Chin. Geogra. Sci. 2010 20(5) 406–413
DOI: 10.1007/s11769-010-0414-4

Field Capacity in Black Soil Region, Northeast China

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Abstract: In this work, 23 black soil profiles were surveyed and 113 soil samples were collected to determine the field capacity (FC) of the black soil in Northeast China. The effectiveness of three methods measuring FC, the Wilcox method (WM), the undisturbed soil pressure plate method (PUM) and the air-dried sieved soil pressure plate method (PDM) were compared to select a suitable laboratory measurement method. Results show that the FC values measured by PDM are greater than those measured by PUM, and the values measured by PUM are greater than those measured by WM. PUM is more suitable for the determination of FC in the study area. One regression equation between PUM and PDM has been established through which undisturbed soil can be replaced by air-dried sieved soil, which is easier to get, to measure FC. FCs vary from 23.50% to 37.00%, with an average of 31.65%, which differ greatly among the 23 black soil profiles. FC is found to be significantly positively correlated with the silt content, clay content and bulk density of the soil, but significantly negatively correlated with the sand content. An empirical pedotransfer function is established to estimate the FC using available soil physical and chemical properties.

Keywords: Wilcox method; plate method; pedotransfer function; field capacity; black soil

1 Introduction

Field capacity (FC) is the maximum soil water holding capacity to plants (Hillel, 1998). It was considered to be a constant of soil water since it was proposed, and has been widely applied in the evaluation of characteristics of water holding and supply, the determination of irrigation volume and the evaluation of soil quality (Lal, 2006; Shao *et al*., 2006). However, the usefulness of this concept has been challenged. Some researchers believe that FC is ambiguous and its value is difficult to be determined accurately (Scott, 2000). Based on these assumptions, researchers believe that FC should not be considered as a constant, but rather a range of soil water content (Jabro *et al*., 2009). Nevertheless, there is currently no better alternative indicator of available soil water capacity. As a result, the FC is still being widely used in scientific research and agricultural production (Kirkham, 2005).

There are three main methods to measure FC, the field plot irrigation method, the laboratory Wilcox method (WM) and the laboratory pressure plate method. The plot irrigation method is a field observation method in which frames are set up around a field of freshly irrigated and gravity-drained soil without plants, after the soil reaches a level of constant water content without evaporation, then FC is measured (Cassel and Nielsen, 1986; Romano, 1993; Soil Science Society of America, 1997; Dane and Topp, 2002). This method is very material-consuming and is also subject to the impact of external factors (weather condition, water availability, *etc*.). Furthermore, it is difficult to control the time to reach the equilibrium level. For these reasons, this method is not suitable for soils with high clay contents (Zhu, 1996; Jiang *et al*., 2006). The WM is a laboratory measurement method with undisturbed and saturated soil samples placed on air-dried and sieved soil samples. The gravity water is then drained by the air-dried and sieved soil beneath. After reaching equilibrium, the water content of the undisturbed soil is considered as the FC (Zhu, 1996; Ministry of Water Resources the People′s Republic of China, 2007). Since it is difficult to collect undis-

