Geoderma Regional 14 (2018) e00175

Contents lists available at ScienceDirect

Geoderma Regional

journal homepage: www.elsevier.com/locate/geodrs

Geomorphometric segmentation of complex slope elements for detailed digital soil mapping in southeast Brazil

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ARTICLE INFO

Article history:
Received 25 December 2017
Received in revised form 1 May 2018
Accepted 7 May 2018
Available online xxxx

Keywords:
Digital terrain analysis
Decision tree
Hillslope elements
Map units
Soil property
Oxisols

ABSTRACT

Hillslope elements have considerable potential in predicting soil properties and types in the landscape, making them likely to be a useful basis for detailed soil mapping. The goal of this research was to apply a previously developed digital hillslope position (DHP) model, calibrate it as needed to a Brazilian landscape, and test its utility as a basis for identification of detailed soil map units. The study area covers 2500 ha and is located on the border between the municipalities of Piracicaba and Santa Bárbara d'Oeste, São Paulo state, Brazil. A digital elevation model, with spatial resolution of 5 m, was used to obtain slope gradient, profile curvature and relative elevation with different analysis scales. Hierarchical rules for these digital terrain derivatives were used to segment the landscape into hillslope positions. The user-calibrated hillslope position model was verified against local experience by identifying the hillslope position in the field and comparing it with the model classification using the Kappa statistic and a confusion matrix. Soil samples were collected across multiple hillslopes with different lithologies. The samples were analyzed for chemical composition and soil particle size separates. The measured soil properties were assessed for statistical significance by variance analysis among hillslope position, parent material, and the interaction between the two. Student's *t*-tests were performed iteratively across each hillslope position within a given parent material to identify specifically which soil properties were significantly different among the hillslope position map units. Variance analysis of soil samples located within the respective parent material map units identified significant differences for all soil properties measured, but only for some soil properties when categorized by DHP. Focusing on the parent material with a sufficient quantity of samples, there was always at least one hillslope position that was significantly different from the others for each soil property. Because each of these map units presented a significant difference in at least one soil property, they are useful for detailed soil mapping.

1. Introduction

The goal of soil mapping is to communicate as much soil variation in the landscape as appropriate for the map scale. Because soil profile properties cannot be observed directly from above ground, soil maps have an assemblage of areas of the same nature, known as map units (Legros, 2006), that associate sets of soil profile properties with features that can be delineated from more readily observable information. Therefore, the challenge is to find the best basis for identifying the map units to differentiate the variation of soil properties in the landscape.

There are only exploratory or reconnaissance soil maps covering most of the Brazilian territory and soil types corresponding to the soil series concept are not yet established (Carvalho et al., 2015; Lepsch, 2013). Because of the available soil maps' coarse cartographic scale, they are not useful for farming and civil engineering management decisions at field or catchment scales (Sanchez et al., 2009). Only 0.25% of the Brazilian territory is covered by 1st or 2nd order soil maps (scale ≤1:35,000) (Carvalho et al., 2015; Mendonça-Santos and Santos, 2007). This coverage is much less than other countries of similar size, such as the USA, where the National Cooperative Soil Survey (NCSS) has mapped the soils of nearly every county at the 2nd order scale (1,15,840–1:24,000), identifying map units at the soil series level.

These soil maps were produced from a combination of soil-landscape relationships based on the tacit knowledge of field experienced pedologists, with field observations and point measured soil properties (Hudson, 1992). Because this knowledge is based on the mapper's experience, it is not explicit for other mappers and it is difficult to quantify and reproduce for detailed scale (Shi et al., 2009). Although the soil-landscape paradigm has been a useful qualitative predictor of similar

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https://doi.org/10.1016/j.geodrs.2018.e00175
2352-0094/

soil forming environments (Hudson, 1992), the many quantitative relationships between soil profile properties and environmental covariates have yet to be fully elucidated.

Slope gradient and profile curvature are known to affect the soil properties' spatial distribution (MacMillan et al., 2000; Mohammadi et al., 2016; Park et al., 2001; Pennock, 2003). However, these digital terrain derivatives do not always appear to correlate with soil properties as expected. This potential mismatch is likely due to the wrong analysis scale being selected for analysis, among other things (Drăguţ et al., 2009; Miller, 2014). A way to improve this situation is to document and make explicit all aspects of defining landscape features mapped according to the tacit knowledge acquired over the years by soil survey experts (Bathgate and Duram, 2003). Thus, a quantitative approach to generate and store information of the landscape characteristics would be useful for soil mapping in an objective, consistent, updatable, and reproducible method.

Among the detailed landscape features, hillslope elements have considerable potential to predict the soil properties and types because they identify functional zones in the context of water and sediment flow in a landscape (Gerrard, 1992; Ruhe, 1960; Ruhe and Walker, 1968; Wysocki et al., 2011). Hillslope position as defined by Ruhe (1960) and Wysocki et al. (2011) consists of five elements: summit, shoulder, backslope, footslope, and toeslope. Summits and shoulders are located in the highest part of a hill. Backslopes are zones of transport where materials are removed and transported through the most inclined part to the lower hillslope elements, which are footslopes and toeslopes (Wysocki et al., 2011). In certain geomorphic conditions, some hillslope elements may be absent and/or occur in an alternating pattern, such as a footslopes below a shoulder, lacking a backslope in between. An example of this type of hillslope element pattern is observed when complex slopes are mapped with a high level of detail (Fig. 1) (Wysocki et al., 2011).

