following method: soil samples were placed on a porous plate (12 samples per batch), fixed by 2 cm high rings (Black et al., 1965). Then the samples and plate were saturated with water for 24 h. Once the porous plate and the samples were completely saturated with water, the plate was installed and nitrogen pressure was used to extract moisture from soil samples under controlled conditions. The vessel for FC determination (0.033 MPa) has space for two plates (24 samples) at a time, whereas only one plate (12 samples) can be placed in the vessel for PWP determination (1.55 MPa). The samples were allowed to stand on the plate 24 h for FC determination and 72 h for PWP. For PWP determination, pressure was gradually applied for 12 h before measurements. As soon as nitrogen pressure was raised above atmospheric pressure, the higher pressure inside the chamber forced excess water through the microscopic pores in the ceramic plate, and through the outflow tube towards the outlet of the pressure plate. During an extraction run at a given air pressure in the extractor, soil moisture flowed from around each of the soil particles and out through the plate until the curvature of the water film throughout the soil was the same as the pores in the plate. When this occurred, equilibrium was reached and the water flow ceased. Wet samples were weighed after removal from the plate and oven-dried at 105 °C during 24 h. Then, samples were weighed again, and water content was obtained. Considering that the samples used were disturbed samples and that only the fine fraction was taken (<2 mm), a correction factor (Equation 1) was included to estimate gravimetric water content (Cancela et al., 2006a). The coarse fraction (>2 mm) was considered to have an almost zero contribution to water content at PWP (Tokunaga et al., 2003):

$$w = \frac{(m_{f,w} - m_{f,d})}{m_{f,d}\left(1 + \frac{F_c}{F_f}\right)} \tag{1}$$

where w is the gravimetric water content in g g^{-1}; $m_{f,w}$ and $m_{f,d}$ are the wet and dry masses of the fine fraction in g; and F_c and F_f are the coarse and fine fraction in % by weight.

In the case of the WAM, the gravimetric water content considering the coarse fraction of the sample was obtained by introducing the correction factor. During data analysis, water potential in MPa was represented against gravimetric water content in g g^{-1}, and the coefficients of the potential equation (Equation 2) that best fitted each scattergram were calculated by estimating the coefficient of determination r^2, with values above 0.74 at the 24 analysed points.

$$h = aw^{-b} \tag{2}$$

where: h is the soil water potential in MPa; w is the gravimetric water content in g g^{-1}; and a and b are shape parameters.

Given that the accuracy of the WAM (0.10 MPa) was not considered suitable for FC determination (Martínez, 2008), PWP was determined with both WAM and PP, whereas FC was determined with PP only.

The estimation methods used in this research comprised PTFs obtained by SOILPAR 2.00 (Acutis & Donatelli, 2003), PTFs obtained by multiple linear regression for the region of Galicia by Soto et al. (2001) (PTF1) and PTFs developed for the study area (Terra Cha) by Martínez et al. (2010a) (PTF2 to PTF11). The results of Martínez et al. (2010b) indicate the suitability of SOILPAR 2.00 to obtain PWP estimates for the study area by two approaches: i) using values obtained from PP with the 'EPIC' method (Erosion Productivity Impact Calculator) (Izaurralde et al., 2001) (r^2=0.79) or ii) using values obtained by WAM with the 'Mayr-Jarvis' method (Mayr & Jarvis, 1999) (r^2=0.81). The following PTFs were analysed: i) the PTF1 proposed by Soto et al. (2001) for the region of Galicia (r^2=0.65) and ii) PTFs specific to the study area for different categories (soil type, crop and sampling depth) (Martínez, 2008) (Table 3). For the analysis of PTFs specific to the study area, all equations with r^2 >0.84 were chosen, which comprised PTFs that included only a few parameters (more general) and PTFs that included a large number of parameters for the area of interest (more specific).

Of the methods considered in the analysis, PP, and WAM, the PTF developed by Soto et al. (2001), specific PFTs and SOILPAR 2.00 were assessed in terms of efficiency of PWP determination. In contrast, only PP and specific PTFs were assessed for FC determination because of their suitability for this purpose.