Received date: 2010-02-01; accepted date: 2010-06-01
Foundation item: Under the auspices of National Natural Science Foundation of China (No. 40671111), Major State Basic Research Development Program of China (No. 2007CB407203)
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turbed soil samples and air-dried soil samples at the same time, this method has not been widely accepted as a standard method. However, it is currently used as a conventional and standard method in China (Zhu, 1996; Ministry of Water Resources the People′s Republic of China, 2007). The pressure plate method is also a laboratory measurement method. In this method, the FC is related to the soil water retention at a particular matric potential, which is controlled by a pressure plate (Cassel and Nielsen, 1986; Sumner, 2000; Dane and Topp, 2002). The FC is measured at potentials of –10 to –50 kPa (Dane and Topp, 2002; Lal, 2006). However, the water content at –33 kPa matric potential is usually used for moderately coarse- and finer-textured soils (Ratliff *et al*., 1983; Cassel and Nielsen, 1986; Addiscott and Whitmore, 1991; Liu, 1996; Gebregiorgis and Savage, 2006; Lal, 2006; Cavazza and Patruno, 2007; Jabro *et al*., 2009). Although it is generally acknowledged that undisturbed soil samples are required in the pressure plate method (Cassel and Nielsen, 1986; Gebregiorgis and Savage, 2006), the disturbed soil samples are still favored for they are easier to collect. Because disparities in water retention may exist between undisturbed soil samples and disturbed soil samples, adjustments are required on many soils by establishing relationships between the two types of data (Aina and Periaswamy, 1985). Much work has been done to analyze the differences between field observation method and laboratory measurement method (represented by the pressure plate method), and significant differences were found, moreover the degrees of difference varied with the physical and chemical properties of soils (Ratliff *et al*., 1983; Julie and Jay, 1997; Gebregiorgis and Savage, 2006). However, few efforts have been made to compare the differences between the WM and the pressure plate method or between the undisturbed soil pressure plate method (PUM) and the air-dried sieved soil pressure plate method (PDM).

Field methods are time-consuming, labor-intensive and difficult (Cassel and Nielsen, 1986; Jiang *et al*., 2006), so it is necessary to estimate FC based on the available and more stable soil physical properties (bulk density, mechanical composition, organic matter content, *etc*.). As a result, many empirical equations named pedotransfer functions (PTFs) have been developed to estimate FC indirectly based on specific soil conditions (Bell and Keulen, 1996; Wosten *et al*., 2001; Acutis and Donatelli, 2003; Bilal *et al*., 2004; Givi *et al*., 2004). But the model parameters should be revised in different areas (Bilal *et al*., 2004; Givi *et al*., 2004).

This study was conducted on the northeastern black soil region of China. The objective of this work is to select a simple and reliable method to measure FC; to determine the FC values in different black soil profiles based on field investigation; and to establish a simple equation to measure FC based on accessible soil physical and chemical properties in the study area.

2 Materials and Methods

2.1 Study area

Black soil belongs to Isohumisols in the Chinese Soil Taxonomy (CST) or Mollisols in the US Soil Taxonomy (ST) (Gong *et al*., 2007), and it is characterized by its high organic matter (OM) content and its parent material is yellow clay (The National Soil Survey Office, 1998). Black soil region, distributed in Northeast China (Fig. 1), with a total area of 94 000 km^2, has a temperate humid climate from the east transition to a semi-humid monsoon to the west, and mean annual temperature and annual precipitation are 2–5℃and 350–700 mm respectively (Li *et al*., 2006). The black soil region is an orographic transition zone from the mountains to plains. The altitude of this region is from 110 m to 300 m, while the grade of the slopes range from 0 to 5% and the lengths are as high as several thousand meters (Liu *et al*., 2005; Liu *et al*., 2008). Due to the gentle slopes and fertile soil, this region is an important grain production base in China, and the main crops include corn, wheat, soybean and rice.

2.2 Collection of soil sample

Field investigation on black soil was conducted from June to September in 2007, including 3 subtypes, black soil (Pachic Udic Haplobarolls in ST), meadow black soils (Pachic Udic Haplobarolls in ST) and albic black soils (Pachic Udic Argibarolls in ST). GPS and a topographic map were used to locate the positions of the surveyed soil profiles recorded in the *Soil Species of China* (The National Soil Survey Office, 1995) (Fig. 1). At each site, topographic positions, topography, slope aspect, land use types and vegetation types were recorded. The soil profiles were then sampled by following national standards methods (field dug investigation) (Wang and Zhang,

