

# CONSTRUCTION OF PEDOTRANSFER FUNCTION FOR PADDY SOIL BULK DENSITY BASED ON DIFFERENT GENETIC HORIZON

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**Abstract.** Bulk density (BD) is a key soil indicator for assessing agricultural sustainability; However, missing data are common due to the time-consuming, labor-intensive sampling, leading to frequent data gaps. Therefore, the objective of this study was to construct the pedotransfer function (PTF) based on other easily accessible properties of paddy soil to predict paddy soil bulk density in different occurrence horizons in Hunan. This study constructs the PTF for the whole profile, the plough horizon (Ap1), the plow pan (Ap2), and the underlying horizon (B horizon) using data on organic carbon (OC), sand, silt, and clay from 343 genetic horizons across 61 paddy soil profiles in Hunan Province. There were significant differences in soil BD and OC contents among different horizons, and also certain differences exist in soil particle compositions among different horizons, which led to the differences in factors affecting the BD among different horizons. BDs of all genetic horizons had moderate negative correlation with OC content ( $R = -0.425, -0.564, \text{ and } -0.509$ , respectively,  $p < 0.01$ ), while BD of B horizons had weak correlation with the content of sands, silts and clays ( $R = 0.292, -0.245, \text{ and } -0.195$ , respectively,  $p < 0.01$ ). PTFs of BD with the highest accuracy were in different forms for different horizons, in which the cubic function of OC was optimal for Ap1,  $BD_{Ap1} = 0.915 + 0.048OC - 0.003OC^2 + 3.870 \times 10^{-5}OC^3$ , the linear regression function of OC, silt and clay for Ap2,  $BD_{Ap2} = 1.483 - 0.014OC + 1.615 \times 10^{-5} \text{ Silt} + 9.660 \times 10^{-5} \text{ Clay}$ , and growth function of OC for B horizon,  $BDB = e^{(0.455 - 0.01OC)}$ .

**Keywords:** *rice planting system, pedotransfer function, soil bulk density, genetic horizon, soil organic carbon*

## Introduction

Bulk density (BD) is an important physical property of soil and a parameter in some soil science models (Huang, 2000; Liu et al., 2023; Harbo et al., 2022) and is commonly used to assess the sustainability of agricultural land production. However, the presence of sand, gravel, and plant roots in soils makes measuring BD using the ring-knife sampling method difficult and time-consuming, leading to frequent missing data on BD. In view of this, the establishment of the pedotransfer function (PTF) based on other easily accessible properties of the soil (mainly organic carbon/organic matter, and to a lesser extent, particle composition) has been an effective way to obtain BD data. For example, using both “Bulk Density” and “Pedotransfer Function” as the keywords appeared simultaneously in the titles, 35 and 10 articles were found on Web of Science (<https://www.webofscience.com/>) and China Knowledge Network (<https://www.cnki.net/>), and the literature were published with the time span of 2005-2023 and 2008-2022, respectively.

Due to the influence of factors such as region, land use, and soil types, the accuracy of the constructed PTF is often limited when used in other regions (Martin et al., 2009; Souza et al., 2016) or other soil types (Yi et al., 2016; Zhang et al., 2019). It has also been shown that since there are some differences in traits between different horizons of soil, the horizon should be considered when building the PTF (Reidy et al., 2016; Richard et al., 2022; Fang et al., 2021; Qiao et al., 2021).

Paddy soil is one of the most important agricultural soil resources in China, with an area of 29.78 million hm<sup>2</sup>, accounting for about 1/5 of the total arable land in the country (Zhang et al., 2022). As a cultivated soil formed by long-term hydroponic maturation, there are certain differences in the genesis and properties of different horizons of paddy soil. For example, the plough horizon (Ap1) is frequently flooded and stirred up by ploughing, has a high humus content, and is mostly of agglomerated or clumped structure; and the plough pan (Ap2) is sticky and compact due to the deposition of clay particles and frequent operation of agricultural machinery, and is mostly in the form of sheets or plates; the lower horizon (B horizon) including gley horizon, waterloggogenic horizon, percogenic horizon, albic horizon, etc., which are affected by surface water and groundwater at the same time, with frequent upward and downward water transport, and the iron and manganese reduction leaching and oxidation deposition are obvious, which can easily produce rust patterns, rust spots and even iron and manganese nodules, which are mostly of blocky or prismatic structure (Li, 1992; Xu et al., 1980).

