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INTERNATIONAL Agrophysics
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Int. Agrophys., 2017, 31, 491-498
doi: 10.1515/intag-2016-0079

Comparison of different models for predicting soil bulk density. Case study – Slovakian agricultural soils**

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Received July 17, 2017; accepted September 14, 2017

A b s t r a c t. Soil bulk density is one of the main direct indicators of soil health, and is an important aspect of models for determining agroecosystem services potential. By way of applying multi-regression methods, we have created a distributed prediction of soil bulk density used subsequently for topsoil carbon stock estimation. The soil data used for this study were from the Slovakian partial monitoring system-soil database. In our work, two models of soil bulk density in an equilibrium state, with different combinations of input parameters (soil particle size distribution and soil organic carbon content in %), have been created, and subsequently validated using a data set from 15 principal sampling sites of Slovakian partial monitoring system-soil, that were different from those used to generate the bulk density equations. We have made a comparison of measured bulk density data and data calculated by the pedotransfer equations against soil bulk density calculated according to equations recommended by Joint Research Centre Sustainable Resources for Europe. The differences between measured soil bulk density and the model values vary from -0.144 to 0.135 g cm^{-3} in the verification data set. Furthermore, all models based on pedotransfer functions give moderately lower values. The soil bulk density model was then applied to generate a first approximation of soil bulk density map for Slovakia using texture information from 17 523 sampling sites, and was subsequently utilised for topsoil organic carbon estimation.

K e y w o r d s : soil bulk density, pedotransfer function, texture, soil carbon content

INTRODUCTION

Soil bulk density is one of the main direct indicators of soil health (Abbott and Manning, 2015; Van der Biest *et al.*, 2014). It also affects the soil biomass productivity and environmental quality (Lal and Kimble, 2001). Soil bulk density is a dynamic soil property, as it varies in time and space. It is influenced by crop and land management practices, as well as by natural processes such as the climate conditions that affect soil cover, organic matter levels, soil structure or porosity (Alletto and Coquet, 2009; Dam *et al.,* 2005; Husnjack, 2002; Kumar *et al.,* 2012; Logsdon, 2012; Norman *et al.,* 2016; Timm *et al.,* 2006; Veiga *et al.,* 2008). Reversible processes in soils always tend to achieve an equilibrium state of soil bulk density (Makovníková and Širáň, 2011), thus, at field capacity, and lacking external degradation influences, the bulk density of soil varies around the equilibrium. Such situation is referred to as the representative bulk density of soil. This directly depends on soil texture (Houšková, 2002). In practice, this value also depends on the type of soil use and intensity of cultivation. Soil bulk density is a very important parameter for evaluating the susceptibility of soil to compaction, as well as the intensity of compaction. Soil bulk density is also used in the quantification of soil carbon (C) stocks, and is therefore an important parameter for national inventories of greenhouse gas emissions, nutrients reserves and water balance. In addition, it is a parameter of models for determining agroecosystem services potential, especially provisioning and regulating services (Makovníková *et al.,* 2017).

The determination of bulk density is not technically difficult, but the associated sampling is laborious and time consuming. This is because a sample of known volume must be extracted by a procedure that causes minimal

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**This work was supported by the Slovak Research and Development Agency contract No. APVV-0098-12 and APVV-15-0160.

disturbance (Lark *et al.,* 2014; Suuster *et al.,* 2011). This is also the reason why data sets for this property are limited compared to other soil characteristics. Therefore, there is a tendency to model bulk density values by means of pedotransfer functions or PTFs (Benites *et al.,* 2007; Heuscher *et al.,* 2005; Kaur *et al.,* 2002; Suuster *et al.*, 2011 Tranter *et al.,* 2007) that are constructed from parameters that are routinely available in soil inventories, such as organic carbon and clay content (Benites *et al.,* 2007; Bouma, 1989). These pedotransfer functions methods can also be used to assess other important soil parameters. Studies in Poland (Walczak *et al*., 2004) have been focused on the impact of soil physical and chemical parameters on the water retention curve and the water conductivity curve. The simplest models of representative soil bulk density use the texture triangle for mineral soils. This consists of a set of soil textural categories. Several authors worked with bulk density models based on pedotransfer functions (Adams, 1973; Bernoux *et al.*, 1998; Federer, 1983; Gupta and Larson, 1979; Hermanz *et al.,* 2000; Manrique and Jones, 1991; Rawls, 1983; Saxton *et al.,*, 1986; Tomasella and Hodnett, 1998).

