Pedosphere **25**(4): 580–591, 2015
ISSN 1002-0160/CN 32-1315/P

Published by Elsevier B.V. and Science Press

PEDOSPHERE

www.elsevier.com/locate/pedosphere

Digital Soil Mapping Using Artificial Neural Networks and Terrain-Related Attributes

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(Received July 20, 2014; revised April 7, 2015)

ABSTRACT

Detailed soil surveys involve costly and time-consuming work and require expert knowledge. Since soil surveys provide information to meet a wide range of needs, new methods are necessary to map soils quickly and accurately. In this study, multilayer perceptron artificial neural networks (ANNs) were developed to map soil units using digital elevation model (DEM) attributes. Several optimal ANNs were produced based on a number of input data and hidden units. The approach used test and validation areas to calculate the accuracy of interpolated and extrapolated data. The results showed that the system and level of soil classification employed had a direct effect on the accuracy of the results. At the lowest level, smaller errors were observed with the World Reference Base (WRB) classification criteria than the Soil Taxonomy (ST) system, but more soil classes could be predicted when using ST (7 soils in the case of ST *vs.* 5 with WRB). Training errors were below 11% for all the ANN models applied, while the test error (interpolation error) and validation error (extrapolation error) were as high as 50% and 70%, respectively. As expected, soil prediction using a higher level of classification presented a better overall level of accuracy. To obtain better predictions, in addition to DEM attributes, data related to landforms and/or lithology as soil-forming factors, should be used as ANN input data.

Key Words: digital elevation model attributes, multilayer perceptron, soil classification, soil-forming factors, soil survey

Citation: Bagheri Bodaghabadi M, Martínez-Casasnovas J A, Salehi M H, Mohammadi J, Esfandiarpoor Borujeni I, Toomanian N, Gandomkar A. 2015. Digital soil mapping using artificial neural networks and terrain-related attributes. *Pedosphere*. **25**(4): 580–591.

Although at present there is a high demand for detailed soil surveys for different purposes, in many countries (particularly developing countries) only a few or no areas are covered by detailed soil maps (scales of 1:25 000 or more detailed). The main reasons are their high cost and the time involved in their elaboration. Due to these constraints, predictions of soil classes in soil mapping have generally been based on the relationships between soil properties and related features that are readily measureable, such as physiographic units and geomorphic landforms. Conventional approaches in soil mapping, such as soil-landscape relationships used in Iran (Mahler, 1970; Bagheri Bodaghabadi, 2011), the interpretation of aerial photography widely used in UK (Areola, 1974) and USA (Soil Survey Division Staff, 1993), and geopedology used in the Netherlands (Zinck, 1988), are relevant examples of different methodologies for soil mapping. In these methods, the relationships between soil development and hydrography, vegetation cover, land use and relief play a very important role. The advent of digital mapping techniques has opened new horizons in soil mapping, with it now being possible to develop new methods to map soils in detail at a lower cost and in a faster time than when conducting conventional soil surveys.

McBratney *et al.* (2003) and Scull *et al.* (2003) reviewed a series of modern approaches for the digital representation of soil maps and environmental variables which, taken together, helped to create the concept of predictive soil mapping. These techniques can be used to improve the understanding of the relationships between soils and the environment, and to exploit the results obtained by digital soil mapping (DSM), which can be defined as the computer-assisted production of soil maps. It entails the creation of spatial soil information based on numerical models, which account for spatial and temporal variations in soil properties on the basis of soil information and related environmental

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variables (Lagacherie and McBratney, 2007). In DSM, many different methods can provide solutions, including fuzzy logic, decision trees, expert knowledge, artificial neural networks (ANNs) and others.