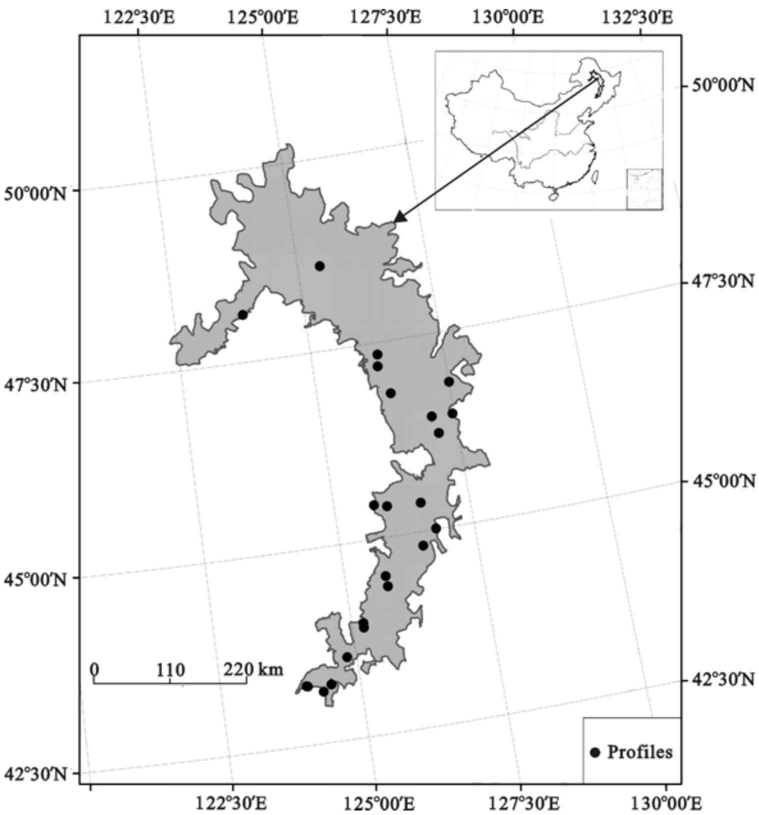

Fig. 1 Location of study area and distribution of soil profiles

1983; Liu, 1996). The soil genetic horizons were determined by following the national soil survey standards (Research Group and Cooperative Research Group on Chinese Soil Taxonomy, 1995; Liu, 1996). For each layer, 1 disturbed soil sample (2 kg of uniform mixture soil was sampled between the top and the bottom of the genetic horizon) and 3 core samples (with a diameter of 55 mm and a height of 50 mm, sampled in the middle part of the genetic horizon) were collected. Samples were collected in 1 sublayer when the genetic horizon thicknesses were less than 300 mm. If the genetic horizons were between 300 mm and 600 mm, the horizon was divided into 2 sublayers, and divided into 3 sublayers if the genetic horizon was greater than 600 mm. A total of 113 disturbed samples and 339 core samples were collected from 23 profiles, which had the same land use types (cultivated land) (Table 1). Core samples were used to analyze the bulk density (BD) and mixed soil samples were used to analyze particle size distribution and OM content in the laboratory.

In order to compare the differences among the three laboratory methods in the study area, another 31 soil layers were collected from 5 farmlands in Heshan Farm (49°00′–49°01′N, 125°16′–125°20′E) in Heilongjiang Province, China, which lies in the northern part of the study area. In Heshan Farm, the dominant soil is typical black soil (Pachic Udic Haplobarolls in ST). One profile was sampled for each farmland, with disturbed and undisturbed soil samples collected from the topsoil to 200 mm below the parent material, at intervals of 200 mm. Three replicated core soil samples were collected from each soil layer separately using a standard core with a diameter of 55 mm and a height of 50 mm, and another three replicated undisturbed soil samples were collected by cutting rings (brass cylinders, Soil Sample Retaining Rings equipped with the Pressure Plate Device) with a diameter of 55 mm and a height of 10 mm from each layer. One disturbed soil sample was collected from the same position (in the middle part of the layer) with the undisturbed soil for each layer. A total of 31 disturbed samples, 93 core soil samples and 93 undisturbed (Table 1) were collected from the five fields. All the samples were sealed and transported to the laboratory for analysis.