Efficiency analysis

The efficiency of the different methods was analysed under the assumption that the level of information used is associated with considerable human effort and cost of obtaining the information, which involves hiring labour. These factors are included in the efficiency indices proposed by Minasny (2000) and Minasny & McBratney (2002):

Efficiency in terms of effort:

Efficiency = quality of information/effort (3)

Efficiency in terms of cost:

Efficiency = quality of information/cost of information (4)

The quality of information is evaluated by the standard deviation of the predicted soil hydraulic properties as a result of the uncertainty of the measurements; effort describes the time required to make the measurements or obtain the information, and cost is associated with the price of the measurements and/or acquiring information.

To analyse the effects of the number of samples on each method, a modification of the index proposed by Rubio (2005) was used (Equation 5); three sample sizes were considered: 5, 50 and 100 samples.

$$E = Ee + \frac{Ef}{n} \tag{5}$$

Table 3. Features of the specific pedotransfer functions (PTFs) proposed in different areas, soil type, sampling depth, crop type, devices used (water activity meters - WAM or pressure plates - PP), and estimated properties (EP) (permanent wilting point - PWP or field capacity - FC)

PTF	Device used	EP	Equation	r^2
			Whole Galicia area	
1	-	PWP	PWP = 0.376Cl + 6.39	0.65
			Whole study area	
2	WAM	PWP	$PWP = -0.18 + 2\ 10^{-3}\ Cl + 0.08\ BD + 1\ 10^{-3}\ FF + 5\ 10^{-3}\ OM - 5\ 10^{-3}\ MO$	0.93
3	PP	PWP	$PWP = -0.02 + 4\ 10^{-3}\ Cl + 0{,}02\ OC + 0.11\ BD - 2\ 10^{-3}\ Si - 1\ 10^{-3}\ FF$	0.93
			Cambisol	
4	WAM	PWP	$PWP = 0.06 + 2\ 10^{-3}\ FF - 0.02\ BD - 6\ 10^{-3}\ Si - 4.76\ 10^{-5}\ Cl + 0.05\ pH\_W - 0.04\ pH\_CL - 1\ 10^{-3}\ OM - 1\ 10^{-3}\ Z$	0.95
			Gleysol	
5	PP	PWP	$PWP = 0.38 - 8\ 10^{-3}\ Z - 2\ 10^{-3}\ Si + 510^{-3}\ Cl - 0.02\ pH\_CL + 0.02\ OM$	0.99
6	PP	FC	$FC = 3.36 + 0.09\ BD + 9.68\ 10^{-5}\ Cl - 6\ 10^{-3}\ Si + - 0.62\ pH\_W + 0.11\ OM$	0.99
			25-40 cm depth	
7	WAM	PWP	$PWP = 0.08 - 1.30\ 10^{-4}\ CF + 0.11\ BD - 6\ 10^{-3}\ Z + 1\ 10^{-3}\ Si - 2.7\ 10^{-4}\ Cl + 0.04\ pH\_W - 0.03\ pH\_CL - 3\ 10^{-3}\ OM$	0.99
8	PP	PWP	$PWP = 0.24 + 2.03\ 10^{-4}\ CF + 0.08\ BD - 2\ 10^{-3}\ Cl - 2\ 10^{-3}\ Si - 0.12\ pH\_W + 0.11\ pH\_CL + 0.01\ OM$	0.97
			40-55 cm depth	
9	PP	FC	$FC = -2.79 + 4\ 10^{-3}\ \mathrm{Cl} + 0.01\ Si + 0.72\ BD + 0.33\ pH\_W + 0.08\ OC$	0.84
			Corn	
10	PP	PWP	$PWP = 0.15 - 2\ 10^{-3}\ Sa + 7\ 10^{-3}\ OM$	0.99
			Grassland	
11	WAM	PWP	$PWP = -0.08 - 2\ 10^{-3}\ CF + 0.08\ BD - 1\ 10^{-3}\ Si + 2\ 10^{-3}\ Cl + 1\ 10^{-3}\ pH\_W + 5\ 10^{-3}\ pH\_CL + 5\ 10^{-3}\ OM$	0.96