Several studies have carried out a quantitative categorization of general landscape features (Burrough et al., 2000; Cunha et al., 2018; Drăguţ and Blaschke, 2006; Drăguţ and Dornik, 2016; Etzelmüller et al., 2007; Iwahashi and Pike, 2007; Jasiewicz and Stepinski, 2013; Jasiewicz et al., 2014; Vannametee et al., 2014), and some others at the sub-landform or hillslope scale (Gökgöz and Baker, 2015; MacMillan et al., 2003; Qin et al., 2009; Zhu et al., 2018). In this regard, Miller and Schaetzl (2015a) captured the tacit knowledge of soil scientists to quantify the analysis scales and thresholds of the digital terrain derivatives equivalent to soil scientists' assessment of hillslope position in the field. This digital hillslope position (DHP) model used slope gradient, relative elevation, and profile curvature at different analysis scales to apply the hillslope position concept to a digital elevation model (DEM). The validation of this model showed 59% agreement between soil scientists' field assessments and the final DHP model's prediction, which was considered reasonable given the potential variability between different soil scientists.

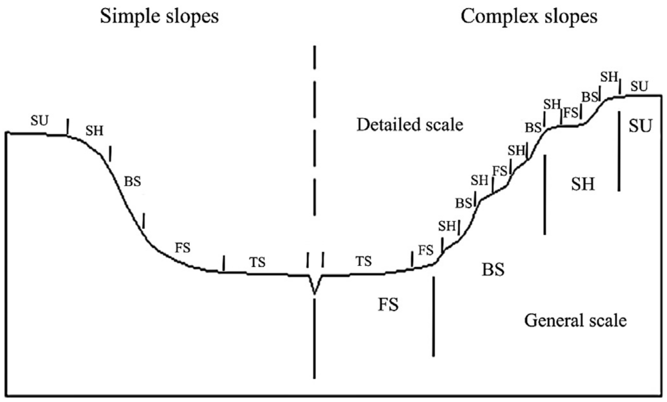

Fig. 1. Diagram of simple slopes *versus* complex slopes based on the hillslope position model by Ruhe (1960) (after Wysocki et al., 2011). SU: Summit, SH: Shoulder, BS: Backslope, FS: Footslope, and TS: Toeslope.

The digital segmentation of hillslope elements is promising for soil mapping for several reasons, among them: (a) consistent selection of representative sites for morphological description and collection of soil samples (Drăguţ and Dornik, 2016; Park and Van De Giesen, 2004; Yang et al., 2012; Zhu et al., 2008; Zhu et al., 2010), (b) delineation of mapping units (Moravej et al., 2012), (c) disaggregation of complexes in the soil map units with more than one soil type, improving both the detail and the applicability (Miller and Schaetzl, 2015a; Odgers et al., 2014), and (d) support in the prediction of soil properties in areas that present similarity of soil formation factors, highlighting both parent material and relief (MacMillan et al., 2000; Pennock and Corre, 2001).

The goal of this research was to calibrate the DHP model developed by Miller and Schaetzl (2015a) as needed for a Brazilian landscape. After that, this model was tested to verify its effectiveness for identification of detailed soil map units.

2. Methods

2.1. Location and characterization of the study area

The study area covers 2500 ha and is located on the border between the municipalities of Piracicaba and Santa Bárbara d'Oeste, São Paulo state, Brazil. The climate is classified as Cwa in the Köppen classification system, which is characterized by a humid subtropical mesothermic temperature regime with dry winters between June and August, and rainy summers between November and January (Alvares et al., 2013). The area is mostly cultivated with sugarcane, with some remnants of native vegetation and exotic species such as Pinus and Eucalyptus trees.

The area is geomorphologically located within the Paulista Peripheral Depression, which has an area approximately 100 km wide and 400 km long (Bigarella et al., 1965; Penteado, 1969). Parent materials are from members of the Irati, Tatuí, and Itararé formations (Fig. 2) (Vidal-Torrado, 1994). During the Upper Neogene and Quaternary periods, unconsolidated clayey sediments recognized as from the Rio Claro Formation (Neo-Cenozoic coverage) were deposited in the study area from other parts. These sediments were reworked and subjected to pedogenesis cycles that occurred during the semiarid phases in Brazil, coinciding with the Late Pleistocene glacial periods of North America (Penteado, 1969). These clayey superficial deposits remain on summits, at altitudes around 600–630 m (Penteado, 1976), and correspond to thick depositions (from five to ten meters), mainly with soils classified as Oxisols (polygenetic soil) (Vidal-Torrado et al., 1999).

This area was selected for this study because of its diversity of parent material and geoforms. Another reason for selecting this area was the availability of a geologic map at the scale of 1:25,000 (Fig. 2), which allowed us to compare the variation of soil properties between hillslope positions within areas mapped as the same parent material.

2.2. Digital segmentation of hillslope position at a detailed level by digital terrain analysis

Contour lines with 5-m equidistance and specific elevation at some points were digitized from planialtimetric maps at the 1:10,000 scale obtained from the Geographic and Cartographic Institute of the São Paulo state. These data were interpolated to obtain a DEM with spatial resolution of 5 m in GRASS GIS 7.0.4 (Geographic Resources Analysis Support System, 2015). The interpolation method used was the Regularized Spline with Tension, because it is considered to be the most suitable for vector data (Mitášová and Hofierka, 1993; Neteler and Mitasova, 2008).

The resulting DEM was used to obtain the following digital terrain derivatives: slope gradient and profile curvature with an analysis scale of 15 m (3 × 3 neighborhood) and 65 m (13 × 13 neighborhood), respectively (Miller, 2014), using the r.paramscale function in GRASS