The main aims of the study were (1) to model soil bulk density by the development of pedotransfer functions from measured data in existing databases, (2) to verify these models at monitoring sampling sites, (3) to apply the developed pedotransfer functions for the assessment and mapping of soil carbon stock, which is basic information for agro ecosystem services regulation.

MATERIAL AND METHODS

In this project, the empirical data on measured bulk density data, soil texture and organic carbon content were extracted from the partial monitoring system – soil database (PMS-S).

This database was generated *via* the soil monitoring system in Slovakia that has been running continuously since 1993. Its role is to provide and assess information on the spatial and temporal variability of soil parameters, as well as to generate an evaluation of soil quality. The monitoring network was based on ecological principles, taking into account land use, climatic regions, main soil types and subtypes, soil organic matter content, regions with emission problems, polluted and non-polluted regions. For this monitoring process, soil properties are observed every five years on agricultural soils at 312 sites. Furthermore, on 15 key sampling sites, selected soil properties are monitored on a yearly basis (Kobza *et al.,* 2014). Soil sampling is done in June. At this time, in typical Slovakian climatic conditions, the bulk densities of the majority of soils are in balanced status. All samples are analysed by uniform analytical procedures (Kolektív, 2011). Additionally, the most significant indicators for soil threats are assessed according to the recommendation of European Commission (EC) for a unified soil monitoring system in Europe (Van Camp *et al.,* 2004). This includes soil organic carbon content (dry way, using CN analyser), texture (modified to Slovakian databases content – particles <0.001, < 0.01 and 0.001-0.05, 0.05-2.00 mm using the pipette method) and bulk density (core samples in 100 cm^3 cylinders, dried at 105°C to constant weight, ISO 11272:1998). In total, empirical data for 262 sites from the monitoring database (texture, bulk density and organic matter content from the depth 0 – 10 cm) were used for bulk density modelling (Table 1). Data from key sampling sites were also used to verify the pedotransfer model.

Statistical processing and interpretation of the results were done using the STATGRAPHIC Centurion IV software package, while graphical processing used ESRI ArcGis 10.3.1. In our work, measured bulk density acted as the dependent variable in the multiple regressions analysis, while soil properties served as the independent variables. Manrique and Jones (Manrique and Jones, 1991) have shown that partitioning of data by suborders is beneficial for purpose of the bulk density prediction. The soil bulk density models by Bernoux (1998) (pedotransfer equation: bulk density: BD_B = 1.398 – 0.0047 clay – 0.042 SOC) and by Manrique and Jones (1991) (pedotransfer equation: BD_{MJ} = 1.51 – 0.113 SOC) are some of the models that are recommended by Joint Research Centre Sustainable

T a b l e 1. Summary statistics partial monitoring system – Soil database (n = 262)

Parameter	Soil bulk density (g cm^{-3})	Clay particles <0.01 mm	Clay <0.001 mm	Silt 0.001-0.05 mm	Sand 0.05-2.00 mm	SOC %
Average	1.362	40.294	17.117	55.073	27.807	1.506
Standard deviation	0.163	11.512	7.7886	13.691	16.221	0.890
Coeff. of variation in %	12.006	28.571	45.500	24.859	58.334	59.101
Minimum	0.657	2.980	2.070	1.720	6.230	0.491
Maximum	1.729	75.660	52.530	81.250	96.210	10.504

Table 2. Analysis of variance for BD_{PTF_1} and BD_{PTF_2}

Source	Sum of squares	Df	Mean square	F-Ratio	P-value	Sum of squares	Df	Mean square	F-Ratio	P-value
			BD_{PTF_1}					BD_{PTF_2}		
Model	1.885	3	0.628	31.91	0.000	3.189	4	0.797	54.010	0.000
Residual	5.099	259	0.019			3.793	257	0.014		
Total (Corr.)	6.985	262				6.983	261			

Resources (JRC) for use in Europe. Comparisons of these soil bulk density models with Slovakian models BD_{PTF_1} and BD_{PTF_2} were made.

RESULTS AND DISCUSSION

Based on the results of the partial component analysis (PCA), the following variables were selected for our pedotransfer models: silt content 0.001-0.05 mm in % (P), sand content 0.05-2.00 mm in % (S), content of particles <0.01 mm in % (Ilc) and soil organic carbon content in % (SOC). As measured parameters for the models, we used textural data as categorized traditionally (0.01 mm for clayey particles), as we wanted to utilise the original database created in the 1960s – the complex soil survey database. This incorporated soil texture data from 17 523 sampling sites for the whole territory of Slovakia. Two main components have been extracted – as these had eigen values greater than or equal to 1.0. Together, they account for 78.29% of the variability in the original data (content of clayey particles <0.01 mm (ILc) and silt content 0.001-0.05 mm in % (P)). The main components have been complemented by silt, sand and SOC. Calhoun *et al.* (2001) found that particle size distribution and SOC generally explain more than 60% of the variation in bulk density.