Additionally, in order to validate FC estimated equation, 29 disturbed and 87 core soil samples (Table 1)

Table 1 Amounts of disturbed, undisturbed and core soil samples

Site	Usage	Disturbed soil sample	Undisturbed soil sample	Core soil sample
Black soil region	To measure FC of 23 black soil species	113	–	339
Heshan Farm	To compare differences among three laboratory methods	31	93	93
Heshan Farm	To validate FC estimated equation	29	–	87
Total		173	93	519

were collected from a farmland in Heshan Farm (6 soil profiles), and the sampling and determination methods were the same as the above mentioned.

2.3 Analysis methods of field capacity

Regular standards were followed in all tests. More specifically, WM followed the Chinese technical standard for soil water monitoring (Zhu, 1996), and PUM and PDM referred to standard methods (Soil Science Society of America, 1997; Dane and Topp, 2002; Gebregiorgis and Savage, 2006).

WM: The mixed soil samples were air-dried, sieved using a 1-mm soil screen, and then packed into a cutting ring with the bottom part covered with gauze. Next, undisturbed soil samples (sampled using a standard cutting ring) were placed in a magnetic tray filled with deaerated water (0.005 mol/L $CaSO_4$ solution) to a level of 2 mm to 4 mm below the upper rim of the cutting ring. The undisturbed samples were then saturated by soaking for 24 h. After the samples were saturated, they were placed on the air-dried and sieved cutting ring soil samples. A brick (1.5 kg) was placed on top of the saturated samples to ensure that the two cutting rings were in tight contacted with each other, after which the samples were allowed to stand for 8 h. The cutting ring of the wet undisturbed soil was then removed and 10–20 g of the wet soil was placed in an aluminum box and weighed immediately. Finally, the soil was dried at 105℃ for approximately 48 h.

PUM: The pressure plate extractor used in this study was made by Soil Moisture Equipment Corp. (USA). To determine the FC using the PUM, the porous ceramic permeable plate was soaked in deaerated water for 2–4 h to wet it. Next, the plate was removed from the water and immediately placed on the undisturbed soil samples (sampled using a cutting ring). The plates were then placed in deaerated water to a depth of the top of the cutting ring for 24 h to ensure that they were saturated. The plate was then pressurized to 33 kPa with the pressure instrument, when there was no water flowing out from the pressure chamber (at least 72 h to reach the equilibrium), the soil was removed from the chamber, placed in an aluminum tray, and weighed. Finally, the aluminum box containing the soil sample was placed in an oven and dried at 105℃ for at least 24 h and then weighed again.

PDM: There were several differences between the PDM and the PUM. Specifically, duplicate 25 g samples that had been passed through a 2-mm sieve were dumped into retaining ring (55 mm in diameter, 10 mm in height). The plates were then placed in deaerated water to a depth below the top of the retaining rings for 24 h to ensure that they were saturated. The remaining steps were the same as those used for the PUM.

2.4 Establishment of pedotransfer function

The primary physical properties, particle size distribution, OM content and BD of all the samples were determined in the laboratory based on the National Soil Analysis Standards (Liu, 1996). The particle size distribution for the international system (sand (0.020–2.000 mm), silt (0.002–0.020 mm) and clay (< 0.002 mm)) was measured by using the pipette method after H_2O_2 treatment to remove organic matter. The OM was measured by using a combustion method after passing the soil samples through a 0.15-mm sieve. The BD was measured by using the cutting ring method.

The FC cannot be obtained from currently available soil databases of China, so this study attempted to establish a pedotransfer function to determine FC using soil physical and chemical properties. A common PTF was used to predict FC (Ahuja *et al*., 1985; Rawls *et al*., 1992):

$$FC = a \times Sand + b \times Clay + c \times OM + d \times BD \quad (1)$$

where *FC* is field water capacity (%); *Sand*, soil sand content (%); *Clay*, soil clay content (%); *OM*, organic matter content (%); *BD*, soil bulk density (g/cm^3); and *a*, *b*, *c*, *d* are regression coefficients.