WAM: Water activity meter; PP: Pressure plate; PWP: Permanent wilting point ($cm^3\ cm^{-3}$) (1.55 MPa); FC: Field capacity ($cm^3\ cm^{-3}$) (0.033 MPa). Cl: Clay content (%), BD: Bulk density, FF: Fine fraction (%) (<2 mm), CF: Coarse fraction (%) (>2mm), OM: Organic matter (%), OC: Organic carbon (%), Si: Silt content (%) Sa: Sand content (%), PH_W: pH (H_2O), PH_CL: pH in chloride, Z: Rooting depth (cm).

where E is the effort per sample generated by the method (h); Ef is the fixed effort needed to develop the method (laboratory work for 24 samples) (h, sample); Ee is the specific effort needed to determine soil properties for each sample (h); n is the number of samples considered.

The 'fixed effort' (E_f) is derived from laboratory work and includes the time required to directly determine soil hydraulic properties by PP and WAM and the time used for introducing the soil properties required for indirect measurements in the database (texture, BD, pH H_2O, pH KCl, OC, OM, and Z). The 'specific effort' (E_e) is defined as the effort required to determine soil properties for each sample. In estimation methods, the specific effort includes the time required to measure texture, BD, pH (H_2O), pH (KCl), OC, OM, and Z. Consequently, it has been assumed that direct determination methods do not require specific effort and that the whole time required for measurements corresponds to fixed effort. On the contrary, the analysis of estimation methods considers both fixed and specific effort. Basically, specific effort is the focus of this analysis.

Efficiency parameters: effort and cost

Effort was quantified by determining the time needed for determination/estimation protocols. It was assumed that some steps, such as sample collection, drying or 2-mm sieving, were common to both protocols. Accordingly, these steps were neglected in the efficiency assessment for making no difference. Based on Cancela et al. (2006a) and Martínez (2008), the time required for WAM determinations was set at 4.5 h/sample whereas the times required by PP were set at 9 h/sample for PWP and 3 h/sample for FC, for the number of samples considered in this research (n=24).

The time required for the determination of soil properties (Table 4) was defined according to the number of samples, considering an 8-hour workday, and according to the protocols for the determination of properties.

In each protocol, as is the case for textural analysis, the fraction of time required for each determination in relation to total time was considered. The two estimation methods based on the use of SOILPAR 2.00 required knowledge of the percent

Table 4. Times required for the determination of soil properties (n=24)

Property	Time needed, h
Texture	230.4
Organic Matter (OM)	38.4
Organic Content (OC)	38.4
pH (H_2O)	2.0
pH (KCl)	2.0
Bulk density (BD)	24.0
Sampling	6.0

distribution of soil texture classes, and of BD. In addition, the 'Mayr-Jarvis' equation required knowledge of OC. In specific PTFs and in the PTF developed by Soto et al. (2001), effort was determined from the properties considered in the estimation. Estimation methods computed an additional time of 2 h, which was required to feed the information pertaining to the 24 samples into the software database.

Costs were estimated based on the operations required for each method assuming two possible approaches: i) estimation as a function of the cost of hiring staff or ii) estimation as a function of the cost of laboratory analyses. The cost of hiring staff was determined based on the salary of a research assistant at the University of Santiago de Compostela - Spain, set at 6.30 € h^{-1}. The cost of laboratory analysis was determined based on the cost of analysis indicated by a regional research centre, *Centro de Investigaciones Agrarias de Mabegondo* (14.31 €/sample for soil texture, 32.94 €/sample for pH (H_2O), 43.92 €/sample for pH (KCl) and 65.88 €/sample for the determination of OM content and OC content). Some soil properties, such as sampling depth (Z) or bulk density (BD) were computed from the cost of hiring staff to make field measurements and the time needed by that person to perform the measurements. Accordingly, the cost of field measurements was added to the cost of laboratory analysis for the properties required, according to the PTF used.

Statistical Analysis

The SPSS 19 package was used to perform analyses of variance (ANOVA) for the different determination/estimation methods using the following dependent variables: time, cost of staff and cost of analysis. Post-hoc tests were conducted to define homogeneous subgroups (HSD Tukey) at a significance level of $\alpha = 0.05$.

RESULTS

Determination of efficiency-related parameters: effort, cost and quality of information

Table 5 summarizes the results of the three parameters (effort, cost and quality of information). To determine effort, it was assumed that direct and estimation methods share some phases. Consequently, these phases were not considered in the analysis because they do not produce differences between methods.

