Pedosphere **26**(3): 362–373, 2016
doi:10.1016/S1002-0160(15)60049-2
ISSN 1002-0160/CN 32-1315/P

Published by Elsevier B.V. and Science Press

PEDOSPHERE

www.elsevier.com/locate/pedosphere

Pedotransfer Functions for Estimating Soil Bulk Density: A Case Study in the Three-River Headwater Region of Qinghai Province, China

YI Xiangsheng[1,2], LI Guosheng[2,*] and YIN Yanyu[3]

[1] *Agriculture Resource Monitoring Station, Chinese Academy of Agricultural Engineering, Beijing 100125 (China)*
[2] *Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101 (China)*
[3] *Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101 (China)*

(Received August 25, 2015; revised January 24, 2016)

ABSTRACT

Bulk density (BD) is an important soil physical property and has significant effect on soil water conservation function. Indirect methods, which are called pedotransfer functions (PTFs), have replaced direct measurement and can acquire the missing data of BD during routine soil surveys. In this study, multiple linear regression (MLR) and artificial neuron network (ANN) methods were used to develop PTFs for predicting BD from soil organic carbon (OC), texture and depth in the Three-River Headwater region of Qinghai Province, China. The performances of the developed PTFs were compared with 14 published PTFs using four indexes, the mean error (ME), standard deviation error (SDE), root mean squared error (RMSE) and coefficient of determination (R^2). Results showed that the performances of published PTFs developed using exponential regression were better than those developed using linear regression from OC. Alexander (1980)-B, Alexander (1980)-A and Manrique and Jones (1991)-B PTFs, which had good predictions, could be applied for the soils in the study area. The PTFs developed using MLR (MLR-PTFs) and ANN (ANN-PTFs) had better soil BD predictions than most of published PTFs. The ANN-PTFs had better performances than the MLR-PTFs and their performances could be improved when soil texture and depth were added as predictor variables. The idea of developing PTFs for predicting soil BD in the study area could provide reference for other areas and the results could lay foundation for the estimation of soil water retention and carbon pool.

Key Words: alpine soil, artificial neural network, multiple linear regression, organic carbon, soil depth, soil texture

Citation: Yi X S, Li G S, Yin Y Y. 2016. Pedotransfer functions for estimating soil bulk density: A case study in the Three-River Headwater region of Qinghai Province, China. *Pedosphere*. **26**(3): 362–373.

INTRODUCTION

Bulk density (BD), an important soil physical property, is mostly measured to calculate soil hydraulic properties (Hillel, 1998; Bruand *et al.*, 2003) or to characterize soil compaction (Abu-Hamdeh, 2003). In addition, BD is also widely used as an essential parameter for soil weight-to-volume conversion, especially for calculating the carbon and nutrient mass of a soil layer (Nanko, *et al.*, 2014). In theory, soil BD is easily measured and does not require complex analyses, but in practice, direct measurement of soil BD in large-scale area remains labor intensive, time consuming, tedious and expensive (Kaur *et al.*, 2002). As a result, BD is frequently missing during routine soil surveys (Morvan *et al.*, 2008; Suuster *et al.*, 2011; Martin *et al.*, 2009) and must be obtained by alternative methods. Therefore, finding an indirect, inexpensive and rapid way to acquire soil BD has received great attention of many scientists.

It is well known that soil BD is related to several other soil parameters, such as soil organic fraction, texture, structure, depth and moisture (Adams, 1973; Rawls, 1983). Pedotransfer functions (PTFs), a term coined by Bouma (1989), have been developed to estimate soil BD from more easily available soil variables, such as organic carbon (OC) (Jeffrey, 1970; Adams, 1973; Harrison and Bocock, 1981; Federer, 1983; Honeysett and Ratkowsky, 1988; Manrique and Jones, 1991; Tamminen and Starr, 1994) and texture (Rawls, 1983; Gosselink *et al.*, 1984; Tamminen and Starr, 1994; Ball *et al.*, 2000; Kaur *et al.*, 2002). However, every PTF developed so far is based on a limited database or a special condition, and there is a lot of uncertainty in applying the PTFs to other soil conditions (Lee, 2005). De Vos *et al.* (2005) further pointed that

---

[*] Corresponding author. E-mail: ligs@igsnrr.ac.cn.

there were large differences in the performance of published PTFs when they were applied to environments different from those used for their calibration. Therefore, published PTFs should be used with care when applied in environments other than the one in which they were developed. Especially, if we want to use one of the established PTFs directly in a limited geographic area, it is necessary to compare their performances in advance.