3 Results and Analyses

3.1 Comparison of different methods

The FC of the 31 soil samples from the Heshan Farm have been determined by the three different methods. Table 2 shows that the FC measured by PDM is the highest and that measured by WM is the lowest. Structure may be a factor for soil water-release curves for sieved and field-structure samples usually differ appreciably (Cassel and Nielsen, 1986). After the soil structure has been destroyed by sieving, the measured FC is significantly greater than that of undisturbed soil in this study. However, the reasons for this discrepancy are not definitely known, and need further study in the future.

Table 2 Field capacity measured by three methods

	Range (%)	Mean (%)	S.D.
WM	17.7–31.8	26.3	3.3
PUM	19.2–41.4	31.9	5.2
PDM	21.5–55.4	41.8	4.8

For the same soil sample, the FCs determined by different methods are different, however, there are significant correlations for FCs determined by the three methods (Fig. 2, Table 3). The correlation of PUM and PDM is the highest, followed by PUM and WM. The results of PUM and PDM are highly correlated even the average FC measured by PDM is significantly greater than that determined by using the PUM. A simple linear regression equation was established with a high correlation coefficient:

$$FC_{\mathrm{PUM}} = 0.6409FC_{\mathrm{PDM}} + 5.0867 \quad (2)$$

where FC_{PUM} is the FC measured by PUM (%), and FC_{PDM} is the FC measured by PDM (%).

It is important to select a reasonable method for FC determination. The scientifically preferable method of determining FC is the field method. Previous results indicated that the FCs vary from 25% to 35%, with an average of 30% for black soil (determined by field method) (The National Soil Survey Office, 1998; Nan *et al*., 2003). The result is consistent with that determined by PUM, but the values determined by WM is lower and PDM is greater. So, it is reasonable to determine FC by PUM in the laboratory (Cassel and Nielsen, 1986; Jiang *et al*., 2006).

3.2 Field capacity of different black soil samples

FCs of the 113 different genetic horizon soil samples were determined by PDM and then converted to the FC_{PUM} (FC, the same below) through Equation (2), and the results are shown in Table 4. The FCs vary from 23.50% to 37.00%, with an average of 31.65% for the 23 types of black soil. The FCs of the A horizon range from 20.37% to 36.73%, the B horizon from 24.98% to 37.81%, and the C horizon from 23.74% to 40.30%.