The analysis of variance for models and pedotransfer functions (262 empirical data were used) are reported in Tables 2 and 3. Figures 1 and 2 show measured bulk density in relation to predicted values. The statistical results show that model BD_{PTF_2}, based on organic carbon content (SOC), gives a more precise estimation of bulk density. This was affirmed by the lower statistical dispersion of values around the line (Fig. 1).

Soil bulk density pedotransfer models:

$$\text{PTF 1 } BD_{PTF_1} = 3.1482-0.0118ILc-0.017S-0.0152P \quad (1)$$

Model BD together with SOC:

$$\text{PTF 2 } BD_{PTF_2}= 2.662-0.0076ILc-0.0102P-0.0108S-0.0855SOC. \quad (2)$$

Table 3. Analysis of variance for BD_{PTF_1} and BD_{PTF_2}

PTF	R-squared (%)	R-squared (adjusted for d.f.) (%)	Durbin-Watson statistic	P-value
BD_{PTF_1}	26.989	26.144	1.772	0.032
BD_{PTF_2}	45.671	46.825	1.678	0.000

Since the P-value in the ANOVA table is less than 0.05, there is a statistically significant relationship between the variables at the 95% confidence level.

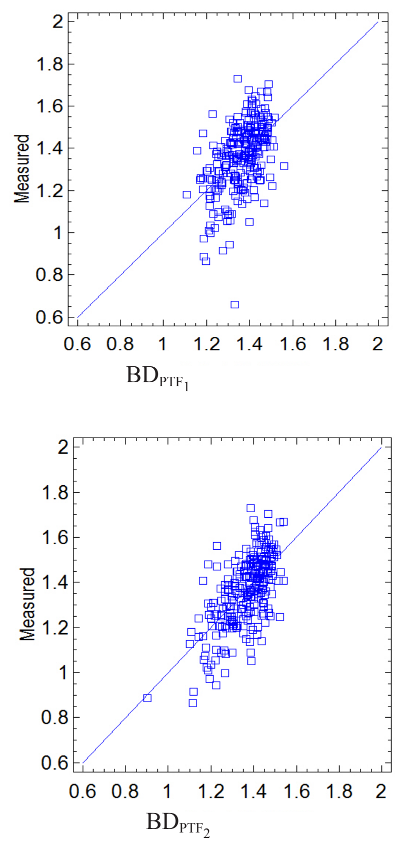

Fig. 1. Measured values versus predicted values (BD_{PTF_1}, BD_{PTF_2}).

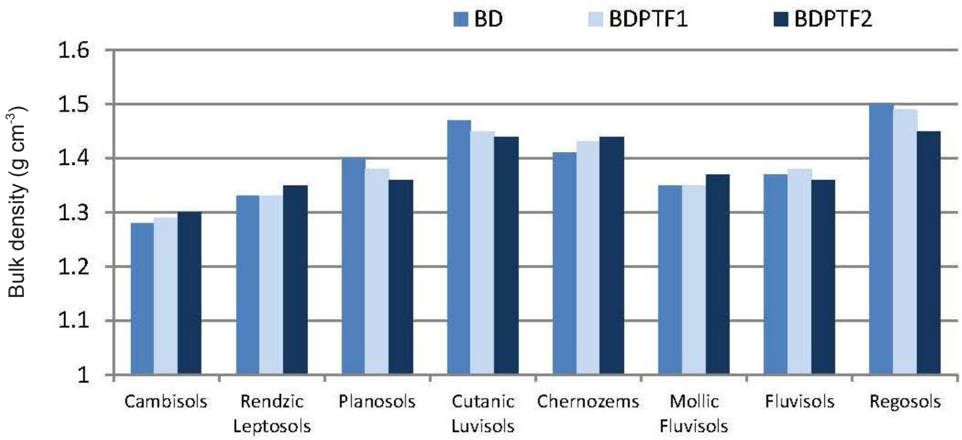

Fig. 2. Comparison between observed bulk density (BD) and predicted values of soil bulk density (BD_{PTF_1}, BD_{PTF_2}) (g cm^{-3}) in main soil types SR.