For PP, the time needed to determine PWP was computed considering an equilibration time of 3 days, which is in agreement with the recommendations made by Klute (1986), who suggested using an equilibration time of 2 to 3 days. Direct determination methods required shorter times for PWP determination. WAM determinations needed the shortest time, 108 h, which accounts for half the hours needed for PWP determination by PP (216 h). Post-hoc tests revealed significant differences.

Of the estimation methods, the PTF proposed by Soto et al. (2001), PTF1, required the least effort (time) because its application depends on clay content data only. Yet, PTF1 is too general, for having been developed for the whole territory of Galicia. The equations proposed by Martínez et al. (2010a) required efforts between 262.8 h (PTF 6 and 9) for FC determination and 304.8 h (PTF4 and 7) for PWP. These equations require knowledge of a larger number of parameters, but texture is determined together with the coarse and fine fractions, silt, sand, and clay. Consequently, the time needed is longer when a larger number of parameters or when other parameters are required, as is the case for PTF4. In contrast, PTF 10 requires sand content data only for textural analysis. With this method, the time needed to obtain estimates decreases in relation to the total time required to obtain the estimates for textural analysis because sand content is not the property that is determined last by the pipette method, which was the analysis method used (Guitián & Carballás, 1976).

Both PTF8 and PTF11 needed 298.8 h, 4 h more than PTF2 and PTF3, which took 294.8 h, equal to the Mayr-Jarvis method. Of the other models of the SOILPAR 2.00 software, the EPIC model reduced the time required by 13 % (256.4 h). Therefore, compared to WAM, the increase in the time required by PTFs and SOILPAR ranged from 130 to 182 %.

To determine FC, 72 h were needed by PP. This short time results from the possibility of placing two plates in the pressure vessel. PTF6 and PTF9 required the same time for analysis, so that no significant differences between them were found in terms of effort ($p<0.05$).

Because FC and PWP determinations by PP and WAM require hiring staff, the staff cost must be added to the cost of analysis. The cost of hiring staff depends on the approach used (i.e., 680.04 € for WAM, 1360.80 € for PWP determination by PP and 453.6 € for FC determination by PP). Because the time required to determine PWP by PP increases costs by 100 % in relation to WAM, the best option for the determination of hydro-physical limits in terms of cost combines both

Table 5. Efficiency-related parameters (n=24)

Estimated property	Method	Time	Staff cost	Analysis cost	Standard deviation
		h	€		MPa
	WAM	108.0	680.04	680.04	0.031
	PP	216.0	1360.80	1360.80	0.053
	PTF1	232.4	1464.12	356.04	0.033
	PTF2	294.8	1857.24	2088.36	0.029
	PTF3	294.8	1857.24	2088.36	0.051
PWP	PTF4	304.8	1920.24	3958.20	0.028
	PTF5	278.8	1756.44	3029.04	0.081
	PTF7	304.8	1920.24	3970.80	0.042
	PTF8	298.8	1882.44	3920.40	0.041
	PTF10	262.8	1655.64	1937.16	0.020
	PTF11	298.8	1882.44	3920.40	0.033
	EPIC	256.4	1615.32	507.24	0.063
	Mayr-Jarvis	294.8	1857.24	2088.36	0.014
	PP	72.0	453.60	453.60	0.210
FC	PTF6	296.8	1869.84	2878.92	0.397
	PTF9	296.8	1869.84	2878.92	0.239

methods (WAM for PWP and PP for FC). For the most general PTFs that require only one soil property, PTF1 and EPIC, costs increase if the analysis is not conducted in commercial laboratories. For the other estimation methods considered, hiring staff is cheaper because of the high cost of analytical determinations. Costs would increase between 218 € and 2,037 € for PWP and would be about 1,000 € for the PTFs used for FC estimation.

The software SOILPAR 2.00 produced the best results for PWP determination in terms of quality of information. With a standard deviation of 0.014 $cm^3\ cm^{-3}$, the Mayr-Jarvis method produced the most reliable and PTF5 the poorest results (0.081 $cm^3\ cm^{-3}$). The reliability of estimates decreased for FC, indicating significant differences between methods. The quality of information was better for PWP than for FC [values of 0.031 $cm^3\ cm^{-3}$ (WAM) and 0.053 (PP) for PWP, compared to 0.210 $cm^3\ cm^{-3}$ (PP) for FC].