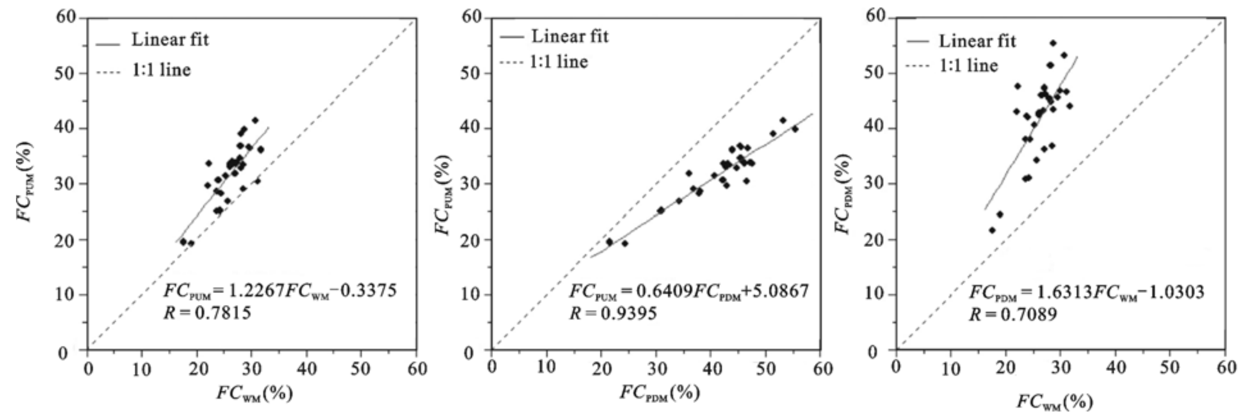

Fig. 2 Regression plot for three methods

Table 3 Statistical characteristics of three regression equations

Equation	Confidence intervals for slope (95%)	Confidence intervals for constant (95%)	R	S.E.
$FC_{\mathrm{PUM}} = 1.2267FC_{\mathrm{WM}} - 0.3375$	0.8548–1.5986	−10.1817–9.5068	0.7815^{**}	3.2734
$FC_{\mathrm{PUM}} = 0.6409FC_{\mathrm{PDM}} + 5.0867$	0.5521–0.7295	1.3178–8.8556	0.9395^{**}	1.7969
$FC_{\mathrm{PDM}} = 1.6313FC_{\mathrm{WM}} - 1.0303$	1.0148–2.2477	−17.3475–15.2868	0.7089^{**}	5.4258

Note: ** indicates statistical significance at the level of 0.01

Table 4 FC of different soil genetic horizon

Subgroups[①]	Soil profile code[②]	Latitude (°N)	Longitude (°E)	FC for different genetic horizons[③]						Average FC (%)
				A		B		C		
				Depth (cm)	FC (%)	Depth (cm)	FC (%)	Depth (cm)	FC (%)	
Black soil	20276	43.20	124.05	0–24	23.93	24–40	27.79	40–80	27.59	26.72
	20278	43.20	124.05	0–22	20.37	22–45	26.06	45–80	23.74	23.48
	20280	43.26	124.50	0–30	30.47	30–52	32.57	52–80	31.92	31.47
	20282	44.53	125.67	0–70	33.96	70–90	34.20	90–150	40.30	35.28
	20284	43.58	124.90	0–59	32.07	59–90	28.77	90–150	32.92	31.75
	20286	43.30	125.62	0–18	33.92	18–51	37.81	51–90	35.38	35.62
	20288	44.82	126.54	0–49	29.64	49–110	30.92	11–140	32.80	31.16
	20290	43.78	125.17	0–60	29.47	60–100	33.71	100–160	36.16	31.66
	20294	48.03	123.65	0–39	36.73	39–60	36.72	60–90	37.42	37.00
	20296	47.16	126.22	0–30	29.09	30–50	33.03	50–70	33.80	31.76
	20300	47.03	127.55	0–40	31.29	40–70	32.60	70–110	34.44	32.81
	20302	47.30	126.24	0–47	32.68	47–75	33.02	75–110	36.76	33.78
	20304	46.44	127.10	0–90	33.35	90–110	31.06	110–160	34.09	26.22
	20306	48.63	125.51	0–30	29.85	30–44	30.57	44–90	34.76	31.26
Meadow black soil	20312	43.17	124.30	0–40	30.67	40–54	33.14	54–83	34.42	32.66
	20314	44.38	125.75	0–90	33.29	90–150	34.97	150–180	35.25	34.02
	20316	45.38	125.76	0–40	25.14	40–70	24.98	70–90	26.25	25.46
	20318	46.80	126.37	0–80	30.01	80–110	30.55	110–150	31.49	30.14
	20320	45.39	125.95	0–30	27.75	30–85	32.33	85–110	32.33	30.10
	20322	45.36	126.57	0–60	33.13	60–120	35.08	120–160	37.42	35.21
Albic black soil	20324	45.03	126.76	0–50	31.71	50–95	35.17	95–120	35.91	33.56
	20326	46.43	127.48	0–44	30.73	44–80	37.01	80–120	36.98	34.49
	20328	46.25	127.12	0–80	31.22	80–100	36.00	100–150	36.14	32.42
Range					20.37–36.73		24.98–37.81		23.74–40.30	23.50–37.00
Average					30.45		32.52		33.83	31.65

Notes: ① Referred to the Genetic Soil Classification of China (Gong *et al*., 2007); ② Soil profile code is the first digit of the volume number plus the last four digits of the page number. For example, 20318 indicates that the soil profile description is on page 318 of Vol. 2 in *Soil Species of China* (The National Soil Survey Office, 1985); ③ A = humus horizon, B = illuvial horizon, C = parent rock

Although the FC is different significantly among different sites, there is little change with soil depth within the same profiles. Results from the individual subgroup evaluation show the range of the black soil subgroup is the highest; the meadow black soil subgroup is slightly less than the black soil subgroup, the albic black soil subgroup is the lowest. However, the average FC values are 32.05%, 31.25% and 33.73% for the black soil subgroup, the meadow black soil subgroup and the albic black soil subgroup respectively, and there are no significant differences among them.