Although the PTF of bulk density of anthropogenic soils has been reported (Kaur et al., 2012), which may include some dry ploughing anthropogenic soil data, so far there are few reports involving the PTF of density function of paddy soils. Thus, in order to establish an optimal model for the PTF of density function of paddy soils, this study was carried out based on the assumptions that (1) there are differences in the factors affecting the PTF of paddy soil in different genetic horizons, and (2) the optimal model for the PTF of different genetic horizon are different.

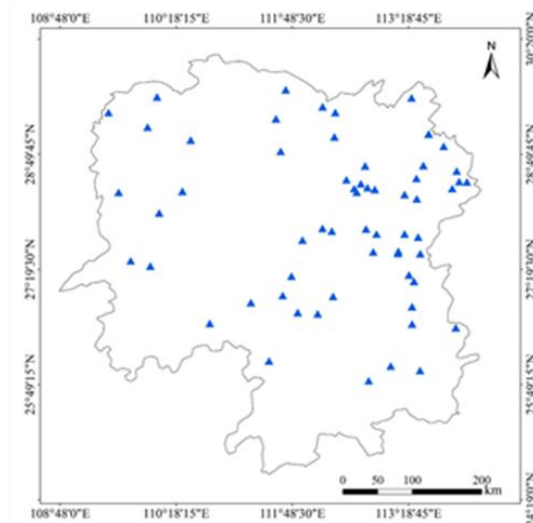
## Materials and methods

### *Basic data sources*

The typical profile data of paddy soil used in this study were obtained from the soil series of China Hunan, with a total of 61 profiles (*Fig. 1*) and 343 occurrences (of which 221 were in the B horizon). Soil properties included BD (determined using the ring-knife drying method), organic carbon (OC, determined using the potassium dichromate volumetric method), and particle composition (sand, silt, and clay; USDA system, determined using the pipette method; Zhang et al., 2012).

### *Data processing*

The data were processed using IBM Statistics SPSS 22.0 software. One-way analysis of variance was used to test the significance of differences between the data in different groups. The two modules of multiple linear regression and curve estimation in SPSS software were used to establish various types of function models between BD and OC, sand, silt and clay, and the optimal function model was determined by comparing the correlation coefficients (R), the mean absolute error (MAE) and the root mean square error (RMSE).



**Figure 1.** Sites of paddy soil profiles studied

## Results and discussion

### *Statistical characteristics of the profile and the thickness of the different genetic horizon*

Table 1 showed the statistical results of the thicknesses of 61 profiles, Ap, Ap2 and B horizon, from which it can be seen that: (1) the thickness of Ap1 ranged from 10 to 22 cm, with an average of 15 cm, of which 56 profiles (91.8%) had Ap1 thicknesses lower than the 20 cm required by the national high-standard farmland; (2) the thickness of Ap2 ranged from 5 to 20 cm, with an average of 9 cm, which was generally in the plough normal range of plow pan thickness (<10 cm) (Li, 1992; Xu et al., 1980), However, shallow rotary tillage resulted in a shallower Ap2 upper boundary and a thicker plow pan in some paddy fields, and 12 profiles (19.6% of the total) had exceeded the Ap2 thickness standard (<10 cm) for high-yielding paddy soil. (3) The thickness of Ap1 was significantly higher than that of Ap2 ( $p < 0.01$ ), and the thicknesses of Ap1, Ap2 and B horizon were all moderately variable ( $10\% < C.V. (\%) < 100\%$ ), but the coefficient of variation value (C.V.) was highest for Ap2 (at 25.64%), followed by Ap1 (at 19.23%).

**Table 1.** Thickness of soil profile and genetic horizons

Genetic horizon	Number	Range (cm)	Mean $\pm$ S.D. (cm)	C.V. (%)	Skewness	Kurtosis
Profile	61	73~150	131 $\pm$ 14	11.07	-1.99	4.76
Ap1	61	10~22	15 $\pm$ 3 A	19.23	0.51	-0.03
Ap2	61	5~20	9 $\pm$ 2 B	25.64	1.58	6.04
B horizon	221	53~125	107 $\pm$ 14	13.51	-1.60	3.11

### *Statistical characteristics of soil properties in the profile and in the different genetic horizon*

Table 2 showed the statistical characteristics of soil properties in the profile and genetic horizon. The following trends can be observed from top to bottom of the profiles:

(1) significant increase in BD ( $p < 0.01$ ), 26.2% and 42.7% in the Ap2 and B horizon, respectively, as compared to Ap1. 42 profiles (68.85% of the total) had low BD ( $< 1.12 \text{ g/cm}^3$ ) in Ap1, and 2 profiles (3.28% of the total) had large BD ( $> 1.27 \text{ g/cm}^3$ ) (Hu, 2013). Frequent ploughing primarily affects soils, gradually reducing OC content and altering soil structure from loose and porous agglomerates or small clumps to larger, compact clumps or prismatic clumps. (2) The OC content was significantly reduced ( $p < 0.01$ ) by 34.0% and 68.2% in the Ap2 and B horizon, respectively, compared with Ap1. 48 profiles (78.69% of the total) had a high level of OC in Ap1 ( $\geq 17.4 \text{ g/cm}^3$ ), and 2 profiles (3.28% of the total) had a low level of OC in Ap1 ( $< 11.6 \text{ g/kg}$ ) (Liang, 2014). This was mainly due to the gradual decrease in fertilizer application, root residue and return when straw was returned to the field. (3) There was no significant difference between Ap1 and Ap2 in terms of both sand and silt content, but both had significantly lower sand content than the B horizon, respectively, while the meal content was significantly higher ( $p < 0.01$ ); the clay content was significantly higher in Ap1 than in Ap2 and the B horizon ( $p < 0.05$ ), whereas there was no significant difference between the other two groups. The downward movement and deposition of clay particles, typically common in paddy soils, was absent in all groups. This may be attributed to irrigation using water from surrounding limestone mountain areas, where the weathered limestone materials, finer in particle size, consistently replenished clay and silt into the Ap1 horizon.

**Table 2.** Statistical descriptions of soil basic properties of profile and genetic horizons

Property	Horizon	Number	Range	Mean $\pm$ S.D.	C.V.	Skewness	Kurtosis
BD	Profile	343	0.75~1.86	1.37 $\pm$ 0.22	16.08	-0.53	-0.27
	Ap1	61	0.75~1.50	1.03 $\pm$ 0.15 C	14.23	0.76	0.97
	Ap2	61	1.03~1.57	1.30 $\pm$ 0.14 B	10.60	0.20	-0.81
	B	221	1.11~1.86	1.47 $\pm$ 0.14 A	9.70	-0.11	-0.21
OC	Profile	343	0.31~44.80	11.16 $\pm$ 8.21	73.59	1.00	0.62
	Ap1	61	0.33~44.80	22.33 $\pm$ 7.61 A	34.07	0.08	1.60
	Ap2	61	0.33~28.30	14.73 $\pm$ 5.63 B	38.23	0.38	0.21
	B	221	0.31~28.10	7.09 $\pm$ 5.05 C	71.32	1.44	1.96
Sand	Profile	343	0-806	298 $\pm$ 202	67.86	0.67	-0.57
	Ap1	61	0~729	247 $\pm$ 181 a	73.22	0.96	0.27
	Ap2	61	5~725	254 $\pm$ 180 a	70.92	0.83	-0.03
	B	221	0~806	324 $\pm$ 209 B	64.60	0.54	-0.82
Silt	Profile	343	15~833	451 $\pm$ 180	39.84	-0.60	-0.41
	Ap1	61	87~694	485 $\pm$ 146 a	30.12	-1.13	0.99
	Ap2	61	142~721	490 $\pm$ 142 a	28.97	-0.70	-0.28
	B	221	15~833	430 $\pm$ 194 B	45.08	-0.40	-0.73
Clay	Profile	343	66~554	252 $\pm$ 76	30.11	0.04	0.21
	Ap1	61	118~466	267 $\pm$ 71 a	26.64	0.07	-0.16
	Ap2	61	107~381	256 $\pm$ 71 b	27.83	-0.34	-0.68
	B	221	66~554	246 $\pm$ 78 b	31.62	0.15	0.50

(1) BD,  $\text{g cm}^{-3}$ ; OC (Organic carbon), Sand, Silt, Clay,  $\text{g kg}^{-1}$ ; (2) C.V., %; (3) upper and lower case letters in Mean  $\pm$  S.D. column indicate significant difference in  $P < 0.01$  and  $P < 0.05$  levels respectively

