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Scale-dependency of LiDAR derived terrain attributes in quantitative soil-landscape modeling: Effects of grid resolution vs. neighborhood extent

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ABSTRACT

Quantifying the spatial distribution of soil properties is essential for ecological and environmental modeling at the landscape scale. Terrain attributes are among the primary covariates in soil-landscape models due to their control on energy and mass fluxes, which in turn control the spatial distribution of soil properties and processes. While numerous studies have demonstrated the importance of terrain attributes for predicting landscape-scale soil variability, considerable uncertainty exists as to the scale-dependency of light detection and ranging (LiDAR) derived terrain attributes on the accuracy of soil-landscape model predictions. Thirty five pedons were sampled by genetic horizon in a 2300 ha forested watershed and three soil properties (clay, sum of bases, and total carbon), representing dominant pedogenic processes within the watershed were analyzed. Soil properties were used as dependent variables and terrain attributes, calculated from LiDAR derived DEMs of various grid resolutions (ranging from 5 to 50 m) and neighborhood extents (ranging from 15 to 350 m), were used as predictor variables in ordinary least-squares (OLS) regression models. Results from this study show that model predictions exhibit a strong scale-dependency, with percent clay, sum of bases, and total carbon having the highest R^2-adj and lowest root mean square error (RMSE) at coarse neighborhood extents (i.e., 150 to 300 m) both between soil variables and across soil depths. Furthermore, in certain instances grid resolution was also shown to affect soil–terrain correlations, although to a lesser degree than neighborhood extent. In many cases fine to moderate scale grid resolutions (i.e.,<30 m) more accurately represented terrain features, resulting in higher correlations to soil properties at fixed neighborhood extents relative to course grid resolutions. Additionally, these results show that fine scale topographic information (i.e., 1 to 5 m) does not necessarily provide a stronger predictor of soil spatial variability relative to moderate scale information. This study provides a robust framework for investigating pedogeomorphological processes on a landscape scale through examination of the scale dependency of modeled terrain attributes in quantitative soil-landscape modeling.

1. Introduction

Within the past century, dramatic increases in population growth combined with rapid industrialization have greatly affected the way in which natural lands are used and managed. Growing anthropogenic pressures resulting from these trends, including urbanization, environmental pollution and the increasing effects of climate change, are altering the structure and function of many ecosystems and the resulting services they provide (Rapport et al., 1998). Consequently, there is a growing need to quantify the biophysical properties of landscapes from a local- to regional- to national-scale, to promote sustainable resource management.

Soils play a fundamental role in transmitting, storing and reacting with natural and human-introduced materials, and thus exert a dominant control on the hydrologic and geochemical processes which drive ecosystem function. Consequently, quantifying the spatial distribution of soil properties is essential for ecological and environmental modeling at the landscape scale. To meet this challenge, soil–landscape modeling has emerged as a methodology for understanding the spatial distribution of soils and their coevolving landscapes (Scull et al., 2003). With the advent of geographic information systems (GIS), the greater accessibility of high resolution remotely sensed data (LiDAR, hyper-spectral/spatial imagery), and the development of spatial statistical techniques, it is now possible to integrate a variety of environmental factors that correlate with soil properties, thus greatly improving our ability to predict their spatial distribution.

Abbreviations: LiDAR, light detection and ranging; DEM, digital elevation model; OLS, ordinary least squares; RMSE, root mean square error; NRCS, Natural Resources Conservation Service.

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Among soil forming factors, topography and modeled terrain attributes have been used extensively to establish statistical associations with soil properties, including soil organic carbon (Arrouays et al., 1995; Gessler et al., 2000; McKenzie and Ryan, 1999; Moore et al., 1993; Ryan et al., 2000), texture (Arrouays et al., 1995; Bishop and Minasny, 2006; De Bruin, 1998; McKenzie and Austin, 1993; Moore et al., 1993), and soil depth (Gessler et al., 1995; McKenzie and Ryan, 1999; Park et al., 2001; Ryan et al., 2000; Sinowski and Auerswald, 1999; Walker et al., 1968). In many cases, terrain attributes provide the best indicator of soil properties in places where the variation of other environmental factors (e.g., climate, lithology, land-use) is relatively small (e.g., mountainous terrain) (Moore et al., 1993; Park and Burt, 2002). Soil development often occurs in response to the way in which water and soil materials move through and over the land surface, which in turn is controlled by local topography (Huggett, 1975). Thus, terrain analysis is most useful in landscapes where topographic shape is strongly related to the processes driving soil formation (McKenzie et al., 2000).

With the increasing availability of LiDAR derived DEMs, there has been a general assumption that terrain attributes derived at fine spatial resolutions will produce stronger correlations to soil properties, however, several recent studies have shown that this may not be true (Kim and Zheng, 2011; Park et al., 2009; Roecker and Thompson, 2010). The spatial relationship that exists between soil properties and terrain attributes is driven by underlying pedogeomorphological processes operating across a range of spatial scales. Most pedogeomorphological processes exhibit a strong scale dependency which results in the spatial pattern and range of soil properties across a landscape (Grunwald, 2006). Therefore, quantifying the scale dependent relationship between soil properties and terrain attributes is important in determining the optimal scale at which terrain attributes most accurately represent soil–landscape processes.