3.3 Field capacity estimation method

The correlation between FC (PUM) and other physical and chemical properties is shown in Table 5. The results reveal that the correlation between FC and sand content is significant negative, and it shows significant positive correlations between FC and silt content, clay content and BD. These results are consistent with the previous researches (Cassel *et al*., 1983; Bilal *et al*., 2004).

A regression equation is obtained from regression analysis of FC and other soil physical and chemical properties including sand content, silt content, clay content, OM and BD (Equation (3)). The correlation coefficient (R) is 0.7721 ($p < 0.001$), and the standard error (S.E.) of the estimate is 2.51.

$$FC = 18.31 - 0.224 \times Sand - 0.018 \times Clay + 0.349 \times OM + 16.561 \times BD \quad (3)$$

Table 5 Correlation between FC and other soil physical and chemical properties

Soil properties	Correlation with FC (R)	p
Sand content (%)	–0.6058	< 0.001
Silt content (%)	0.4631	< 0.001
Clay content (%)	0.3975	< 0.001
OM (%)	–0.1003	> 0.01
BD (g/cm^3)	0.4842	< 0.001

To validate Equation (3), the FC of the 29 soil samples is calculated by Equation (3), and the results are compared with those of the measured FCs (Fig. 3). The calculated and measured FCs are significantly correlated (R = 0.7591, p < 0.001). The result of linear regression analysis based on an intercept of 0 has a slope of 1.0156, which is not significantly different from 1. Therefore, it is feasible to estimate the FC of black soils based on the soil properties using Equation (3).

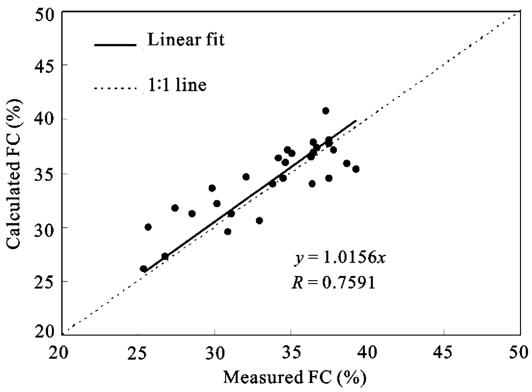

Fig. 3 Validation of FC estimation method

4 Conclusions

Different FC measuring methods were compared to select a suitable laboratory measurement method. FC determined by PUM is more reasonable, and that measured by PDM is the highest, while that measured by WM is the lowest. Soil structure has a great influence on the FC. If the soil structure is destroyed, the measured FC is significantly greater. Undisturbed soil samples should be used to measure FC in the study area, if disturbed soils are used, a conversion equation should be established. Soil texture characteristics also have significant effect on FC. The FCs vary with the change of soil texture characteristics among different black soils. Silt and clay contents are significantly positively correlated with FC, while the correlation of sand content and FC is significantly negative.

FC can be estimated by simple PTFs involving texture characteristics, BD and OM, which can be rapidly determined by routine laboratory or can be directly obtained from the current soil database, and the PTFs has been validated. However, we recommend to determine FC directly by PUM for precision purpose (such as estimation of irrigation), and to calculate FC by PTFs for general purpose (such as assessment of soil productivity) in the study area.

Acknowledgements

The authors thank the anonymous reviewers for their valuable comments. Thanks are due to Martin Persson, Ou Tianhai and Zhang Tianyu for polishing the manuscript.

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