The combined analysis of the two types of costs and their associated uncertainty reveals an inconsistency in the methods used to determine PWP, regardless of the increase in the costs associated with each method, except for FC (Figure 2).

WAM determinations/estimates showed a low uncertainty (0.031 $cm^3\ cm^{-3}$) and a low cost (680.04 €), particularly when compared to PP, with twice the cost and a 70 % decrease in reliability.

No significant differences were found between PTF1 and WAM in terms of uncertainty or costs. However, PTF1 is too general for the study area (Terra Cha). PTF10 and the Mayr-Jarvis method requires a small number of properties, resulting in reduced costs and good quality of information. For the determination/estimation of FC, costs tend to decrease with increased reliability of determinations/estimations, except for

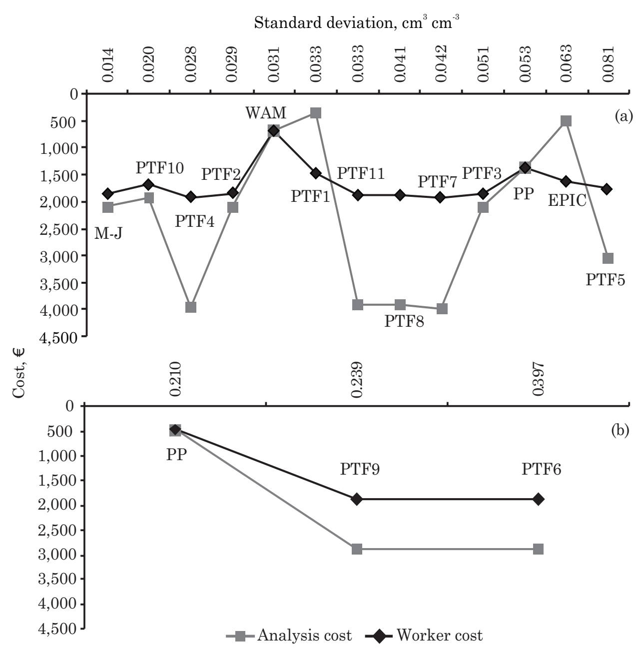

Figure 2. Relation between cost of information and uncertainty in the determination/estimation of hydro-physical limits, (a) PWP and (b) FC. WAM: Water activity meter used for PWP estimation, PP: pressure plate, PTF_i: pedotransfer functions, M-J: Mayr-Jarvis method.

PTF 6 and PTF9, which generated high costs but had highest uncertainties. It was observed that analysing the three efficiency parameters separately contributed to a better overall view of the characteristics of the selected methods.

Analysis and assessment of efficiency

Given the two types of costs considered, derived either from hiring staff or from performing the analyses in a commercial laboratory, efficiency was analysed using equations 3 and 4, proposed by Minasny (2000) and Minasny & McBratney (2002), and considering both types of costs (Figure 3). The most efficient method in terms of effort and staff cost was PTF5, a specific equation for gleysols with an initial r^2=0.99. However, PTF5 was not considered the most efficient method in terms of analysis cost because the EPIC method reduces the time needed to obtain estimates and improves efficiency in terms of analysis cost. Of the direct determination methods, WAM provides the best results for overall efficiency and PP the best results of efficiency in FC determination. The options for FC were more limited but there was a clear difference between the maximum efficiency obtained by PTF 6 and by PTF 9, particularly in terms of effort. Yet, PTF 6 yielded the same results as PTF9 in terms of time, but showed a higher standard deviation and, consequently, PTF6 did not provide the best quality of estimation.