Comparative studies of established PTFs for estimating soil BD have been conducted since the late 1990s by many scholars (Boucneau *et al.*, 1998; De Vos *et al.*, 2005; Martin *et al.*, 2009; Jalabert *et al.*, 2010; Han *et al.*, 2012). It was found that the applicability of existing PTFs is limited for their local soil data, and the PTFs or a set of parameters require modifications for better applicability to their local soil data (Nanko *et al.*, 2014). Thus, if we want to get the best estimation of soil BD, it is necessary to develop PTFs for the local soil data and compare their performances with those of the published PTFs, in addition to compare the performances of published PTFs. The methods to develop PTFs for predicting soil BD include fitting of various types of equations, such as linear, exponential, logarithmic, decimal and polynomial equations, which vary from basic to multivariate spatial statistics (Suuster *et al.*, 2011). However, most published PTFs are generally derived from regression methods that aim to fit a single model for the estimation of soil BD (Jalabert *et al.*, 2010). Other methods, such as artificial neural network (ANN), bagging, random forests and boosting, are rarely used to develop PTFs for predicting BD (Najafi and Givi, 2006; Tranter *et al.*, 2007).

Alpine soil is an important soil type in the world, which is mainly distributed in the high-altitude areas, especially in the Tibetan Plateau, China. Compared to other soils, alpine soil has unique physical and chemical properties because of its special formation environment. Published PTFs for predicting BD have been developed for forest soils (Prévost, 2004; De Vos *et al.*, 2005), agricultural soils (Calhoun *et al.*, 2001; Tranter *et al.*, 2007), soils of the Brazilian Amazon (Bernoux *et al.*, 1998) and several other regions. However, though alpine soils cover more than 1 500 000 km^2 in the world, there are still few literatures about PTFs for BD estimation of alpine soils. Especially, to our knowledge, there are no studies developing PTFs for estimating soil BD in the Tibetan Plateau, China.

This study was conducted in the Three-River Headwater region in Qinghai Province, China, which is the main distribution region of alpine soil in the Tibetan Plateau. The objectives of this study were to: 1) develop PTFs for estimating BD from soil OC, texture and depth data based on multiple linear regression (MLR) and ANN; 2) see whether published PTFs were suitable to apply in the study area or not and 3) test/compare the applicability of proposed and published PTFs in order to verify which is better.

MATERIALS AND METHODS

Study area

This study was conducted in the Three-River Headwater region (31°39′–36°12′ N, 89°45′–102°23′ E) of Qinghai Province, China, which is in the hinterland of the Tibetan Plateau and is a typical permafrost region (Niu *et al.*, 2012). There are three principal rivers in this region, namely, the Yangtze River, the Yellow River and the Lancang River. The altitude in the study area ranges from 2 610 to 6 950 m, with an average of 4 500 m. According to the 12 meteorological stations over the whole region (Yi *et al.*, 2012, 2013), the annual mean temperature varies from −5.38 to 4.14 °C, and the annual mean precipitation ranges between 262.2 and 772.8 mm.

Soils of the Three River Headwater region include 16 soil great groups and 41 soil subgroups according to Genetic Soil Classification of China (GSCC) and the main soil great groups are alpine meadow soils, alpine steppe soils and alpine desert soils (Fig. 1). The characteristics of referencing among the GSCC, Soil Taxonomy (ST), World Reference Base for Soil Resources (WRB) and Chinese Soil Taxonomy (CST) could be seen in Shi *et al.* (2004, 2006a, 2006b) and Yu *et al.* (2005).

Soil sampling and analysis

A total of 495 soil samples were taken from 100 soil profiles in the study area (Fig. 1), which covered 11 soil great groups and 27 soil subgroups. The detailed numbers of the soil profiles and soil samples from each soil great group and subgroup are listed in Table I.

Soil sampling to measure BD was carried out in three replications using the core method with standard sharpened steel cylinders of 100 cm^3 volume (53 mm diameter, 50 mm height). At the same time, about 1 kg disturbed soil samples were collected at the same soil depth using individual plastic bags for the measurement of soil texture and OC. The depths of the soil samples ranged from 5 to 120 cm, with an average of 50 cm and a median of 43 cm. All the coordinates of the sampling locations were determined with a highly accurate global positioning system (GPS).

Before the analysis of their properties in laborato-