T a b l e 4. Comparison between measured bulk density and predicted values BD_{PTF_1}, BD_{PTF_2} (g cm^{-3})

Statistical parameter	BD	BD_{PTF_1}	BD_{PTF_2}
Average	1.362	1.362	1.363
Standard deviation	0.163	0.084	0.110
Coeff. of variation (%)	11.986	6.227	8.139
Minimum	0.657	1.107	0.574
Maximum	1.729	1.561	1.551

T a b l e 5. Summary of statistics of measured bulk density and model values of soil bulk density (key sampling sites, n=15)

Statistical parameter	BD	BD_{PTF_1}	BD_{PTF_2}	BD_B	BD_{MJ}
Average	1.360	1.365	1.321	1.284	1.235
Standard deviation	0.089	0.090	0.123	0.110	0.038
Coeff. of variation (%)	6.544	6.606	9.287	8.604	3.047
Min	1.240	1.215	1.060	1.039	1.173
Max	1.534	1.526	1.487	1.416	1.344

Since the P-value in the ANOVA table is less than 0.05, there is a statistically significant relationship between the variables at the 95.0% confidence level.

The values of bulk density of agricultural soils from Slovakia range between 1.2-1.6 g cm^{-3} (Kobza *et al.,* 2014). Despite the fact that the BD_{PTF_2} model explains a higher percentage of the variation than model BD_{PTF_1}, this model shows stronger predictive power for modelling within soil types (Fig. 2).

The model was validated using a data set consisting of 15 key sampling sites of PMS-S database which were different from those used to generate the equations. The set of key sampling sites represents the six dominant soil types of Slovakia (Cambisols, Stagnosols, Planosols, Fluvisols, Chernozems, Luvisols) with a rather wide range of agrochemical properties. A comparison of measured bulk density (BD) and soil bulk density as calculated by the pedotransfer equations (BD_{PTF_1} and BD_{PTF_2}) following the updated input parameters that have been evaluated in the PMS-S database (Table 5, Fig. 3) were made. Bulk density values calculated according to Bernoux *et al.* (1998) – BD_B and to Manrique and Jones (1991) BD_{MJ} (recommended by JRC for Europe) for comparison.

Sampling sites 6 to 8 are utilized as permanent grasslands, the rest of the sampling sites are of arable land. We found that models based on pedotransfer functions generally slightly lower the value of bulk density (with the exception of sampling sites 3, 9, 10 and 13 (Fig. 3)). Moreover, the best prediction of BD in the set of key sampling sites was from the BD_{PTF_1} model, according to the average values, together with minimum and maximum values (Table 6). The differences between measured soil bulk density and the model values vary from -0.144 to 0.243 g cm^{-3}. Furthermore, the average value of differences between the measured soil bulk density and the model values varies from 0.002 to 0.129 – and increases in the order: BD_{PTF_1} < BD_{PTF_2} < BD_{MJ} < BD_B. BD_{PTF_1} gave results closest results to the measured values. Barros and Fearnside (2015) in their work also describe lower values of bulk density in comparison with regional models. It is clear that locally generated equations will provide better estimations of soil bulk density, thus models BD_{PTF1_1} and BD_{PTF_2} are more suitable for

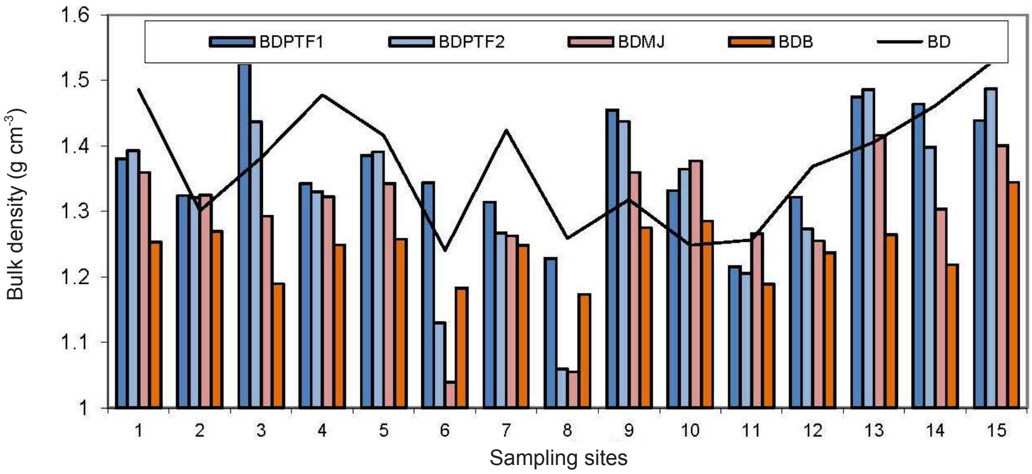

Fig. 3. Comparison between measured bulk density and bulk density values calculated by pedotransfer models (BD_{PTF_1}, BD_{PTF_2}, BD_B, BD_{MJ}).