### ***Correlation between soil capacity and other attributes***

Table 3 showed the correlation between BD value and other attributes, as can be seen from Table 3: (1) BD was moderately negatively correlated with OC at all three levels (R values were -0.425, -0.564, and -0.509, respectively,  $p < 0.01$ ), and the scatterplot of the correlation between BD and OC WAS shown in Figure 2. The negative correlation between BD and OC was in agreement with the results of all the existing studies (Bernoux et al., 1998; Zhang et al., 2019; Crnobrna et al., 2022; Khodaverdiloo et al., 2022). (2) Only the B horizon showed a weak correlation between BD and particle composition, with a negative correlation with the content of silt and clay particles (R of -0.242 and -0.195, respectively,  $p < 0.01$ ) and a positive correlation with the content of sand particles (R = 0.292,  $p < 0.01$ ), a result that is in agreement with the results obtained by Abdelbaki (2018) and Khodaverdiloo et al. (2022), but contrary to the results of Palladino et al. (2022). The positive, negative and high correlation between capacity and particle composition may be related not only to the soil-forming parent material and soil type, but also to the high variability of its particle content, such as the coefficients of variation of the sand content in the three occurring horizons in the present study (64.60%-73.22%) were significantly higher than that of the silt particles (28.97%-45.08%) and the clay particles (26.64%-31.62%) in terms of Ap1, In comparison between Ap2 and B horizon, the B horizon had the lowest coefficient of variation for sand content (64.60%) but the highest coefficients of variation for silt and clay content (45.08% and 31.62%, respectively).

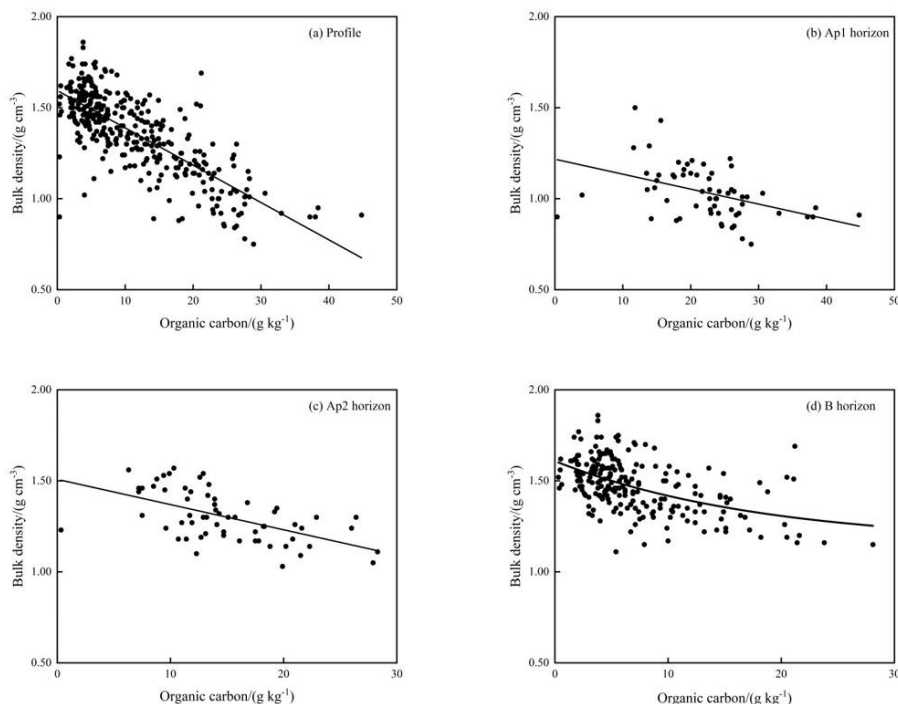
**Table 3.** Pearson correlations between soil bulk density and other properties

<b>Horizon</b>	<b>OC</b>	<b>Sand</b>	<b>Silt</b>	<b>Clay</b>
Profile	-0.767**	0.259**	-0.213**	-0.189**
Plough horizon (Ap1)	-0.425**	-0.060	0.124	-0.103
Plow pan (Ap2)	-0.564**	0.194	-0.186	-0.120
B horizon	-0.509**	0.292**	-0.242**	-0.195**

\*Means correlation is significant at 0.01 and 0.05 levels (two-tailed), respectively

### ***Establishment of optimal tolerance transfer function***

The PTF of BD with the highest accuracy for Ap1, Ap2 and B horizon were screened by comparison using SPSS software (Table 4). As shown in Table 4: (1) The highest accuracy of the PTF of BD of different occurrence horizon differ in model representation, with Ap1 being the cubic function of OC, Ap2 being the multiple linear regression function of OC, Silt and Clay, and B horizon being the growth function of OC. (2) The established PTF of Ap1, Ap2 and B horizon had high accuracy with R2 values of 0.756, 0.753 and 0.723, which could meet the requirements of tolerance prediction, respectively. (3) In predicting the BD of each genetic horizons, the accuracy of the profile BD was lower than that of the PTF of each genetic horizons, especially Ap1, whose RMSE is 15.7% lower than that of the profile PTF; similarly, the RMSE of Ap2 and B horizon were also lower than that of the full profile by 8.33% and 7.69%, which suggested that when establishing the PTF of the paddy soil, in order to obtain a higher accuracy, one should consider specific paddy of occurrence, especially the tillage horizon.