ANNs are being widely used in soil science research. They are mainly used for predicting soil properties and, though to a lesser extent, the spatial distribution of taxonomic classes. Some examples of the use of ANNs for prediction of soil properties are: soil physical properties (Pachepsky and Rawls, 1999; Sarmadian and Taghizadeh Mehrjadi, 2008; Khalilmoghadam *et al.*, 2009; Banu Ikizler *et al.*, 2010; Erzin *et al.*, 2010), soil chemical properties (Patel *et al.*, 2002; Amini *et al.*, 2005; Saffari *et al.*, 2009; Zhao *et al.*, 2010), yield prediction (Kaul *et al.*, 2005; Alvarez, 2009; Norouzi, 2010; Dai *et al.*, 2011), heavy metals (Shang *et al.*, 2004; Amegashie *et al.*, 2006; Anagu *et al.*, 2009), and soil erosion (Licznar and Nearing, 2003; Kim and Gilley, 2008; Abdollahzadeh *et al.*, 2011). Another important application of ANNs has been the prediction of pedotransfer functions, particularly soil hydraulic properties (McBratney *et al.*, 2003).

Some researchers such as Lehmann *et al.* (1999), Zhu (2000) and Behrens *et al.* (2005) have conducted soil mapping based on the spatial distribution of soil taxonomic classes by means of ANNs. The work of Lehmann *et al.* (1999), which was one of the first in this field, described the ANN topologies and the learning algorithms applied. However, because they did not provide the details of the results and the accuracy of using these soil maps to make predictions, it has not been possible to carry out any meaningful comparison. Zhu (2000) developed an ANN approach to populate a soil similarity model using fuzzy logic. The output was a set of similarity values for a given number of soil classes, which were used for the hydroecological modeling of watersheds. The soil map derived from the ANN was much more detailed and accurate than the conventional soil map (Zhu, 2000). McKenzie and Ryan (1999) reported that the use of suitable environmental variables was more important than the choice of the prediction method. Along these lines, Behrens *et al.* (2005) focused on the development of a methodology based on ANN and digital elevation data to predict the spatial distribution of soil units. They found that the combination of ANN and digital terrain analysis was time-saving and also cost effective, providing notable results. Another example of this approach can be found in the work of Bagheri Bodaghabadi *et al.* (2011), who demonstrated a relatively strong correspondence between soil series distribution and topographical properties using a digital elevation model (DEM) and canonical correspondence analysis (CCA). The topographical factors measured in their study explained 71.8% of the total variation in soil distribution. However, the part of the variation not explained by the model suggested that other factors or interactions that were not taken into account should also be considered. These could include parent material and vegetation, which could help to elucidate the complexity of the relationships between DEM attributes and soil series (Bagheri Bodaghabadi *et al.*, 2011).

Pedogenetic factors can also play an important role in digital soil mapping. Grinand *et al.* (2008) and Möller *et al.* (2008) demonstrated that predictive soil distribution models could be generated on the basis of the relationships between soil classes and geomorphological units. Jafari *et al.* (2012) showed that digital terrain analysis with clear descriptions of geomorphological, geological and pedological processes could be a promising key technology in future soil mapping, since pedogenic factors and terrain-related attributes have a high correlation. Gessler *et al.* (2000) used terrain attributes for modeling soil-landscape properties and argued that the distribution of soil classes suggested 3 topographically driven pedogeomorphic process zones: i) concave areas dominated by processes of accumulation or gain of water and sediment, ii) convex areas dominated by losses of sediment and water, and iii) a relatively stable shoulder area dominated by *in situ* soil forming processes such as vertical translocation. Terrain analysis quantifies the relief component of models characterizing soil formation. Accordingly, terrain analysis will be more useful in the environments where topography is one of the main processes driving soil formation (McKenzie *et al.*, 2000).

From this background, and with the aim of improving soil unit predictions based on digital soil mapping techniques, the main objective of the present work was to use ANNs and terrain-related attributes extracted from a DEM to predict the spatial variability of soil units. The geopedological approach, which assumes the existence of soil-relief relationships, was adopted for this purpose. The work also evaluated the application of the obtained ANNs to similar soil-landscape relationships in Central Iran.

MATERIALS AND METHODS

Study area and sampling design

The study area (31°54′–31°56′ N, 51°12′–51°15′ E) covered approximately 1 000 ha and was located in the