T a b l e 6. Summary of statistics of soil bulk density in topsoil of Slovakia

	Soil bulk density (g cm^{-3})
Average	1.301
Median	1.301
Standard deviation	0.113
Coeff. of variation (%)	8.685
Minimum	0.730
Maximum	1.810

Slovak soils. According to Adams (1973), Rawls (1983), Federer (1983), Tomasella and Hodnett (1998), Manrique and Jones (1991) and Bernoux *et al.* (1998), the differences between measured and modelled BD values are in the range of 0.010 to 0.380 g cm^{-3}.

The soil bulk density model (BD_{PTF_1} = 3.14816 - 0.0118028ILc - 0.0169725S - 0.0152297P) that was used for the preparation of the soil bulk density map of Slovakia (Fig. 4), utilised soil textural data from 17 523 sampling sites held in the complex soil survey database. The original paper database was transformed into a digital version by Skalský and Balkovič (2002).

Model values of representative bulk density for agricultural soils are presented in Fig. 4. The higher values of bulk density are located in regions with a greater representation of light (sandy and sandy-loamy) soils. These regions are mainly found in Zahorie, Podunajska and

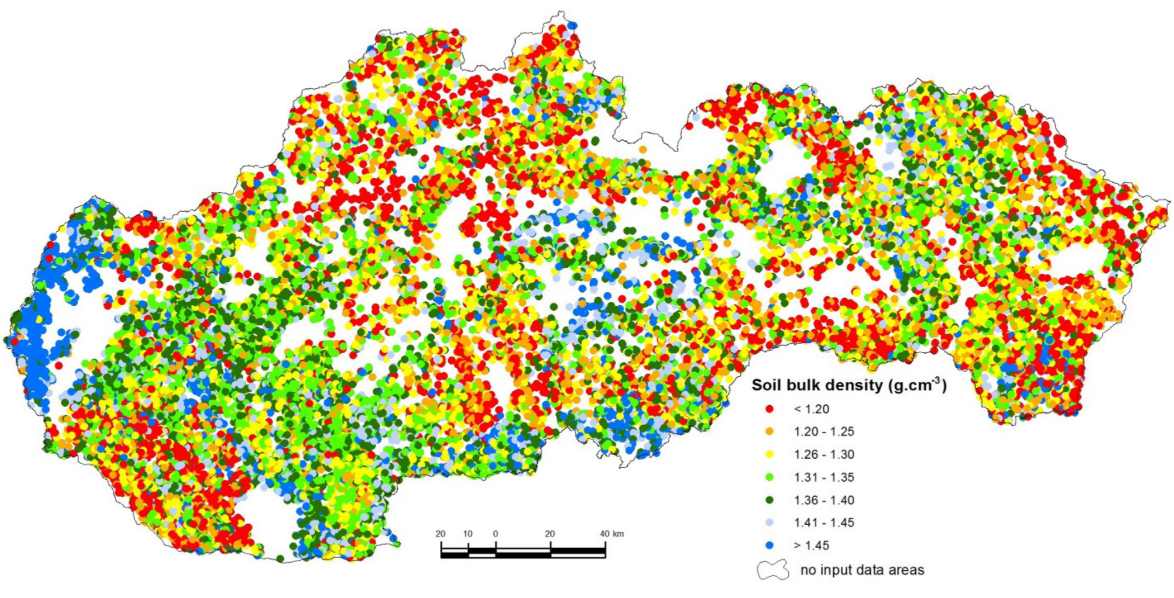

Fig. 4. Bulk density of agricultural soils.