**Figure 2.** Scatter plots of soil bulk density and other properties

**Table 4.** Soil bulk density PTFs of profile and different genetic horizon

Horizon	PDF model	Number	R2	p	MAE	RMSE
Profile	$BD_p = e^{(0.479-0.016OC)}$	243	0.863	0.000	0.11	0.14
Ap1	$BD_p = e^{(0.479-0.016OC)}$	243	0.863	0.000	0.14	0.19
	$BD_{Ap1} = 0.915 + 0.048OC - 0.003OC^2 + 3.870 \times 10^{-5}OC^3$	61	0.756	0.000	0.13	0.16
Ap2	$BD_p = e^{(0.479-0.016OC)}$	243	0.863	0.000	0.10	0.12
	$BD_{Ap2} = 1.483 - 0.014OC + 1.615 \times 10^{-3}Silt + 9.660 \times 10^{-5}Clay$	61	0.753	0.000	0.10	0.11
B Horizon	$BD_p = e^{(0.479-0.016OC)}$	243	0.863	0.000	0.10	0.13
	$BD_B = e^{(0.455-0.010OC)}$	221	0.723	0.000	0.10	0.12

It should be pointed out that: (1) although there are many PTFs for BD, this study did not verify the suitability of these existing models for predicting the BD of paddy soils in Hunan Province, considering that most of the existing models are not specific to paddy soils, and that some studies have shown that PTFs based on other regions or soil types are more difficult to be used in other regions or other soil types. Therefore, it is still necessary to seek suitable PTFs with higher accuracy for new regions and new soil types. For example, Xu et al. found that the uncertainty in the estimation results was related to the different PTFs used in estimating soil OC in terrestrial ecosystems in China (Xu et al., 2015). (2) There are many types of B horizon in paddy soils, such as gley horizon, waterloggogenic horizon, percologenic horizon, albic horizon, etc. In this study, the B horizon were not subdivided in order to establish the corresponding PTFs, considering that subdividing the B horizon may lead to the small number of some horizon, which will affect the accuracy of the modelling, but these different types of B horizon may also have some differences in the genesis and properties, and in the future, the way to increase the number of profiles of the B horizon may be considered. to establish its corresponding PTF.

## Conclusions

This study showed that the different horizons of paddy soils (Ap1, Ap2, B horizon) differed somewhat in bulkiness, OC content and particle composition, with OC being the factor affecting bulkiness in the Ap1 and Ap2, while OC was predominant in the B horizon, followed by particle composition. The three horizon with the highest accuracy of the PTFs differed in the form of the model, with a cubic function of OC in the Ap1, a linear regression function of OC, silt and clay particles in the Ap2, and a growth function of organic carbon in the B horizon. For paddy soils, the PTF of BD should be built based on the specific occurrence horizon.

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**Conflict of interests.** The authors declare no conflict of interests.