The spatial scale of terrain attributes is related to both the grid resolution of the DEM used and the neighborhood extent or size of the window over which they are calculated. While there have been many studies that have examined the effect of grid size on derived terrain attributes and their relationship to various biophysical landscape attributes (Vaze et al., 2010; Wechsler, 2007 and references therein) and soil properties (Anderson et al., 2006; Kim and Zheng, 2011; Park et al., 2009; Smith et al., 2006; Thompson et al., 2001), most of these studies calculate terrain attributes from adjacent grid cells in a 3 by 3 moving window. However, with this conventional approach, as the grid-size increases the neighborhood extent is also increased, thus making it impossible to differentiate between the effects of changing grid-size and changing neighborhood extent. Several recent studies have explicitly controlled for these two scale effects, allowing for the examination of each scale effect independently (Roecker and Thompson, 2010; Smith et al., 2006). When the grid resolution of a DEM is increased, there is a loss of topographic detail as the values from smaller resolution grid cells, representing micro-topography, are aggregated producing an average value for the larger grid area. Although this approach allows one to calculate terrain attributes at the spatial scale at which soil properties vary, the resulting decrease in accuracy may negatively affect soil–topography correlations. An alternative approach, first proposed by Wood (1996) and more recently promoted by Roecker and Thompson (2010), is to maintain a small grid resolution (e.g., 1–5 m) while varying the neighborhood extent of terrain attributes to match the spatial scale of the property being modeled, thus more accurately representing soil–landscape processes. Several studies have demonstrated the importance of neighborhood extent in influencing soil–landscape relationships (Park et al., 2001; Roecker and Thompson, 2010; Smith et al., 2006).

The main objective of this study is to characterize the scale-dependent soil–topography relationships in a forested watershed in Oregon's Coast Range mountains, with an explicit examination of the effects of changing grid resolution versus changing neighborhood extent. The specific objectives are to: (i) examine grid resolution effects while controlling for neighborhood extent, (ii) examine neighborhood extent effects while controlling for grid resolution, and (iii) assess the utility of high resolution terrain data over conventional scale DEM resolutions (e.g., 10–30 m) in predicting soil properties.

2. Materials and methods

2.1. Study site

The study was conducted in the Panther Creek Watershed, located on the east side of the Oregon Coast Range Mountains, USA. The Panther Creek study area (45° 18′ N, 123° 21′ W) is approximately 2300 ha and the elevation ranges from 100 to 700 m. Slopes and drainage basins are consistently steep throughout the watershed, approaching 90° in some areas. The Panther Creek Watershed has a marine-influenced climate with cold, moist winters and warm dry summers, with approximately 70% of precipitation occurring between November and March. At the higher elevations (i.e., 400–700 m), the watershed has a udic moisture regime with mean annual precipitation (MAP) ranging from 200 to 250 cm, and at lower elevations (i.e., 70–400 m) a xeric moisture regime, with MAP ranging from 100 to 150 cm. Mean annual temperature in the study area is 12 °C, with the temperature regime ranging from frigid at higher elevations to mesic at lower elevations. The soils in the western portion of the study area (high elevation areas) are formed from basalt bedrock (diabase), transitioning to the east where soils are formed over basalt and sedimentary bedrock (deep-water marine siltstone/sandstone) at lower elevations. Soils within the watershed are predominantly well-drained silt loam, silty clay loam, and clay loam soils. The dominant taxonomic classifications are Typic Haplohumults, Xeric Palehumults, and Andic Dystrudepts. Vegetation within the watershed is dominated by planted stands of Douglas-fir (*Pseudotsuga menziesii*), with significant amounts of western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), grand fir (*Abies grandis*), red alder (*Alnus rubra*), and big leaf maple (*Acer macrophyllum*). The study area is actively managed for timber production with an average rotation age from 40 to 60 years, resulting in a patchwork of even-aged Douglas-fir stands ranging from recent clear-cuts to mature second-growth forests (Fig. 1). Within the watershed, the land holdings are split between private (54%) and public (46%) ownership resulting in a range of different land-use practices and long-term management goals.

2.2. Soil sampling and analysis

Thirty-five soil sampling locations were selected by a purposive sampling design driven by pre-stratification of the watershed into homogeneous landscape units using multiple geospatial data layers (e.g., geological information, climatic data, aerial photography, land ownership maps, vegetation maps). At each of the thirty-five sampling locations, a single pedon was described and sampled by NRCS soil scientists, and sent off for analysis of soil physical and chemical properties of the <2-mm soil material at the NRCS National Soil Survey Laboratory (Lincoln, NE), following standard laboratory methods (Burt, 2004). The <2-mm soil fraction was dispersed for particle-size analysis following removal of organic matter and soluble salts. The sand fraction was separated by wet sieving. The silt and clay fractions were measured by the pipette method. Exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) were extracted with ammonium acetate (1 N, pH 7) and measured by an atomic absorption spectrophotometer (AAS). Total C (TC) analysis was performed by dry combustion.

Each soil pedon was sampled and described by genetic horizon, however, to facilitate comparison between profiles we segmented each profile into 1 cm slices and then aggregated the slices (weighted average) using a standardized soil depth structure consisting of two depth increments: 0 to 20 and 20 to 50 cm. The segmentation procedure