Effects of the number of samples considered

The results of effort per sample (E) for the three sample sizes considered (Figure 4) reveal that fixed effort decreases with the increase in the number of samples. This decrease is more pronounced in direct determination methods. By increasing the number of samples from 5 to 50, the decrease in fixed effort was 19.4 h for WAM, 38.88 h for PWP determination by PP and 12.96 h for determination by PP. For the estimation methods, the decrease in fixed effort was much lower, with a value of 0.36 h. By increasing the number of samples from 5 to 100, the fixed effort decreases 0.38 h for PTFs, whereas the decrease for direct determination methods amounts to 20.52 h for WAM, 41.04 h for PWP determination by PP, and 13.68 h for FC determination by PP. The effects of the decrease in fixed effort are greater for direct methods than for estimation methods. This decrease is higher for large samples compared to determinations performed in isolated samplings.

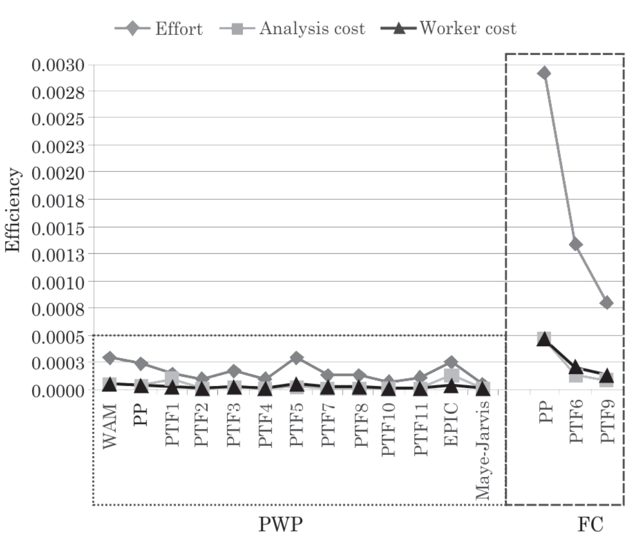

Figure 3. Efficiency of different methods determining and estimating hydro-physical properties in terms of effort and cost.

DISCUSSION

The analysis of the effort required by direct methods reveals that the time needed to determine hydraulic properties by these is much lower than by estimation methods. The determination of the time required by PP depends directly on two key factors: time of pressure application and number of samples that can be introduced at a time on the porous plate for wetting and in the pressure vessel. There is no agreement in the literature on the number of samples that should be introduced per plate. Actually, Artigao & Guardado (1993) suggested 30 samples/plate, while Cancela (2004) and Martínez et al. (2008) suggested 12 samples/plate in studies conducted in Terra Cha. Although PP requires twice as much time as WAM to determine PWP, the application of PP to soil samples is more versatile and allows for the determination of both PWP and FC, so that WAM alone can be used to determine one of hydro-physical limit.

The equation proposed by Soto et al. (2001) is the only PTF available for Galicia. However, this equation is not specific to the region of Terra Cha. The PTFs

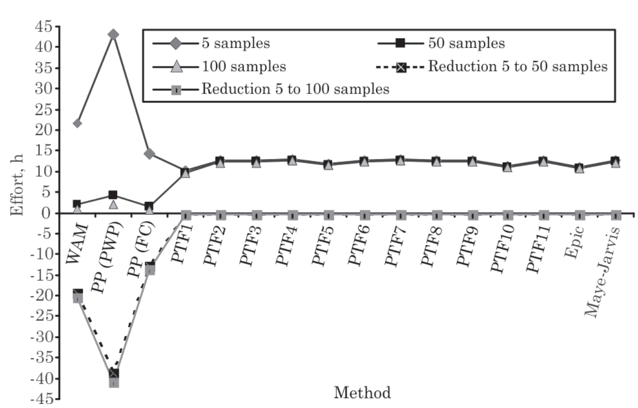

Figure 4. Effort per sample generated by the method and decrease in effort caused by the increase in the number of samples considered.

proposed by Martínez et al. (2010a) produce a higher coefficient of adjustment (r^2>0.84) and, therefore, are more suitable than the estimates calculated with SOILPAR 2.00 [EPIC (r^2=0.79) and Mayr-Jarvis (r^2=0.81)]. Because both methods are included in the group of indirect methods, the reliability of the estimates is lower. Therefore, some error was assumed with respect to determinations by direct methods such as PP (Díaz-Zorita et al., 2004) or WAM, a recent but verified method (Cancela et al., 2006a; Martínez, 2008; Martínez et al., 2011) used by Bittelli & Flury (2009) as a reference for PP calibration. The efforts required by PP and WAM were the lowest, which is in contrast with the results reported by Rubio et al. (2008), who claimed that the direct determination of the water retention curve represents most effort with least error. Rubio et al. (2008) used the sand box method and pressure membrane apparatus as direct methods and specific PTFs obtained by multiple regression and the ROSETTA model developed by Schaap et al. (2001). These results indicate the need to analyse the most suitable or frequent methods for each soil type and study area.