## REFERENCES

- [1] Abdelbaki, A. M. (2018): Evaluation of pedotransfer functions for predicting soil bulk density for U.S. soils. – *Ain Shams Engineering Journal* 9: 1611-1619.
- [2] Bernoux, M., Cerri, C., Arrouays, D., Jolivet, C., Volkoff, B. (1998): Bulk densities of Brazilian Amazon soils related to other soil properties. – *Soil Science Society of America Journal* 62: 743-749.
- [3] Crnobrna, B., Llanqui, I. B., Cardenas, A. D., Panduro Pisco, G. (2022): Relationships between organic matter and bulk density in Amazonian peatland soils. – *Sustainability* 14(19): 12070.
- [4] Fang, B., Wu, S. C., Chen, H. Y., Song, Q., Zhuang, H. J., Zhou, P. F., Yang, B., Zhang, S. W. (2021): Comparison of modeling methods for region soil bulk density in different soil layers. – *Southwest China Journal of Agricultural Sciences* 34(10): 2258-2268.
- [5] Harbo, L. S., Olesen, J. E., Liang, Z., Christensen, B. T., Elsgaard, L. (2022): Estimating organic carbon stocks of mineral soils in Denmark: impact of bulk density and content of rock fragments. – *Geoderma Regional* 30: e00560.
- [6] Hu, W. (2013): Effects of soil bulk density on tobacco growth and soil chemistry properties of tobacco growth. – Kunming University of Science and Technology.
- [7] Huang, C. Y. (2000): *Soil Science*. – China Agriculture Press, Beijing.
- [8] Kaur, R., Kumar, S., Gurung, H. P. (2002): A pedo-transfer function (PTF) for estimating soil bulk density from basic soil data and its comparison with existing PTFs. – *Soil Research* 40(5): 847-858.
- [9] Khodaverdiloo, H., Bahrami, A., Rahmati, M., Vereecken, H., Miryaghoubzadeh, M., Thompson, S. (2022): Recalibration of existing pedotransfer functions to estimate soil bulk density at a regional scale. – *European Journal of Soil Science* 73(3): e13244.
- [10] Li, Q. K. (1992): *Paddy Soils of China*. – Science Press, Beijing.
- [11] Liang, H. (2014): Evaluation of Soil Fertility Status for Tobacco Growing Area in Chongqing. – Southwest University, Chongqing.
- [12] Liu, S., Huang, Q., Zhang, W., Ren, D., Xu, X., Xiong, Y., Huang, G. (2023): An improved estimation of soil water and salt dynamics by considering soil bulk density changes under freeze/thaw conditions in arid areas with shallow groundwater tables. – *Science of the Total Environment* 859: 160342.
- [13] Martin, M. P., Lo Seen, D., Boulonne, L., Jolivet, C., Nair, K. M., Bourgeon, G., Arrouays, D. (2009): Optimizing pedotransfer functions for estimating soil bulk density using boosted regression trees. – *Soil Science Society of America Journal* 73(2): 485-493.

- [14] Palladino, M., Romano, N., Pasolli, E., Nasta, P. (2022): Developing pedotransfer functions for predicting soil bulk density in Campania. – *Geoderma* 412: 115726.
- [15] Reidy, B., Simo, I., Sills, P., Creamer, R. E. (2016): Pedotransfer functions for Irish soils–estimation of bulk density ( $\rho_b$ ) per horizon type. – *Soil* 2(1): 25-39.
- [16] Richard, C., Lemerrier, B., Michot, D., Pichelin, P., Rémy, A., Berthier, L., Walter, C. (2023): End-user-oriented pedotransfer functions to estimate soil bulk density and available water capacity at horizon and profile scales. – *Soil Use and Management* 39(1): 270-285.
- [17] Souza, E. D., Fernandes Filho, E. I., Schaefer, C. E. G. R., Batjes, N. H., Santos, G. R. D., Pontes, L. M. (2016): Pedotransfer functions to estimate bulk density from soil properties and environmental covariates: Rio Doce basin. – *Scientia Agricola* 73: 525-534.
- [18] Xu, L., He, N. P., Yu, G. R., Wen, D., Gao, Y., He, H. L. (2015): Differences in pedotransfer functions of bulk density lead to high uncertainty in soil organic carbon estimation at regional scales: evidence from Chinese terrestrial ecosystems. – *Journal of Geophysical Research: Biogeosciences* 120(8): 1567-1575.
- [19] Yi, X., Li, G., Yin, Y. (2016): Pedotransfer functions for estimating soil bulk density: a case study in the three-river headwater region of Qinghai Province, China. – *Pedosphere* 26: 362-373.
- [20] Zhang, G. L., Gong, Z. T. (2012): *Soil Survey Laboratory Methods*. – Science Press, Beijing.
- [21] Zhang, H. M., Zhang, W. J., Huang, J. (2022): *Spatial and Temporal Variation and Improvement of Soil Fertility in Typical Paddy Growing Areas*. – Science Press, Beijing.
- [22] Zhang, X., Zhu, J., Wendroth, O., Matocha, C., Edwards, D. (2019): Effect of macroporosity on pedotransfer function estimates at the field scale. – *Vadose Zone Journal* 18(1): 1-15.
- [23] Zhong, H. P., Qiao, Y. X., Zhu, H. Z., Shao, X. M., Li, Y. Z. (2021): Stratified data reconstruction based on spatial pattern of soil bulk density in temperate grasslands of Northern China. – *Acta Prataculturae Sinica* 30(1): 1-11.