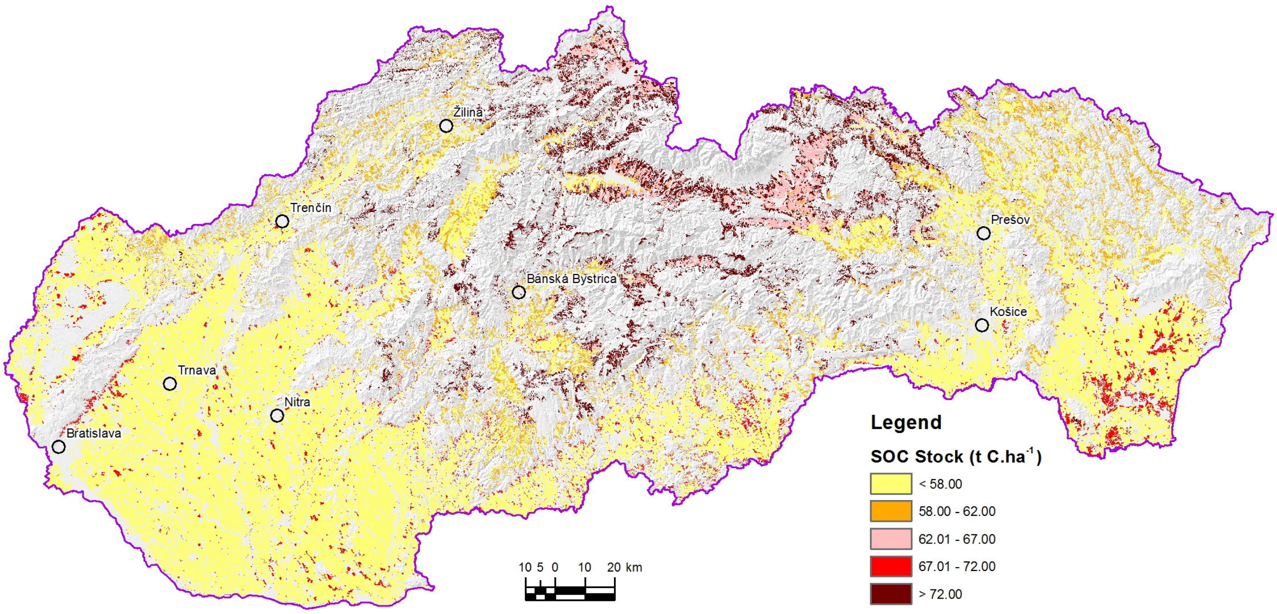

Fig. 5. Soil organic carbon stock in topsoil of agricultural soils.

Vychodoslovenska nizina (lowland), and also partly in the flysh region and Juhoslovanska kotlina (hollow basin). The lowest BD values have been observed in regions with heavy soils (predominantly clay loamy and clayey soils). These findings are in accordance with the measured values of bulk density for individual soil types and representative soil textural categories (Houskova, 2002). From such representative values, it is possible to assess the susceptibility of soils to compaction. Sandy soils are the most resistant, have the lowest susceptibility to compaction, in comparison with heavy clayey soils. The latter have the highest susceptibility to compaction even when exposed to lower loads. They are so-called 'minute soils', with very narrow intervals of suitable water content (around field capacity) for cultivation (Houškova, 2008).

In general, topsoil is considered to be the most important soil layer according to the carbon content (Taalab *et al.,* 2013), which generally decreases with the depth. The map of topsoil carbon stock for agricultural soils in Slovakia (depth 0 – 30 cm) was prepared using the BD_{PTF_1} model and actual values of SOC from the CMS-P database monitoring database (Fig. 5). It should be noted that data obtained from BD_{PTF_1} model have been elaborated further using the ROTh C model for estimation of carbon stock (Barančíková *et al.,* 2010). Average carbon stock in soils in the depth 0 – 30 cm in Slovakia is seen to range between 59 to 67 t C ha^{-1}, depending on altitude. Lower amounts are typical for areas with altitude 0 – 300 m above sea level and higher for areas with altitude above 600 m above sea level (Širáň *et al*., 2013). This method is used to report national soil carbon inventories.

CONCLUSIONS

1. Using multiregression methods a distributed prediction of soil bulk density was produced. This was subsequently used in topsoil carbon stock determination.
2. It was created and compared pedotransfer models of bulk density that employed available empirical soil data.
3. These models generally generate slightly decreased predicted bulk density values, in comparison with measured ones.
4. The utilisation of models in the verification set showed good prediction capacity for bulk density also in the case of soils with high variation of input data.
5. The soil bulk density model was used for preparation of first approximate soil bulk density map for Slovakian agricultural soils. The data obtained from pedotransfer model have been further elaborated using the Rothamsted carbon model, so as to generate an estimation of carbon stock in topsoil layer for Slovakian agricultural soils map.

Conflict of interest: The Authors do not declare conflict of interest.

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