The determination of effort is particularly important because of the possibility of extrapolating the cost derived from implementing the method by qualified staff. By either method of cost estimation, some operations must be performed by qualified staff. In this paper, we question the suitability of paying a commercial laboratory to perform the analyses since costs per sample are very high and rise notably when the number of samples is increased.

The quality of the assessed methods is better for PWP than for FC, which apparently points to some problem in PP protocols, i.e. insufficient time of pressure application, causing this inconsistency. The results obtained for quality of information and cost of PWP determination/estimation are in agreement with those reported by Minasny & McBratney (2002), who found that the increase in analysis cost induced a decrease in the associated uncertainty, and that the direct method used (disc permeameter) provided high reliability with low uncertainty at low cost, compared to the estimation methods (PTF) (Minasny & McBratney, 2002). The same pattern was observed for PWP determination by WAM.

Minasny & McBratney (2002) claimed that the uncertainty and efforts of an efficient method should be low, i.e. a high efficiency value. The assessment of efficiency, both in terms of effort and cost, suggests the suitability of WAM compared to PP, since WAM requires half the effort for PWP determination and reduces uncertainty by 41.5 %, while increasing efficiency by 1.16 %. In agreement with these results, Rodriguez (2004) and Cancela et al. (2006a) presented WAM as a method requiring less effort than PP, whereas Bittelli & Flury (2009) considered WAM measurements to be more reliable than PP measurements.

For the effects of sample size, Rubio et al. (2008) reported stronger effects of sample size on direct methods. In our case, the number of samples affected the time (effort) needed to determine the physical properties required by estimation methods, but also the time required by direct methods. The times estimated by Cancela et al. (2006a) and Martínez (2008) [4.5 h/sample for WAM, 9 h/sample (PWP) and 3 h/sample (FC) for PP], considered the number of samples that can be analysed per batch for WAM or simultaneously for PP as a fixed parameter. Consequently, a greater sample size would involve an increase in the number of batches and in the time required to perform the analysis. Rubio (2005) minimized the effect of sample size by using an index (Equation 5), so that sample size affected mainly fixed effort instead of specific effort, which is a major component in direct methods.

CONCLUSIONS

1. The analysis showed that efficiency is an index indicating the performance of a method, rather than defining the method. Efficiency must be carefully assessed, and the criteria for efficiency estimation must be thoroughly analysed since a higher efficiency does not necessarily decrease costs and time required or minimize standard deviations.

2. The combined use of the two direct determination methods, WAM for PWP determination and PP for FC determination, provides the most economic (lowest cost), rapid (lowest effort) and reliable (lowest associated uncertainty) measurements.

3. The use of estimation methods based on PTFs obtained by multiple linear regression or by using software developed for that purpose, such as SOILPAR 2.00, can be recommended in some cases and for some soil types. However, these methods are generally time- and cost- consuming, with an initial associated uncertainty that questions their reliability because these methods were developed for the estimation of hydro-physical properties.

4. The direct determination methods considered in this paper (WAM and PP) can be used in different study areas and soil types since both WAM and PP are general methods that have been used, tested and validated by many authors. In contrast, the estimation methods considered are specific and depend on the boundary conditions of each analysis. For these reason, estimation methods require previous validation, which involves additional costs and times.

5. It is recommended not to generalize the analysis by using indices that define and characterize the different methods used. The results of a general analysis could mask unwanted characteristics of the chosen method or beneficial characteristics of a method

that was discarded. Therefore, indices should be used as indicators of the performance of a method rather than to define the method.

6. Consequently, the selection of the suitable method must be based on an overall analysis that considers all factors together that define the method (cost, effort or uncertainty, among others) and analyses each factor separately, so that the results do not interfere with each other in the assessment of the suitability of the selected method.

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